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Faculty of Science and Technology Mohammedia
Hassan II University of Casablanca
BP 146, 28806 Mohammedia Morocco

amstesmaroc@amstes.org

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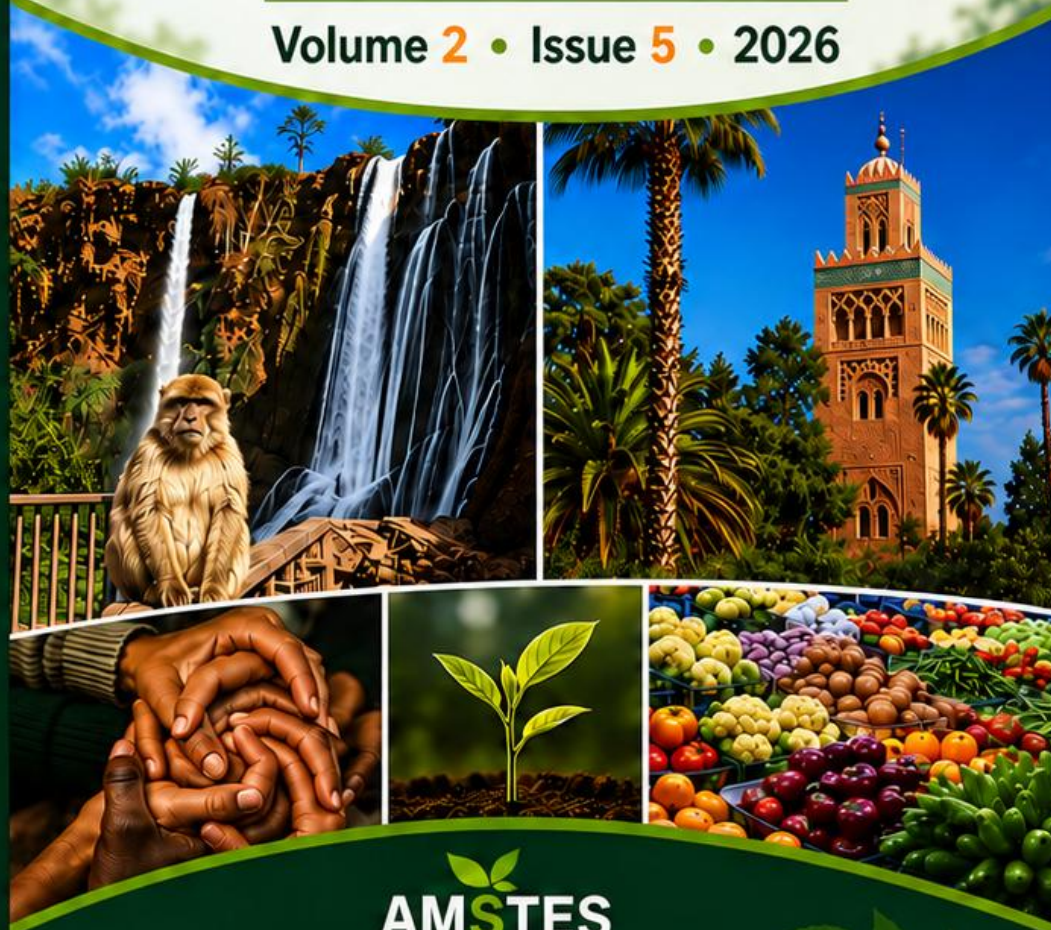
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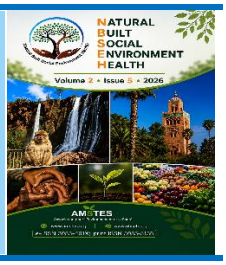
Understanding and utilising soil microbiomes for a more sustainable agriculture, edited by Kari E. Dunfield. Cambridge, UK: Burleigh Dodds Science Publishing, 2025. xxiv + 424 pp. Hardback, £155.00. ISBN 978-1-80146-474-1. eISBN 978-1-80146-476-5. DOI: 10.19103/AS.2024.0136
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LETTER TO THE EDITOR

Nepal Catastrophe: Some Implications

Sir,

Nepal has experienced catastrophic flooding and is bravely struggling with the consequences. Although Nepal contributes much less than 0.1% of global emissions compared to developing countries, such as China and India, Nepal's trivial addition to emissions does not exempt her from disproportionate devastation [1]. Nepal's natural and human resources are vulnerable to global heating through erratic rainfall, floods, landslides, and glacial lake outburst risks. All these have disrupted rural livelihoods, water availability, and agriculture across the country [2].

Nepal – and everyone else – had received ample warnings of this catastrophe. The April 2024 Birendra Lake outburst in Manaslu region, was started by a small ice-avalanche. This showed that the melting Himalaya can threaten downstream settlements and infrastructure [3]. The August 2024 Glacier Lake Outburst Flooding (GLOF) devastated Thame village in Khumbu region [4]. The unprecedented September 2024 disasters, when immense late-monsoon rainfall breached high-altitude glacial basins, caused widespread flooding and slope failure across Nepal [5].

The catastrophe of August 2026, after a massive glacier detachment, unleashed a vast debris torrent through the Trishuli river system. At least 1200 lives have been lost with more than 4000 still missing as of early September 2026. Vital infrastructure is now under millions of tonnes of pulverized rocks and mud [6]. Climate breakdown in Nepal is not just an abstract idea but a current reality with costly and painful effects. These are asymmetric: falling hardest on mountain communities, subsistence farmers, women, and all who have the least adaptability [7, 8].

This indicates a moral and practical imperative. The authors believe that the rest of the world should join forces to help our country, and thus prepare for the worst for their own countries. This is not simply a plea for humanitarian aid. The Polluter Pays principle and the Common but

Differentiated Responsibilities (CBDR) principle argue where we cannot argue, being now crushed and terrified [9].

The urgent help Nepal seeks is deeply embarrassing to our nation [10]. Without rapid, accessible, non-debt financial lifelines from developed nations, countries like Nepal will endure economic and non-economic losses that can reverse development gains and deepen vulnerability [11]. But with international support, Nepal can establish sustainable resilience —by investing in real-time early warning systems, climate-resilient infrastructure, vulnerable watershed management, climate-smart agriculture, and community-based disaster preparedness. Nepal's sufferings and her own courageous rescue efforts provide examples for others, opportunities for learning. The real world applies what is learned in principle and tests it so that the next endeavours by emergency workers can be even more robust and successful.

Supporting Nepal's survival is an investment in regional security, ecological integrity, and genuine global climate solidarity. Direct climate compensation should now become the central pillar of the international community's climate response and shared responsibility. The principle of thinking globally, acting locally, can transform global concerns into collective action.

References

[1] Crippa, M., Guizzardi, D., Pagani, F., Banja, M., Muntean, M., Schaaf, E., Quadrelli, R., Risquez Martin, A., Taghavi-Moharamli, P., Köykkä, J., Grassi, G., Rossi, S., Melo, J., Oom, D., Branco, A., Suárez-Moreno, M., Sedano, F., San-Miguel, J., Manca, G., Pisoni, E., & Pekar, F., 2025, *GHG Emissions of All World Countries – 2025 Report* (Luxembourg: Publications Office of the European Union)

[2] Dhakal, M., Ullah, A., Pandey, S., Khanal, S. N., Kafle, K. R., Yadav, A., & Saeed, F., 2026, Climate-induced loss and damage in Nepal: attribution analysis and institutional readiness for international support. *Frontiers in Climate* **8**, 1782991. https://doi.org/10.3389/fclim.2026.1782991

[3] Shakya, S., 2024, "The Thame Flood: A Window into the Himalayan Climate Crisis," *Nepal Economic Forum*, 26 August.

[4] Fujinami, H., Takahashi, N., Kanamori, H., Sato, Y., Sunako, S., Kato, M., Higuchi, A., Kadel, I., Shrestha, D., Kayastha, R. B., & Fujita, K., 2026, Multiscale Aspects of an Extreme Precipitation Event over Nepal in September 2024. *Scientific Online Letters on the Atmosphere* **22**, 27. https://doi.org/10.1007/s44393-026-00024-0

[5] Poudel, U., Gouli, M.R., Hu, K., Khadka, N., Regmi, R. K., & Thapa, B. R., 2025, Multi-GLOF hazard and exposure analysis of Birendra Lake in the Manaslu Region of Nepal. *Natural Hazards Research* **5**(4), 800-813. https://doi.org/10.1016/j.nhres.2025.03.007

[6] The Hindu Bureau, "Nepal flash floods aftermath updates: Death toll near 1,250 as more than 4,000 still missing," *The Hindu*, 03 September.

[7] Kandel, G. P., Bavorova, M., Ullah, A., Kaechele, H., & Pradhan, P., 2023, Building resilience to climate change: Examining the impact of agro-ecological zones and social groups on sustainable development. *Sustainable Development* **31**(5), 3796-3810. https://doi.org/10.1002/sd.2626

[8] Osemwegie, I., Sarkar, A., Akhtar, F., Kamau, H. N., Kumar, A., Kumar, N., Shrestha, S., Stellmacher, T., & Borgemeister, C., 2026, Gendered dimensions of climate-induced disasters: Unequal burdens and non-economic losses in the lesser Himalaya, Nepal. *Progress in Disaster Science* **31**, 100674. https://doi.org/10.1016/j.pdisas.2026.100674

[9] Damanik, Y. A. P., Sudibya, D. P. S., Wicaksono, S. S., Abidah, S. Q., Masyhar, A., Wulandari, C., Wilson, J. A., & Rahman, A. N., 2024, Who Pays for Climate Loss and Damage? State Obligations Under International Law Explained. *Indonesian Journal of Environmental Law and Sustainable Development* **3**(2), 40214. https://doi.org/10.15294/ijel.v3i2.40214

[10] Scown, M., Du, H., Jackson, G., De Rosa, S. P., & Boyd, E., Towards CS4L&D: Advancing climate services for loss and damage. *Climate Services* **30**, 100563. https://doi.org/10.1016/j.cliser.2025.100563

[11] Huber, J. & Murray, U., 2023, Turning climate justice into practice? Channeling loss and damage funding through national social protection systems in climate-vulnerable countries. *WIREs Climate Change* **15**(2). https://doi.org/10.1002/wcc.867

Yours sincerely,

Sahil Shrestha [a, b], **Shukra Raj Paudel** [a] ✉

[a] *Environmental Engineering Program, Department of Civil Engineering, Pulchowk Campus, Institute of Engineering, Tribhuvan University, Lalitpur, Nepal*

[b] *Department of Water Supply and Sewerage Management (DWSSM), Ministry of Infrastructure Development, Government of Nepal, Kathmandu 44600, Nepal*

✉ **Corresponding Author:**
Shukra Raj Paudel
✉ Email: srpaudel@ioe.edu.np | 📞 +977-9851220184 | ORCID: 0000-0002-5764-2990

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Nepalese Calamity of 2026: Manmade or Climate Driven

Capt. (Dr.) Nitin Agarwala *

Visiting Lecturer, Naval War College, Verem, Goa, India

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***Corresponding author**: Capt. (Dr.) Nitin Agarwala; **Email:** nitindu@yahoo.com

Graphical Abstract

The flash floods of August 26, 2026, along the Nepal-Tibet border were among the most devastating Himalayan disasters since the 2015 earthquake, resulting from climate-induced cryospheric instability whose impacts were greatly amplified by unplanned development, vulnerable infrastructure, high-risk hydropower projects, and gaps in transboundary early-warning systems. The calamity can therefore be considered a compound disaster rather than purely natural or manmade, highlighting the need for stronger climate-resilient planning and transboundary disaster risk reduction in the warming Himalayas.



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Abstract: The flash floods of August 26, 2026, along the Nepal-Tibet border are one of the most devastating Himalayan disasters since the 2015 earthquake. Some believe that the event was driven by anthropogenic activities. Others attribute it to climate change. To have greater clarity of the primary cause and to draw lessons for the future, this paper examines the catalysts behind the disaster. Although the primary geological event may have been rooted in climate change, the catastrophic scale of downstream destruction seems to have been greatly amplified by manmade vulnerabilities. Unplanned development leading to high density of downstream settlements, unabated infrastructure activities in the seismically weak Himalayas, and proliferation of high-risk hydropower infrastructure in narrow valleys significantly multiplied the economic and human toll. Hence, the calamity cannot be categorized as purely natural or manmade but a compound one, where climate-induced cryospheric instability collided with systemic failures in climate-resilient engineering and transboundary early-warning systems. The study concludes with policy recommendations for transboundary disaster risk reduction in the warming Himalayas.

Keywords: *Flash floods, Nepal, China, Glacier Failure.*

Introduction

Flash floods are relatively more frequent and destructive in the mountains than in the plains. Because of steep slopes and narrow valleys, the water accelerates and attains a much higher velocity than it would in the plains. This accelerated water brings with it boulders from the mountains, leaving a trail of destruction visible in downstream settlements and infrastructure [1]. These flash floods are caused by intense and heavy rainfall, sudden snow or ice melt, glacial collapses, glacial lake outbursts, or blockages caused by dams and landslides [2]. Many factors modify the environmental conditions in mountain areas which eventually impact the local geomorphic processes, frequency, magnitude, and timing of these flash floods. Activities such as deforestation, in-channel gravel mining, infrastructure development, damming of rivers in the mountains, and deeply incised foreland areas cause weakening of the soil holding capacity to result in massive soil erosion, destructive landslides, and major disruptions to water flow that trigger downstream floods. Most of these events occur through human activities. Climate change events increase the frequency and severity of these disasters.

One such flash-flood disaster occurred on August 26, 2026 along the Nepal-Tibet border, along the Bhote Koshi River and Trishuli River valley (see **Fig. 1**). In these narrow river valleys, the destruction was unprecedented and is considered the most devastating regional disaster since the 2015 Gorkha earthquake [3,4]. Rapid physical and environmental transformation by means of expansion of such socio-economic assets as high-risk hydropower installations and expanding commercial corridors [5] during decades of ambient warming leading to cryospheric instability provided a recipe for disaster.

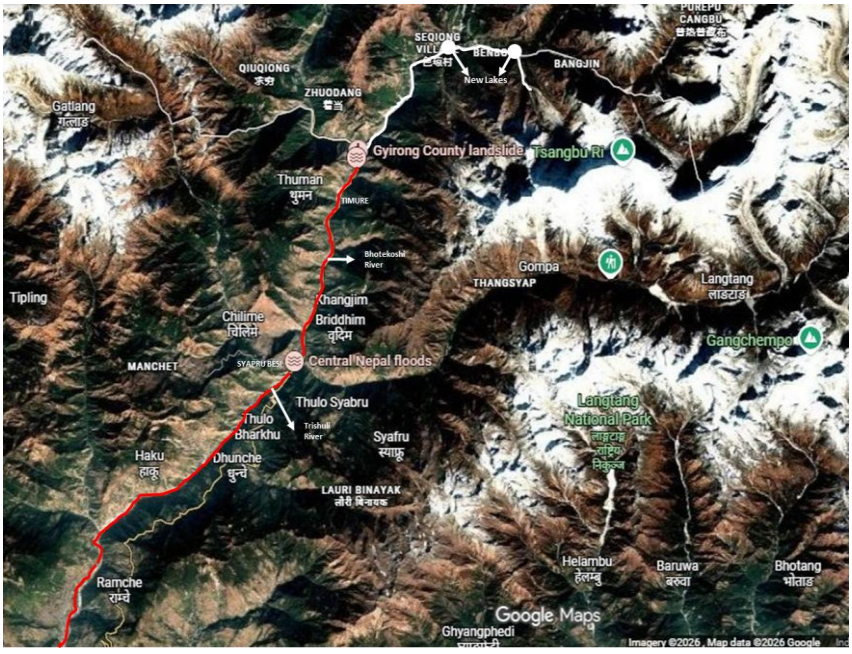


Figure 1. Map showing the mudslide (Source: Author using Google Maps)

Since the disaster occurred, there has been much speculation as to the causes. The first reports that were available indicated that an earthquake in the region, as experienced in 2015, was responsible for the flash floods [6]. Subsequently, environmental groups blamed the construction activities being conducted by the Chinese companies near the Tibet border as a part of their Belt and Road Initiative and infrastructure activities linked with the Gyrong town that required cutting hills and altering the Trishuli's course as being responsible for this disaster and many others that are occurring in Nepal regularly [7]. Eventually, the U.S. Geological Survey (USGS) using satellite imagery and seismic data made a preliminary confirmation that the disaster resulted from a Glacial Lake Outburst Flood (GLOF) that was caused by a major ice collapse from the frontal part of a glacier, followed by the rapid downstream mobilization of ice, rock, debris, and water [8].

Although the reason for the disaster has been identified with scientific evidence, a closer look makes one ask if the larger scientific question of what triggered this particular event has been answered and if similar events can happen elsewhere in the Himalayas. This query demands a closer look at the socio-economic activities in the region and also the impact of climate change on the glaciers of the Himalayas. The intention is to assist policymakers to identify resilience mechanisms that can be developed to counter such disasters in the future.

Accordingly, the paper begins by understanding and evaluating the infrastructure and developmental activities being implemented in the region as well as the impact of climate change on the glaciers of the Himalayas. The aim is to define possible efforts that can be undertaken to minimize impact and destruction of these disasters.

Socio-economic developments in Nepal

Geographically, Nepal is situated in the Central Himalayas between India and China that makes it a landlocked, aid-dependent economy. The nation faces recurrent natural hazards like landslides, floods, and earthquakes that routinely damage infrastructure. To overcome structural hurdles in its economic growth, the government in coordination with multilateral development partners, has targeted high-priority economic sectors to drive sustainable growth. These include hydropower expansion from Karnali, Gandaki, and Koshi river basins and subsequent cross-border power trade, and cross-border transport and digital connectivity to end their geographic isolation. Their dedicated efforts will help them to graduate from the United Nations Least Developed Country (LDC) category by November 24, 2026 [9].

To further developmental projects in Nepal, funding and construction activities are being pursued by India, China, and Nepal. These projects include transit and road corridors (see Table 1),

hydropower projects (see Table 2), infrastructure projects (see Table 3), and cross-border projects to connect Nepal with its neighbours (see Table 4). Most of these projects are spread over Nepal. Although China does not hold the developer contracts for most of the major projects, Chinese firms remain involved in Nepal's hydropower sector through specific roles as construction subcontractors, as financiers, and in the construction of smaller hydropower plants (see Table 5).

Table 1. Major Transit and Road Corridors: Inventory, Status, and Stakeholders (2015 – to date) (Source: [10-12])

Project Name & Route	**Strategic Purpose**	**Implementation Status (as of 2026)**	**Key Entities & Contractors Involved**
Pushpalal Mid-Hill Highway *(Chiyobhanjyang, Panchthar → Jhulaghat, Baitadi)*	•Creates an alternative East-West spine through the middle hills. • Connects 215 hill settlements across 26 districts to check migration.	**~82% Physical Progress**. • Out of 1,879 km, roughly 1,550 km is blacktopped. • Facing extreme cost overruns: budget inflated from Rs. 33.36B to a projected Rs. 84.33B. • Target completion pushed to 2027/28.	**Implementing Agency:** Department of Roads / Mid-Hill Highway Directorate. • **Contractors:** Multiple domestic and international joint ventures. Some stagnant packages face contract terminations.
Hulaki (Postal) Highway *(Jhapa → Kanchanpur)*	• Upgrades the oldest historic postal tracks in the southern Terai plains. • Serves 8–10 million citizens across 21 districts bordering India.	**~74.35% Complete**. • Total footprint spans 1,857 km (including 882 km of vital north-south links). • Over 1,380 km is blacktopped. • **Major Bottleneck:** Only 153 out of 300 planned river bridges are built. Financial allocation for completion raised by Rs 4.65B.	**Implementing Agency:** Postal Highway Directorate. • **Funding Partners:** Jointly financed by the Government of India (via grant-aid packages) and the Government of Nepal.
Madan Bhandari Highway *(Bahundangi, Jhapa → Rupal, Dadeldhura)*	• Integrates the Chure and Inner Terai valleys. • Acts as an industrial logistics bypass corridor above the Terai plains.	**~52% Physical Progress**. • Spans 1,390 km globally, with the central project office constructing 740 km. • 369 km blacktopped, and 152 out of 185 bridges built. • Slowed heavily by tree-felling forest clearances, land disputes, and contractor cash flow constraints.	**Implementing Agency:** Madan Bhandari Highway Project Office. • **Contractors:** Joint ventures like Shrestha–Saksham JV. Completely self-funded by the Government of Nepal.
Mahendra Highway Expansion (East-West Highway) *(Mechi → Mahakali)*	• Upgrades Nepal's main transit lifeline from 2 lanes to a modern 4-to-6-lane Asian Highway standard.	**Under Active Multi-Section Construction**. • The *Narayanghat–Butwal* and *Kamala–Dhalkebar–Pathlaiya (KDP)* legs are highly active but face chronic delays from traffic management during construction. Target for full alignment modernization set within 3 years.	**Financing & Oversight:** Supported by major multilateral players including the World Bank, Asian Development Bank (ADB), and the US Millennium Challenge Corporation (MCC).
Strategic Road Connectivity & Trade Improvement Project (SRCTIP)	• Widens and improves the pivotal Nagdhunga–Naubise–Mugling (NNM) trade artery linking Kathmandu to the Birgunj dry port.	**Under Construction**. • Progressing on the 94.7 km stretch. • Includes construction of a critical 12 km 2-lane bypass from Sisne Khola to Dharke to bypass mountainous traffic blocks.	**Implementing Agency:** Department of Roads. • **Funding Partner:** Funded via a $450 Million credit agreement with the World Bank.

Table 2. Major Hydropower Projects (2015–Present): Inventory, Status, and Stakeholders (Source: [13-14])

Project Name & Capacity	Technology Type	Implementation Status (as of 2026)	Key Entities & Contractors Involved
Upper Tamakoshi Hydropower Project (456 MW)	Peaking Run-of-the-River (PROR)	**100% Completed & Operational**. • Nepal's largest operational domestic project. • Fully commissioned in July 2021 after long delays from the 2015 earthquake. • Currently constructing the *Rolwaling diversion* to boost winter output.	**Owner/Operator:** Upper Tamakoshi Hydropower Ltd. (A subsidiary of the Nepal Electricity Authority - NEA). • **Financing:** 100% domestically mobilized public capital.
Arun-III Hydropower Project (900 MW)	Peaking Run-of-the-River (PROR)	**Under Construction (~75% Complete)**. • Massive mega-dam structure under active execution. • Headworks and 11.7 km tunnel well advanced. Cross-border 400 kV transmission line to Sitamarhi (India) is over 58% complete. Target completion extended to late 2026.	**Implementing Developer:** SJVN Arun-3 Power Development Company (SAPDC), a wholly owned subsidiary of India's state-owned SJVN Limited. • **Civil Contractor:** Jaiprakash Associates (India).
Tanahu Hydropower Project (140 MW)	Storage / Reservoir	**Under Construction (~75.5% Overall Progress)**. • One of Nepal's rare storage-type projects on the Seti River. • Concreting of the 140-metre-high main dam began in March 2025. Underground excavation is 100% complete. Expected commissioning set for late 2026/early 2027.	**Owner:** Tanahu Hydropower Limited (subsidiary of NEA). • **Financing:** Concessional loan packages via Asian Development Bank (ADB), JICA, and the European Investment Bank (EIB). • **Contractors:** Song Da-Kalika JV (Package 1) and Sinohydro Corp (Package 2).
Upper Trishuli 3A Hydropower Project (60 MW)	Run-of-the-River (ROR)	**Completed but Temporarily Defunct**. • Originally commissioned in 2019 following long post-earthquake rehabilitations. • **Recent Update:** In August 2026, severe flash flooding completely swamped and heavily damaged its powerhouse and adjacent 220 kV substation hub, forcing a total shutdown.	**Owner/Operator:** Nepal Electricity Authority (NEA). • **Primary Contractor:** China Gezhouba Group Company (CGGC). • **Funding:** Export-Import Bank of China loan.
Rasuwagadhi Hydropower Project (111 MW)	Run-of-the-River (ROR)	**Completed but Flood-Damaged**. • Built near the northern border belt. • **Recent Update:** Suffered extensive structural damage to its surface components during the August 2026 Trishuli basin disaster, forcing total generation suspension.	**Owner:** Rasuwagadhi Hydropower Company (JV of Chilime Hydro & NEA). • **Contractor:** China International Water & Electric Corporation (CWE).
Budhigandaki Hydropower Project (1,200 MW)	Storage / Reservoir	**Pre-Construction / Stalled**. • Plagued by persistent geopolitical shifts and contract reversals over the past decade. • **Current Status:** The Ministry of Environment officially approved its updated Environmental Impact Assessment (EIA) in July 2026. The government is attempting local resource mobilization to kickstart construction.	**Implementing Agency:** Budhigandaki Hydropower Project Development Committee (Government of Nepal).

Table 3. Major Infrastructure Project Inventory, Status, and Key Stakeholders (Source: [15-16])

Project Name	Type / Sector	Implementation Status (as of 2026)	Key Entities & Contractors Involved
Kathmandu–Terai Fast Track Road (71 km Expressway)	Transport & Logistics	**Under Construction (approx. 38%–45% physical progress)**. Facing localized start-point land disputes in Khokana. Target completion extended to April 2027.	**Implementing Agency:** Nepal Army (assigned management in May 2017). **Contractors:** Various international firms for complex tunnelling and bridge sections.
Nagdhunga–Sisnekhola Tunnel Road Project	Transport & Logistics	**Main Construction Phase Completed**. Breakthrough achieved; moved into operations and maintenance planning.	**Owner:** Department of Roads (DoR). **Contractor:** Hazama Ando Corporation (Japan). **Funding:** Japan International Cooperation Agency (JICA).
Bheri Babai Diversion Multipurpose Project	Water Resources / Irrigation	**Tunnelling Completed (100%)**. Hydro and downstream irrigation network works remain ongoing.	**Owner:** Government of Nepal. **Contractor:** China Overseas Engineering Group Co., Ltd. (COVEC) (used Nepal's first Tunnel Boring Machine).
Sunkoshi Marin Diversion Project	Water Resources / Irrigation	**Under Construction (approx. 74% complete)**. Tunnel breakthrough achieved early; canal networks underway.	**Owner:** Ministry of Energy, Water Resources and Irrigation. **Contractor:** China Overseas Engineering Group Co., Ltd. (COVEC).
Pokhara Regional International Airport	Aviation	**Completed & Inaugurated**. Operationally open, though international commercial traffic remains low.	**Owner:** Civil Aviation Authority of Nepal (CAAN). **Contractor:** China CAMC Engineering. **Funding:** Export-Import Bank of China (Exim) loan.
Gautam Buddha International Airport (Bhairahawa)	Aviation	**Completed & Inaugurated**. Operational, serving as Nepal's second international gateway.	**Owner:** Civil Aviation Authority of Nepal (CAAN). **Contractor:** Northwest Civil Aviation Airport Construction Group (China).

Table 4. Cross-Border Infrastructure (2015–Present): Inventory, Status, and Stakeholders (Source: [17-19])

Project Name & Sector	Strategic Purpose	Implementation Status (as of 2026)	Key Entities & Contractors Involved
Jaynagar–Bardibas Railway Link *(Rail Transit)*	• Establishes Nepal's first modern, operational passenger broad-gauge rail corridor connecting to the Indian railway system.	**Partially Operational / Under Phase 3 Construction**. • Phase 1 (Jaynagar–Kurtha, 34.9 km): Operational since April 2022. • Phase 2 (Kurtha–Bijalpura, 17 km): Operational since July 2023. • Phase 3 (Bijalpura–Bardibas, 17 km): Active civil work tenders issued in mid-2026 for bridges and tracks following delayed land clearances.	**Financing & Execution:** Funded via Indian Grant Assistance. • **Lead Contractor:** IRCON International Limited (India). • **Operator:** Nepal Railway Company (with initial technical support from Konkan Railway).
Dhalkebar–Muzaffarpur 400 kV Transmission	• Serves as the primary high-capacity energy highway for cross-border power	**100% Completed & Upgraded**. • Fully operational at its designated 400 kV capacity following final substation	**Implementing Agencies:** Cross Border Power Transmission Company (CPTC) on the Indian side and

Line *(Energy Grid)*	trading. • Vital for exporting Nepal's summer hydro surplus and importing winter power.	completions after 2015. • Successfully sustained massive power transfers during peak seasonal trading blocks.	Power Transmission Company Nepal (PTCN) on the Nepal side. • **Substation Work:** Nepal Electricity Authority (NEA).
Gorakhpur–New Butwal 400 kV Transmission Line *(Energy Grid)*	• Creates a second 400 kV cross-border trunk route to transmit bulk electricity directly into India's energy-hungry Uttar Pradesh grid.	**Under Active Construction (~2025–2026 Phase)**. • Civil infrastructure, substation layout foundations, and tower installations are advancing. • Regularly monitored via bilateral Joint Steering Committee (JSC) reviews.	**Joint Venture Entity:** Financed and executed via a 50:50 joint venture company between the Nepal Electricity Authority (NEA) and the Power Grid Corporation of India (POWERGRID).
Motihari–Amlekhgunj Petroleum Pipeline *(Fuel Logistics)*	• Replaced hazardous, cost-heavy tanker transit with South Asia's first cross-border petroleum pipeline. • Eliminates fuel supply shortages in Kathmandu Valley.	**Phase I Completed; Phase II Nearing Completion**. • Phase I (69 km pipeline): Completed and inaugurated in September 2019. • Phase II (Smart storage tanks & pumping infrastructure at Amlekhgunj): Advanced installation phase under active deployment.	**Implementing Partners:** Nepal Oil Corporation (NOC) and Indian Oil Corporation (IOC). • **Financing:** Funded largely through GoI grants alongside internal NOC reserve capital.
Integrated Check Posts (ICPs) *(Trade Logistics)*	• Consolidates immigration, customs, security, and dry-port cargo handling under a unified automated facility to slash cross-border logistics friction.	**Progressive Multi-Site Deployment**. • Birgunj & Biratnagar ICPs: Fully operational. • Nepalgunj (Rupaidiha) & Bhairahawa (Sunauli) ICPs: Inaugurated and handling traffic. • Banbasa & Dodhara-Chandani ICPs: Active engineering procurement construction (EPC) civil works tenders advanced in early 2026.	**Coordinating Authorities:** Land Ports Authority of India (LPAI) and the Ministry of Urban Development (Nepal). • **Financing:** Implemented via Government of India financial packages.
Kolkata–Biratnagar Direct Rail Cargo Corridor *(Multi-Modal Transit)*	• Creates direct broad-gauge freight train cargo movements directly from Indian sea ports into Nepal's interior trade yards.	**Operational Milestone Achieved**. • Officially operationalized following crucial amendments to the *Nepal-India Transit Treaty*. • First full direct shipments (such as bulk agricultural grains) arrived directly at the Biratnagar Customs Yard.	**Implementing Partners:** Indian Railways, Nepal Bureau of Customs, and international cargo carriers.
Koshi Highway (NH08) *(Rani, Biratnagar → Kimathanka)* *(Road Corridor)*	Links Jogbani (India border) to Chentang (China border) through eastern Nepal.	**Track Fully Connected**. The final, highly challenging 14 km Chyamptang–Ghongghoppa rocky section achieved a historic breakthrough. Overall physical progress sits at ~41% as the route remains a rough track awaiting blacktopping and permanent bridges. Final completion target is set for mid-July 2029.	**Implementing Agencies:** Department of Roads & Nepali Army (mobilized for the toughest cliff-carving packages). **Contractors:** Joint ventures like Yakthumhang-Khampache JV.
Kaligandaki Corridor (NH48) *(Sunauli → Korala)* *(Road Corridor)*	Connects Belahiya/ Bhairahawa (India border) to Korala (China border) via western mountains.	Most Advanced Corridor (~82%–86% Complete). The road is widely trafficable, drastically cutting travel times (e.g., Butwal to Muktinath dropped to a single day). But, the northern *Beni–Korala* section	**Implementing Agency:** Department of Roads / Nepali Army. **Financing:** Government of Nepal (~Rs. 10.57 Billion spent/allocated).

		lags at 80% with regular monsoon landslide disruptions. The government recently unveiled a master plan to upgrade the entire corridor into a Premier Tourist Highway.	
Karnali Corridor *(Jamunaha → Hilsa) (Road Corridor)*	Connects Rupaidiha/ Nepalgunj (India border) to Hilsa (China border) via the remote far-western region.	**Track Connected / Basic Upgrading Phase**. Vehicular tracks are roughly opened to the Tibetan border, but the corridor suffers from the lowest percentage of blacktopping. It remains highly vulnerable to structural damage and cuts off during heavy weather.	**Implementing Agency:** Nepali Army (entrusted with deep canyon blasting and initial track alignment).

Table 5. Chinese-Involved Infrastructure Projects in Nepal (2015–Present) (Source: Author)

Project Name	Infrastructure Category	Specific Chinese Entity Involved	Nature of Involvement & Status (as of 2026)
Pokhara Regional International Airport	Aviation	• China CAMC Engineering (Contractor) • Export-Import Bank of China (Funder)	**EPC Contractor & Loan Financing**. Built via a $215 million soft loan. Fully completed and inaugurated, though struggling with low international traffic.
Gautam Buddha International Airport (Bhairahawa)	Aviation	• Northwest Civil Aviation Airport Construction Group	**Main Construction Contractor**. Executed the runway expansion, terminal, and core airside civil works. Completed and operational.
Bheri Babai Diversion Multipurpose Project	Water Resources / Irrigation	• China Overseas Engineering Group Co., Ltd. (COVEC)	**Lead Civil Contractor**. Successfully deployed Nepal's first Tunnel Boring Machine (TBM) to complete the 12.2 km tunnel. Downstream irrigation works continuing.
Sunkoshi Marin Diversion Project	Water Resources / Irrigation	• China Overseas Engineering Group Co., Ltd. (COVEC)	**Lead Civil Contractor**. Achieved an early tunnel breakthrough using TBM technology. Canal network construction is currently about 74% complete.
Kathmandu–Terai Fast Track Road (Expressway)	Transit & Road Corridors	• China State Construction Engineering Corp (CSCEC) • China Overseas Engineering Group (COVEC)	**Section Contractors**. Hired by the Nepal Army for the most complex engineering packages, including the multi-lane tunnel segments at Chhededanda and Dhedre. Under active construction.
Upper Trishuli 3A Hydropower Project (60 MW)	Hydropower	• China Gezhouba Group Company (CGGC) (Contractor) • Export-Import Bank of China (Funder)	**EPC Contractor & Loan Financing**. Completed in 2019. (Note: Powerhouse and substation suffered heavy damage during the severe August 2026 floods).
Rasuwagadhi Hydropower Project (111 MW)	Hydropower	• China International Water & Electric Corporation (CWE)	**Main Civil Contractor**. Completed construction near the northern border. (Note: Currently undergoing repairs caused by structural damage from the August 2026 floods).
Koshi Highway (NH08) *(North-South Corridor)*	Cross-Border Connectivity	• China CAMC Engineering (Historically linked to northern border dry port studies)	**Northern Terminal Context**. While the road track itself is carved by the Nepali Army, China is involved in developing the matching border infrastructure on the Tibet side (Chentang/ Kimathanka).

Glaciers and Climate Change

The Himalayas are referred to as the Third Pole as they house the largest concentration of frozen water outside the polar ice caps. Within Nepal, an estimated 3,800 to 4,000 individual glaciers cover thousands of square kilometres that feed the river basins of the Koshi, Gandaki, and Karnali systems [20]. These glaciers act as a natural water tower that feeds perennial rivers to support agriculture, water supplies, and hydroelectric infrastructure for millions of people both in Nepal and across South Asia.

But, increasing global temperatures are melting these glaciers. Studies show that the ice loss rates have doubled since the year 2000 [21-22] with the total loss being as high as 27 metres of ice thickness since 1975. A comprehensive analysis reveals that between 1990 and 2020, Hindu Kush Himalayas (HKH) glaciers lost about 12% of their total area and 9% of their estimated ice reserves. The most immediate threat is seen from smaller glaciers (below 0.5 km²) which shrink more rapidly than others. This poses a high risk to mountain communities from hazards like Glacial Lake Outburst Floods (GLOF) as *three-quarters of the region's glaciers fall into this vulnerable size class*. To address this, current Himalayan hazard frameworks extrapolate data from a limited subset of well-studied catchments, assuming uniform melting rates and structural behaviour across the entire Third Pole. But, this extrapolation creates an uncertainty of 25% to 40% in regional Peak Water calculations and GLOF risk assessments. By leaving these smaller glaciers as blind spots, predictive models are fundamentally incapable of forecasting sudden, non-meteorological cryospheric failures. This oversight ensures that downstream risk parameters remain dangerously underestimated, transforming highly preventable high-altitude hazards into catastrophic, un-warned downstream disasters.

Impact of Climate Change

The impact of climate change on glaciers is so profound that environmental assessments from institutions like the International Centre for Integrated Mountain Development (ICIMOD) indicate that even if global warming is limited to 1.5°C, the Hindu Kush Himalayan region is projected to lose up to one-third of its total ice volume by the end of the century [23]. The key impacts of climate change on Nepalese glaciers include:

(a) *Accelerated Mass Loss and Retreat* of glaciers across the Nepalese Himalayas, with average glacial surface area shrinking by more than 20% over recent decades [20, 23]. High-altitude glaciers such as those in the Khumbu, Langtang, and Annapurna regions are thinning and undergoing accelerated terminus retreat.

(b) *Fragmentation*: As glaciers melt, they divide into smaller, isolated ice bodies. This increases the total number of individual glaciers while drastically reducing the total ice volume and surface area.

(c) *Formation of Glacial Lakes and GLOF Risks*: Melting ice accumulates behind weak, unstable natural barriers formed by loose rocks and soil (moraines) (see Fig. 2). Though moraine-dammed lakes such as Tsho Rolpa and Imja Tsho exist, these lakes carry a high risk of an outburst that can be triggered by ice avalanches, rockfalls, or heavy rain, threatening downstream communities, roads, and hydropower projects [23-24].

(d) *Hydrological Alterations*: Glacial retreat causes a temporary increase in annual streamflow due to accelerated melt. But, once glaciers shrink past a critical tipping point, called 'peak water', annual discharge declines sharply. This transition imperils seasonal irrigation and Nepal's developing hydroelectric grid [25].

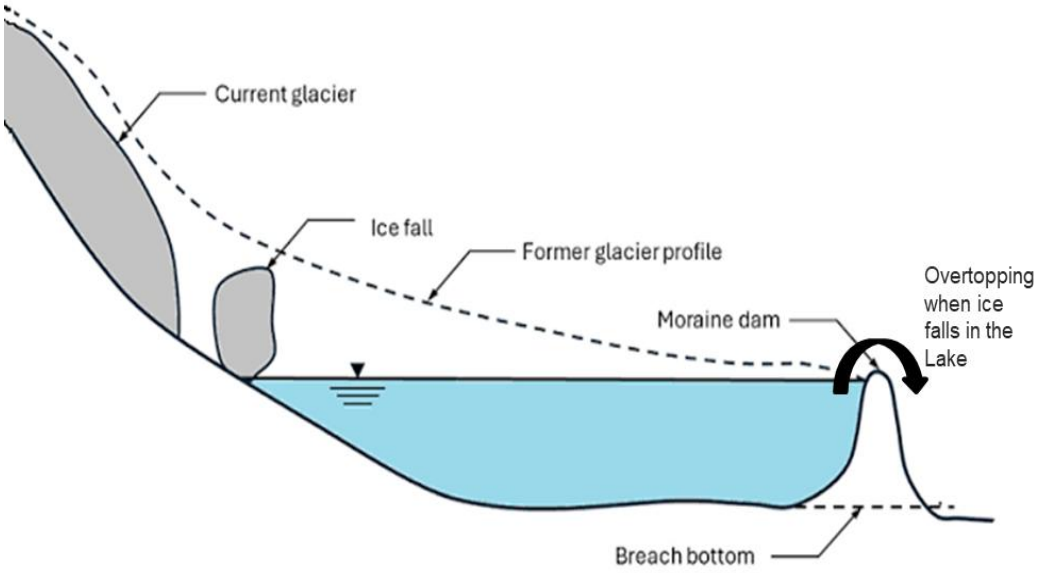


Figure 2. Formation of a Glacial Lake and the resultant GLOF (Source: Author)

Cryospheric Failure of Glaciers

Cryospheric failure in glaciers is the structural breakdown of glacial ice, driven by gravity, structural mechanics, and thermal dynamics. The fundamental mechanics include stress propagation, basal conditions, and environmental forcing, which transitions stable ice masses into avalanches, surges, or calving events [26]. Glacial ice behaves like a viscoelastic material. Under gravitational stress, it deforms slowly via internal viscous flow and when the driving stress exceeds the critical shear or tensile strength of ice, brittle failure occurs. This manifests as crevassing and structural fracturing. On steep terrain, loss of basal resistance causes entire ice tongues to detach, producing ice avalanches [27].

There have been a handful of instances of glacial collapse over the last decade, and scientists and geologists see them as highly unusual and rare. Tibet is considered a hotspot for some of the world's largest documented glacier collapses, although scientists say their causes are site-specific. Some of these collapses have been documented in Tibet's Arun Range (2016), Tibet's Sedongpu Basin (2018), Tibet's Bukadaban Feng glacier (2022), India's Ronti Peak (2018), Switzerland's Blatten (2025), and now Nepal's Langtang Lirung Glacier (2026).

Anthropogenic Amplification and Systemic Vulnerabilities

Since the magnitude of the economic and human loss along the Bhote Koshi and Trishuli River corridors cannot be explained by hydrology alone, there is a need to examine the contribution of uncontrolled expansion of un-engineered settlements and high-risk run-of-the-river (RoR) hydropower infrastructure in transforming a high-altitude hazard into a cascading regional disaster.

Un-engineered Settlements and Floodplain Encroachment

The expansion of cross-border trade via the Gyirong Port economic corridor has driven unprecedented, high-density real estate growth directly inside the narrow riparian zones of the Trishuli and Bhote Koshi Rivers (see Fig. 3). Table 6 shows the proximity and elevation of the infrastructure developed and the vulnerabilities created in the un-engineered structures.

Table 6. Comparison of vulnerability parameters across vulnerable nodes

Settlement Node	Proximity to River Axis (m)	Elevation Above Baseline (m)	Severity of a 9-metre surge wave			Core Structural Vulnerabilities
			Peak Discharge Velocity (m/s)	Sediment Vol. Concentration (%)	Max Hydrodynamic Force (KN/m)	
Gyirong Port Border Facility	15–30	2.5–4.0	6.5 – 7.2	35% – 40%	608.4 – 746.5	Customs infrastructure and commercial warehouses built directly on un-compacted alluvial fans.
Timure Bazaar	10–25	3.0–5.5	8.0 – 9.5	42% – 48%	921.6 – 1,300.0	Dense multi-story masonry commercial buildings serving the transit corridor; zero horizontal floodplain setbacks.
Syabrubesi (Confluence Zone)	5–20	2.0–5.0	10.2 – 11.5	50% – 55%	1,500.0 – 1,904.4	High-density tourism and residential structures situated inside the dynamic river-bend active erosion zone (see Fig. 3).

As seen, local zoning laws consistently failed to account for dynamic hazards. Buildings were constructed using rigid, un-reinforced brick-and-mortar masonry that possessed high vulnerability to lateral hydrostatic pressures. These multi-story buildings collapsed vertically, lacking foundational support. This significantly increased the human casualty count. Furthermore, the proximity of the buildings from the Axis of the river significantly elevated their vulnerability to severe flooding, soil liquefaction, and structural erosion.



Figure 3. Syabrubesi Village, Langtang Region at the confluence of the Bhote Koshi River — Before and After the Devastating Flood (Source: [28])

Gaps in Climate-Resilient Engineering

Deep flaws are observed in the current architectural paradigms governing the civil infrastructure of the region. The engineering parameters used for the Trishuli basin's infrastructure rely exclusively on historical meteorological rainfall data to calculate the 100-year Flood Return Period (Q100). This methodology completely omits non-meteorological, cryospheric surge risks like landslide-dammed lake breaches, underestimating peak instantaneous discharge potentials by over

250%. Similarly, critical assets along the river corridors remained unprotected as no debris-deflection walls or energy-dissipating slit dams were used. Structural elements were exposed directly to the full kinetic force of the debris flow, ensuring that any geomorphic surge would result in catastrophic structural loss.

The Cascade Failure Loop

Since the Trishuli River basin is one of the most hydro-ecologically exploited corridors in the Hindu Kush Himalaya (HKH), a basin-wide cumulative risk assessment should have been used. Instead, it seems that individual projects were engineered as isolated units, completely ignoring the potential for cascading structural interactions during an upstream cryospheric breach. The structural designs of the upper run-of-the-river projects proved entirely inadequate against the 9-metre surge wave. Similarly, hyper-concentrated sediment matrix instantly choked the intake gates, rendering the automated sediment sluice gates inoperable. Close proximity of projects within the narrow valley created higher vulnerability to cascading failures as debris and steel fragments from upstream projects acted as battering rams against downstream facilities. The vulnerability resulting from treating assets as isolated units is clearly demonstrated by the structural destruction of the Rasuwagadhi Hydropower Project (111 MW) and the Upper Trishuli 3A Hydropower Project (60 MW) during these flash floods.

Transboundary Governance and Early-Warning Gaps

Nepal's transboundary disaster risk governance is anchored in multi-tiered legal and bilateral mechanisms designed to manage shared hydro-meteorological hazards across the Hindu Kush Himalaya. The Disaster Risk Reduction and Management (DRRM) Act of 2017 provides the overarching domestic legal structure, delegating disaster response, monitoring, and early warning functions down to local municipal governments.

At the international level, transboundary governance relies on bilateral treaties and joint working groups, mainly with India and China. Hydro-meteorological risk sharing between Nepal and India is governed under the Joint Committee on Inundation and Flood Management (JCIFM) and the broader Joint Commission on Water Resources (JCWR). These frameworks facilitate the operational exchange of real-time hydrological data from upstream monitoring stations in major shared catchments—such as the Koshi, Gandaki, Karnali, and Mahakali river basins—to downstream flood management authorities [29]. But, the catastrophic human and economic toll during the flash flood highlights a critical breakdown in institutional communication and cross-

border risk governance. Identifying the gaps between regional telemetry networks, bilateral data pipelines, and localized last-mile alerting systems is thus considered critical.

The Transboundary Data Sharing Bottleneck

Despite a shared geography prone to cascading hazards, the exchange of real-time hydro-meteorological data between China and Nepal on August 26 was highly restrictive and siloed. Even while automated water-level radar gauges and upstream seismic sensors located within Tibet correctly registered an anomalous drop in downstream discharge at 08:44 AM, signalling a major upstream valley blockage, this telemetry was routed to regional data hubs in Lhasa and Beijing and not shared directly with Nepal. Finally, when it was shared through formal bureaucratic diplomatic channels, *90 precious minutes had been lost.* Had there been automated protocols to mirror *instantly* these critical sensor logs to Nepal's Department of Hydrology and Meteorology (DHM), the extent of damage and loss of lives could have been reduced. Such manual data relays must be replaced by machine-to-machine information sharing. This can be achieved by using an upstream sensor from which data are converted to standard JSON format over a secure protocol, and broadcast real-time at one-minute intervals directly to the Kathmandu DHM warning servers, bypassing the national data security filters in Beijing and Lhasa during active geological emergencies.

Technical and Structural Deficiencies in Last-Mile Alerts

When the landslide dam suffered its catastrophic breach at 11:51 AM, the lack of automated, integrated early warning networks left downstream populations with virtually zero response time. The notification loop was entirely reactive. Because downstream warning stations were programmed to trigger alerts based on physical water-level increases at local gauges rather than upstream predictive breach modelling, the alert moved at nearly the same velocity as the debris-laden surge wave itself. In critical settlement centres like Timure and Syabrubesi, automated sirens failed to sound entirely or were completely drowned out by the thunderous acoustic noise generated by the approaching boulder-laden flood front. Cellular-based SMS alerts reached local residents' mobile devices hours after the flood crest had already decimated the river basin, highlighting *a complete systemic failure* in disaster communication (see **Table 7**).

Table 7. Comparative Analysis of Early-Warning Telemetry Operations

Node Line Segment	Intended Warning Mechanism	Actual Performance (August 26, 2026)	Primary Failure Vector
Upstream-to-Border Link	Direct satellite telemetry and official cross-border hotline.	Outbound alert received by Nepali border security 6 minutes after the dam breached.	Absence of automated, instantaneous trigger mechanisms between regional nodes.
Border-to-District Hubs	VHF radio relays and cellular messaging networks.	Cellular towers overwhelmed by immediate local traffic; voice networks dropped.	Over-reliance on non-redundant commercial telecom infrastructure during peak load.
District Hubs-to-Communities	Automated siren towers and localized SMS broadcasts.	Siren alerts initiated less than 4 minutes before the 9-metre wall of water struck.	Lack of predictive modelling; alerts were strictly reactive to physical water arrival.

Gaps and Operational Challenges

Despite structural advancements, several governance and technical bottlenecks hinder end-to-end transboundary risk communication.

(a) *Asymmetric Data Exchange*: Formal bilateral agreements remain focused on seasonal flood data, often omitting critical real-time sub-daily telemetry data required during extreme flash flood events or high-altitude cryospheric hazards.

(b) *Institutional Decentralization Gaps*: Although Nepal's 2015 federal constitution empowered local municipalities to manage local DRRM functions, local governments often lack the financial resources and technical expertise to process complex transboundary hydrological forecasts into localized alerts.

(c) *Standardization and Lead Time Constraints*: The rapid travel time of debris flows and GLOFs originating in transboundary catchments severely limits the operational lead time, making standard top-down bureaucratic communication protocols inefficient without automated, localized alert infrastructure.

Discussion

Although the USGS has attributed the flash floods due to GLOF, they have also indicated that these are their preliminary findings and the final findings may vary as new inputs are received and analysed. The initial findings of other scientists, however, point out that it may not have been ice alone that collapsed [30,31]. Visuals of the glacier area after the disaster suggest that it is most likely not simply the detachment of an unstable mass of glacier ice. Instead a massive slope collapse occurred in which rock and ice have failed together. Thus, there is a need for greater study of the event and the related cause of the flash flood.

Studies show that rock and ice failing together (called Rock-Ice Avalanches (RIAs) or combined glacier-bedrock slope failures) are rare events compared to standard landslides and snow

avalanches. But, their frequency is increasing rapidly because of global warming [32]. This said, it is important to understand that even anthropogenic activities like construction, heavy engineering, and blasting can trigger or accelerate rock-ice failures and avalanches [33]. These events cannot be initiated by a single dynamite blast at a valley floor. Instead, these activities act as accelerators and structural destabilizers. Heavy machinery vibrations, deep-slope cutting, and explosive blasting introduce widespread micro-fractures into fragile mountain rock formations. When this mechanical stress interacts with a landscape already weakened by climate change and permafrost thaw, it can push an unstable glacier-bedrock system past its breaking point [34].

There is, therefore, good reason to analyse the role of rampant blasting for mega-dams and national highways in the Hindu Kush Himalayan region where geologists have documented rampant blasting that eventually can have a significant impact on the mountain slopes to cause catastrophic failures. In disasters like the 2021 Chamoli avalanche (India) and the 2026 Langtang Lirung failure (Tibet-Nepal border), although the ultimate structural release occurred high on the peaks because of climate-driven permafrost thaw, they have been driven by the 'domino effect' of instability up the slopes caused by intense valley-level blasting [35].

Thus, it is necessary to examine the role and responsibility of China regarding glaciological hazards, specifically the catastrophic rock-ice avalanches and downstream flash floods in Tibet and Nepal. An analysis of China's multifaceted role and responsibility in this crisis highlights four distinct categories which are strongly rejected by the Chinese government. China categorizes these disasters as natural cryospheric phenomena. To support the argument, the Chinese official research institutions, the Institute of Tibetan Plateau Research (CAS), point to data showing that the Tibetan Plateau's glacier area has shrunk by 24% over the last 60 years, completely erasing 7,000 small glaciers. They argue that the primary trigger is global climate change (e.g., El Niño effects, thinning ice, and extreme thermal spikes), which are global responsibilities rather than local construction defects [36]. In addition, China highlights that it has co-developed early warning systems with Nepal to monitor hundreds of hazardous glacial lakes. But, scientists note that these systems are built to track gradual lake breaches rather than the highly unpredictable, sudden shearing of high-altitude mountain ice chunks [37]. China may not directly cause the initial high-altitude rock-ice fractures, but its massive development footprint in an ecologically sensitive zone introduces mechanical vulnerabilities and downstream exposure, and its tight control over hydrological data actively hinders cross-border disaster preparedness. This issue is largely relevant to Nepal where many of the road and tunnel projects run through sensitive environments, including national parks, and the construction of hydropower plants has been criticized by environmental organizations and

local communities for destroying river ecosystems [38]. These four distinct categories that highlight China's multifaceted role and responsibility in this crisis are:

Indirect Anthropogenic and Geotechnical Destabilization. China has executed massive engineering projects across the fragile southern Tibetan Plateau (SETP), including highways (such as the China-Nepal Friendship Highway), railway expansions, and mega-hydropower dams [39,40]. These activities use heavy machinery, deep slope-cutting, and explosive blasting to carve mountain tunnels. The result is an altered local stress balance of the surrounding rock. It introduces micro-fissures into vulnerable bedrock structures that are already under tension from thermal permafrost loss. Additionally, extensive infrastructure along the transboundary river basins (like the Bhote Koshi / Trishuli corridors) alters natural sediment flows and river paths. When a rock-ice failure occurs, this intense infrastructure footprint amplifies the impact of debris because of narrow channels, transforming a high-altitude collapse into a much larger and more destructive mudslide downstream.

Information Monopoly and Cross-Border Warning Gaps. A critical aspect of China's responsibility concerns geopolitical data-sharing and communication delays during active cascading disasters, especially hydrological and glaciological data from the Tibetan Plateau which they consider strategically sensitive. Consequently, real-time telemetry from automated mountain sensors or glacial lake levels is often closely held rather than openly integrated into transparent international frameworks. As a result, during high-altitude cryospheric failures near the border, Beijing often fails to provide immediate, real-time emergency notifications downstream. An instantaneous alert regarding a sudden upstream surge or barrier lake formation could prompt immediate evacuations in vulnerable Nepali communities, directly reducing the death toll. Instead, China's strict information security controls often hamper cross-border crisis management [41].

Reports also indicate that although Chinese and Nepalese officials met in Kathmandu in May 2026 to discuss glacial lake inventories and hazard mitigation, Nepalese hydrologists felt that Beijing was withholding crucial predictive data regarding water level spikes and upstream anomalies. Even when social media allegations surfaced accusing Chinese hydrological infrastructure and dams in Tibet of exacerbating the deluge, alongside a perceived failure to issue a timely early warning, they have been rejected vigorously by the Chinese Embassy asserting the primary cryospheric collapse originated on the Nepalese side. Concurrently, Beijing heavily censored non-state-sanctioned drone

photographs and civilian footage of the collapsed glacier on Chinese platforms to control the disaster narrative.

Escalation of Future Risk (The Himalayan 'Super-Dam' Gamble). A major concern regarding China's future responsibility concerns its grand-scale infrastructure layout near major geological faults. China is progressing with plans for a mammoth 'super-dam' on the Yarlung Tsangpo (Brahmaputra) River at the Great Bend near the Indian border [42]. Yet another project is the mega-reservoir being built directly beneath active, hanging glaciated peaks that introduces extreme systemic risk. If a massive rock-ice avalanche plunges into a full artificial reservoir, it can create a tsunami-like impulse wave. This could instantly overtop or breach the concrete structure, sending an unprecedented, catastrophic wall of water through downstream sections of India and Bangladesh [42].

Warning from Chinese Climate and Environment Scientists. The warning provided by the Chinese Academy of Sciences (CAS) and official climate tracking agencies validates the vulnerabilities associated with these aggressive state-backed infrastructure development projects. Although China's state entities push forward with monumental engineering feats along the southern Tibetan Plateau and transboundary river basins, their own scientific community have confirmed that the high-altitude Hindu Kush Himalayan (HKH) range is becoming too unstable to sustain heavy development safely. These vulnerabilities arise during heavy engineering, deep mountain-slope cutting, and blasting for highways and hydro-tunnels: activities which introduce macro- and micro-fissures into bedrock, removing the natural structural 'toe support' at the base of the mountains which could lead to turning the terrain into a highly reactive hazard zone [43].

These scientists have even warned that monitoring the glaciers fully is not feasible and hence high-density construction in areas where technical forecasting cannot be guaranteed should be avoided [44]. Similarly, it is not recommended to choke any valley with infrastructure as avalanches will destroy downstream communities [45]. The increasing rate of global temperature rise is impacting infrastructure being developed in these mountains as the frozen soil supporting them is turning into soft slurry thereby threatening the stability of these structures [46].

The scientific advice supports environmental risk aversion, but China is unlikely to urge a pullback from high-altitude zones because the changing climate has rendered the terrain fundamentally untameable. The state planning of China operates on geopolitical and economic expansion, assuming that modern engineering can override natural cryospheric degradation. Thus, scientific

warnings are ignored, leaving downstream river corridors vulnerable to cascading failures. Gyirong is planned as the starting point for the high-altitude China-Nepal railway corridor and China wants to develop a 'national ring road' circling the country's borderlands, most of which will pass through the Himalayas [47]. Continued activities in these regions and of this nature are likely to create more disasters in the future.

Even though this calamity may be attributed largely to climate change [48] – with losses exacerbated by human activities – economic revival remains a challenge for a developing country like Nepal. Getting the much required US$ 5 billion for total rebuilding will be difficult even though Nepal has made an initial claim of US$ 20 million in damages from the UN Fund for Responding to Loss and Damage that came into operation in 2025 [49]. With 120 countries submitting claims totalling US$ 3 billion against an available pool at US$ 300 million, the full realization of Nepal's claim seems highly unlikely.

Nepal contributes only 0.1% to global warming [50], but it bears a disproportionate burden of climate impact. No amount of adaptation can fully shield their people from such destruction. Still Nepal has to provide the desired evidence to substantiate its claim at the UN Fund. Although there are physical limits to adaptation in the Himalayas where infrastructure can only be developed along rivers [51], unabated infrastructural development close to the flood plains could weaken their case for financial aid as losses could have been minimized if adequate adaptation mechanisms had been used.

Even as science confirms that anthropogenic activities are responsible for climate change [52], political responses are far from uniform. Developed nations continue to debate historical responsibility and financial accounting. Developing nations like Nepal, continue to bear the brunt of indecision and endure economic losses and cost towards rebuilding. Recurrent natural disasters demand that humankind realize that climate change is real. There is a need for cooperation on international policies, carbon pricing, green technology, community adaptation, and building resilience. But all of this can be successful only if nations come together and local policymakers ensure that adequate planning is applied and adhered to when undertaking infrastructure development in ecologically fragile areas. Till then weak countries will continue to pay with their lives for a crisis driven by fossil fuel emissions occurring in some other part of the world [53].

Policy Recommendations and Future Frameworks

The structural and institutional failures observed during the August 2026 disaster demand an immediate paradigm shift in how transboundary risks are managed in the high-mountain

Himalayas. Some comprehensive, action-oriented recommendations across three progressive operational horizons are discussed for consideration.

Immediate Institutional Reform (0–12 Months)

The first priority is the elimination of administrative friction in transboundary disaster signalling. The 90-minute data transmission lag needs to be removed.

(a) *Automated Data Democratization:* China and Nepal must establish a direct, machine-to-machine API data exchange procedure that mirrors telemetry from upstream Tibetan gauges directly to Nepal's Department of Hydrology and Meteorology (DHM) and the National Disaster Risk Reduction and Management Authority (NDRRMA). This bypasses traditional, slow diplomatic channels completely.

(b) *Low-Frequency Seismic Trigger Arrays:* Deploy an array of specialized, low-frequency seismic sensors near high-risk slopes along the massif. These sensors should be programmed to broadcast, automatically, an instantaneous regional warning if they detect the specific spectral signature of a massive land-slip or cryospheric collapse—shifting early warnings from a reactive system to a predictive model.

(c) *Satellite-Based Cellular Redundancy:* Replace vulnerable terrestrial cell towers along the river corridors with dedicated satellite communication links to power the automated siren networks. This ensures that last-mile alerting systems remain operational even during total local power outages and network congestion.

Medium-Term Regulatory Adjustments (1–3 Years)

Medium-term policies must focus on transforming infrastructure planning from isolated projects to basin-wide, climate-resilient frameworks.

(a) *Mandatory Basin-Wide Cascade Modelling*: No new hydropower projects should be authorized in the Trishuli or Bhote Koshi basins without completing a comprehensive, multi-variable hazard model. These models must simulate upstream landslide-dammed lake failures (LDEFs) and glacial lake outburst floods (GLOFs), evaluating the cumulative structural resilience of all projects along the river cascade.

(b) *Revision of Engineering Baselines:* The outdated 100-year flood design standard (Q_{100}) must be retired for critical high-mountain infrastructure. Regulatory agencies must inaugurate use of a new standard based on Maximum Climate-Induced Volatility (MCIV),

which explicitly factors in non-meteorological surge volumes and extreme sediment loading.

(c) *Enforcement of Strict Riparian Buffer Zones:* Enact and strictly enforce land-use zoning laws that mandate a 200-metre horizontal safety setback from the active river axis for all permanent residential and commercial structures. Existing high-density settlements in high-risk zones, such as sections of Timure and Syabrubesi, should be phased out through state-supported relocation incentives to safer, higher ground.

Long-Term Civil Engineering & Financial Architecture (3–5+ Years)

Long-term resilience requires significant financial backing and physical structural defence capable of deflecting high-velocity debris flows.

(a) *Deployment of Structural Debris Deflection Arrays*: Construct heavy, reinforced-concrete debris-slit dams and energy-dissipating barriers upstream of critical infrastructure nodes and major settlements. These structures are engineered to capture mass-wasting boulders and coarse sediment while letting normal river flows pass through safely, dampening the kinetic energy of any future surge wave.

(b) *Establishment of a Transboundary Climate-Risk Treasury:* Create a regional, pooled emergency fund backed by international climate finance institutions, alongside joint contributions from regional governments and private hydropower developers. This will provide rapid, pre-approved liquidity to accelerate recovery, finance climate-resilient retrofits, and fund joint transboundary monitoring research, ensuring that disaster mitigation is decoupled from localized budget constraints.

Conclusion

The August 26, 2026, transboundary disaster demands a fundamental shift from single-variable hazard attribution to confront future Himalayan hazard management. This study demonstrates that the tragedy cannot be categorized as a purely natural event or a simple infrastructure failure. Instead, it represents a classic socio-environmental compound disaster where a climate-induced cryospheric collapse intersected directly with systemic vulnerabilities in cross-border governance and civil engineering. The responsibility of state actors undertaking infrastructure activities in a seismic weak zone cannot be overlooked The chronological and physical analysis of the event reveals a highly interconnected chain of failures that amplified a high-altitude natural hazard into

a downstream economic and humanitarian catastrophe. This could have been minimized but for the institutional communication gap that caused a devastating 90-minute data transmission delay between upstream sensors and downstream communities. This technical and administrative friction effectively reduced last-mile warning times to less than four minutes. The policy recommendations detailed offer a phased blueprint to transition from reactive disaster management to proactive risk mitigation. Implementing automated cross-border API data loops, adopting Maximum Climate-Induced Volatility engineering baselines, and building physical debris deflection arrays are no longer optional engineering choices. They are essential prerequisites for safeguarding human lives and securing multi-billion-dollar investments in an increasingly warming alpine environment.

References

[1] Roohi, M., Dehghani, J., Irani, M., & Mina, P., 2025, A comprehensive review of flood damage in mountainous regions: challenges, solutions, and advanced management technologies. Discover Geoscience **3**, 59. https://doi.org/10.1007/s44288-025-00145-2

[2] [Stoffel, M., Wyżga, B., & Marston, R. A., 2016, Floods in mountain environments: A synthesis, *Geomorphology* **272**, 1-9, https://doi.org/10.1016/j.geomorph.2016.07.008

[3] Al Jazeera, 2026, Nepal-China flood disaster: What's the latest toll, how many are missing? *Al Jazeera English*, August 30. Available at https://www.aljazeera.com/news/2026/8/30/nepal-china-flood-disaster-whats-the-latest-toll-how-many-are-missing (accessed 04 September 2026).

[4] Wong, T., 2026, Collapsed glacier likely caused devastating Nepal-Tibet flash flood. *BBC News*. August 28. Available at https://www.bbc.com/news/articles/cly464k252yo (accessed 04 September 2026).

[5] Murtaza, M., 2026, When a mountain falls: How ice and rock triggered Nepal's catastrophic flood – and why climate change is raising the risks. *The Conversation*, August 29. Available at https://theconversation.com/when-a-mountain-falls-how-ice-and-rock-triggered-nepals-catastrophic-flood-and-why-climate-change-is-raising-the-risks-290779 (accessed 04 September 2026).

[6] The Guardian, 2026, Nepal-Tibet flash flood: what we know so far, *The Guardian*, August 28. Available at https://www.theguardian.com/world/2026/aug/27/nepal-tibet-flash-floods-what-we-know-so-far-flooding (accessed 04 September 2026).

[7] DTE, 2026, Journalist group in Nepal blames Chinese construction activities on Tibetan border for triggering Rasuwa flash flood, *Down To Earth*, August 26. Available at https://www.downtoearth.org.in/natural-disasters/journalist-group-in-nepal-blames-chinese-construction-activities-on-tibetan-border-for-triggering-rasuwa-flash-flood (accessed 04 September 2026).

[8] USGS, 2026, 2026 Nepal Debris Avalanche and Flash Flood, *U.S. Geological Survey*, August 27. Available at https://www.usgs.gov/programs/landslide-hazards/science/2026-nepal-debris-avalanche-and-flash-flood (accessed 04 September 2026).

[9] UNCDP, 2024, Nepal graduation status and Smooth Transition Strategy framework, *UN Portal for Least Developed Countries*, Available at https://www.un.org/ldcportal/content/nepal-graduation-status (accessed 04 September 2026).

[10] Dahal, K., & Timalsina, K. P., 2017, New Towns Development: A Wave of the Future Planning Practices in Nepal. *Tribhuvan University Journal* **31**(1-2), 139-152. https://doi.org/10.3126/tuj.v31i1-2.25346

[11] World Bank, 2020, *Nepal - Strategic Road Connectivity and Trade Improvement Project: Environment and Social Impact Assessment (English). *Washington, D.C.: World Bank Group. Available at http://documents.worldbank.org/curated/en/122051582322813326 (accessed 04 September 2026).

[12] ADB, 2023, Roads Enhance Connectivity and Create Opportunities in Isolated Hills in Nepal, *Asian Development Bank*, March 17. Available at https://www.adb.org/results/roads-enhance-connectivity-create-opportunities-isolated-hills-nepal (accessed 04 September 2026).

[13] Manan Sharma, S., & Rawat Sharma, 2025, Why Hydropower Projects in Nepal Get Delayed: Understanding the Bottlenecks in Development, *International Journal Of Engineering Research & Technology* (IJERT) 14(05). https://doi.org/10.5281/zenodo.18106575

[14] Pangeni, R., 2026, Nepal's flood disaster puts its hydropower-first strategy, exports to the test. *Mongabay Conservation news* https://doi.org/10.66709/news-328384

[15] Gautam, R., Shakya, A., & Kadariya, S., 2025, The Realities of Government Construction Projects in Nepal: Systemic Inefficiencies and Challenges. *Journal of Himalaya College of Engineering* 2(1), 88-96. https://doi.org/10.3126/jhcoe.v2i1.91581

[16] Bista, I., 2022, Issues with Development Projects in Nepal: A Case Study of the Development Projects in Nepal and its Issues Using the Agent Based Approach (ABA). *Systems Thinking* **2**(1), 1-20. https://doi.org/10.54120/jost.2025-0066IB

[17] Dhakal, B., 2026, Nepal's National Pride Projects: Progress, Promise and Persistent Hurdles, *Nepal News*, April 05. Available at https://english.nepalnews.com/s/business/nepals-national-pride-projects-progress-promise-and-persistent-hurdles/ (accessed 04 September 2026).

[18] Yadav, P., & Adhikari, R., 2026, Connecting Margins to the Mainstream: Road Construction by the Nepali Army as a Catalyst for National Unity, *Unity Journal* **7**, 189-216. https://doi/org/10.3126/unityj.v7i1.90445

[19] Shah, R., Mishra, S., Neumann, A., Adhikary, B., & Gurung, S., 2026, Electricity policies and market dynamics in Nepal: Implications for renewable integration and regional trade, *Energy Reports* **16**, 109507,https://doi.org/10.1016/j.egyr.2026.109507

[20] Bajracharya, S. R., Maharjan, S. B., Shrestha, F., Bajracharya, O. R., & Baidya, S., 2014, Glacier Status in Nepal and Decadal Change from 1980 to 2010 Based on Landsat Data. *International Centre for Integrated Mountain Development (ICIMOD)*.

[21] Maharjan, S. B., & Sherpa, T. C., 2026, Changing dynamics of glaciers in the Hindu Kush Himalayan region from 1990 to 2020, *International Centre for Integrated Mountain Development (ICIMOD)*. https://doi.org/10.53055/ICIMOD.1122

[22] Azam, M. F., 2026, HKH Glacier Outlook 2026: Understanding Change Through 50 Years of Field Observation. *International Centre for Integrated Mountain Development (ICIMOD)*. https://doi.org/10.53055/ICIMOD.1123

[23] Wester, P., Mishra, A., Mukherji, A., & Shrestha, A. B. (Eds.), 2019, The Hindu Kush Himalaya Assessment: Mountains, Climate Change, Sustainability and People. *Springer Nature/ICIMOD, Switzerland*

[24] IPCC, 2023, Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. *IPCC*. Available at https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_FullVolume.pdf (accessed 04 September 2026).

[25] Shrestha, A. B., Wake, C. P., Mayewski, P. A., & Dibb, J. E., 1999, Maximum temperature trends in the Himalaya and its vicinity: An analysis based on temperature records from Nepal for the period 1977–1994. *Journal of Climate* **12**(9), 2775–2786. https://doi.org/10.1175/1520-0442(1999)012%3C2775:MTTITH%3E2.0.CO;2

[26] Faillettaz, J., Funk, M., & Vincent, C., 2015, Avalanching glacier instabilities: Review on processes and early warning perspectives, *Reviews of Geophysics* **53**, 203–224, https://doi.org/10.1002/2014RG000466

[27] Kääb, A., Jacquemart, M., Gilbert, A., Leinss, S., Girod, L., Huggel, C., Falaschi, D., Ugalde, F., Petrakov, D., Chernomorets, S., Dokukin, M., Paul, F., Gascoin, S., Berthier, E., & Kargel, J. S., 2021, Sudden glacier collapses: A neglected hazard. *The Cryosphere* **15**(4), 1933–1946. https://doi.org/10.5194/tc-15-1751-2021

[28] Instagram, 2026, Earthpulase111, August 28. Available at https://www.instagram.com/p/DcjFkmBhVJi/ (accessed 04 September 2026).

[29] Kafle, S. K., 2017, Disaster Early Warning Systems in Nepal: Institutional and Operational Frameworks. *Journal of Geography & Natural Disasters* **7**(1), 196. https://doi.org/10.4172/2167-0587.1000196

[30] Mcdermott, J., 2026, Satellite images show bedrock and glacier collapsed on Nepal-China border, then rivers flooded, *AP News*, August 28. Available at https://apnews.com/article/climate-change-nepal-tibet-glacier-collapse-floods-b3eda9410f9941f69add384944047bc3 (accessed 04 September 2026).

[31] Science Media Centre, 2026, Expert reaction to flash floods in Nepal-Tibet, *Science Media Centre*, August 28. Available at https://www.sciencemediacentre.org/expert-reaction-to-flash-floods-in-nepal/ (accessed 04 September 2026).

[32] Fan, X., Yunus, A. P., Yang, Y.-H., Subramanian, S. S., Zou, C., Dai, L., Dou, X., Narayana, A. C., Avtar, R., Xu, Q., & Huang, R., 2022, Imminent threat of rock-ice avalanches in High Mountain Asia, *Science of The Total Environment* **836**, 155380, https://doi.org/10.1016/j.scitotenv.2022.155380

[33] EBSCO, n.d, Avalanches, *Research Starter* Available at https://www.ebsco.com/research-starters/earth-and-atmospheric-sciences/avalanches (accessed 04 September 2026).

[34] Ramanathan, K. & Vasudevan, N., 2021, Anthropogenic causes of landslides and their implications for monitoring, *vEGU21, the 23rd EGU General Assembly, held online 19-30 April, 2021*. https://doi.org/10.5194/egusphere-egu21-6933

[35] Gurung, N., 2019, Natural Disasters Versus Anthropogenic Activities in Nepal Himalayas: Case Study from Ghatte Khola , Myagdi, *Technical Journal* 1(1), 65–70. https://doi.org/10.3126/tj.v1i1.27593

[36] Yang, C., 2026, Unstable Tibetan Plateau risks cascading disasters as glacier losses mount in Nepal, China, *South China Morning Post*, September 03. Available at https://www.scmp.com/news/china/article/3366180/unstable-tibetan-plateau-risks-cascading-disasters-glacier-losses-mount-nepal-china (accessed 04 September 2026).

[37] Tong, Z., 2026, China and Nepal built an early warning system for melting glaciers in Himalayas. Does it work?, *South China Morning Post*, August 27. Available at https://www.scmp.com/news/china/science/article/3365488/china-and-nepal-built-early-warning-system-melting-glaciers-himalayas-does-it-work (accessed 04 September 2026).

[38] Augustin, J., 2021, China's building spree in Nepal casts shadow over Himalayan ecosystem, *Mongabay Conservation news*, December 31. Available at https://doi.org/10.66709/news-251342

[39] Li, S., Li, C., Li, Z., Li, L., & Wang, W., 2025, Ice Avalanche-Triggered Glacier Lake Outburst Flood: Hazard Assessment at Jiongpuco, Southeastern Tibet, *Water* **17**(14), 2102. https://doi.org/10.3390/w17142102

[40] Tian, X., Yao, X., & Zhou, Z., 2025, Distribution patterns and risk assessment of potential ice avalanches and glacier lake outburst floods in southeastern Tibetan Plateau, *Ecological Indicators* **179**, 114217, https://doi.org/10.1016/j.ecolind.2025.114217

[41] Hawkins, A., 2026, Chinese control of information hampers assessment of Tibet flood damage, *The Guardian*, August 28. Available at https://www.theguardian.com/world/2026/aug/28/chinese-controls-information-hamper-assessment-tibet-flood-damage (accessed 04 September 2026).

[42] Chellaney, B., 2026, Nepal-Tibet floods expose dangers of China's Himalayan gamble, *Nikkei Asia*, August 28. Available at https://asia.nikkei.com/opinion/nepal-tibet-floods-expose-dangers-of-china-s-himalayan-gamble (accessed 04 September 2026).

[43] He, M., & Wang, L., 2026, Engineering challenges of deep-buried tunneling in the Alps and Himalayas, *Rock Mechanics Bulletin* **5**(3), 100283, https://doi.org/10.1016/j.rockmb.2025.100283

[44] Wei, S. T., 2026, Seven minutes to disaster: How climate change exposed a Himalayan blind spot, *Think China*, August 31. Available at https://www.thinkchina.sg/society/seven-minutes-disaster-how-climate-change-exposed-himalayan-blind-spot (accessed 04 September 2026).

[45] Bai, Y., Li, D., Wangchuk, S., Kettner, A., Zhao, Y., Deng, R., Liu, Y., Xiao, C., Ni, J., & Cui, P., 2025, Flood complexity and rising exposure risk in High Mountain Asia under climate change, *Science Bulletin* **70**(10), 1601-1604. https://doi.org/10.1016/j.scib.2025.01.055

[46] Ran, Y., Cheng, G., Dong, Y., Hjort, J., Lovecraft, A.L., Kang, S., Tan, M. & Li, X., 2022, *Permafrost degradation increases risk and large future costs of infrastructure on the Third Pole*, *Communications Earth & Environment* **3**, 238. https://doi.org/10.1038/s43247-022-00568-6

[47] Chen, F., 2026, China is building a vast 'national ring road' circling the country's borderlands, *South China Morning Post*, August 23. Available at https://www.scmp.com/economy/china-economy/article/3364884/china-building-vast-national-ring-road-circling-countrys-borderlands (accessed 04 September 2026).

[48] Clarke, B., Zachariah, M., Davies, B., Hock, R., Immerzeel, W., Jha, R. & Robinson, T.R., 2026, *Rapid warming in the Himalaya exacerbates geohazard cascades beyond adaptation limits*, *WWA Scientific Report No. 92*, World Weather Attribution. https://doi.org/10.25560/136420

[49] Ewe, K., & Khadka, N. S., 2026, Nepal to use new flood study to claim millions from UN climate disaster fund, *BBC*, September 17. Available at https://www.bbc.com/news/articles/cmlyrzve5pwzo (accessed 18 September 2026).

[50] Ritchie, H. & Rosado, P., 2025, CO_2 and Greenhouse Gas Emissions, *OurWorldinData.org*. Available at https://ourworldindata.org/profile/co2/Nepal (accessed 18 September 2026).

[51] Arasu, S., 2026, Climate change made deadly Nepal glacier and rock collapse more likely, according to analysis, *Independent*, September 17. Available at https://www.independent.co.uk/news/himalayan-nepal-india-bengaluru-imperial-college-london-b3051593.html (accessed 18 September 2026).

[52] Agarwala, N. & Polinov, S., 2021, Curtailing Anthropogenic Carbon Dioxide to Meet the Targets of the Paris Agreement using Technology Support Mechanisms, *Journal of Human-centricResearch in Humanities and Social Sciences* **2**(1), 1-24. http://dx.doi.org/10.21742/jhrhss.2021.2.1.01

[53] Gayle, D., 2026. Climate crisis probably weakened glacier that caused devastating Nepal-Tibet floods, first study finds, *The Guardian*, September 17. Available at https://www.theguardian.com/science/2026/sep/17/climate-crisis-likely-behind-deadly-nepal-tibet-floods (accessed 18 September 2026).

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Identification of Environmental Hotspots in Concrete Pavements of Nepal: A Cradle-to-Grave Life Cycle Assessment

Astha Devkota [1,2a] & Sahil Shrestha [1,3b*]

[1] *Environmental Engineering Programme, Department of Civil Engineering, Pulchowk Campus, Institute of Engineering, Tribhuvan University, Lalitpur 44700, Nepal*

[2] *Department of Roads (DoR), Ministry of Infrastructure Development, Government of Nepal, Kathmandu 44600, Nepal*

[3] *Department of Water Supply and Sewerage Management (DWSSM), Ministry of Infrastructure Development, Government of Nepal, Kathmandu 44600, Nepal*

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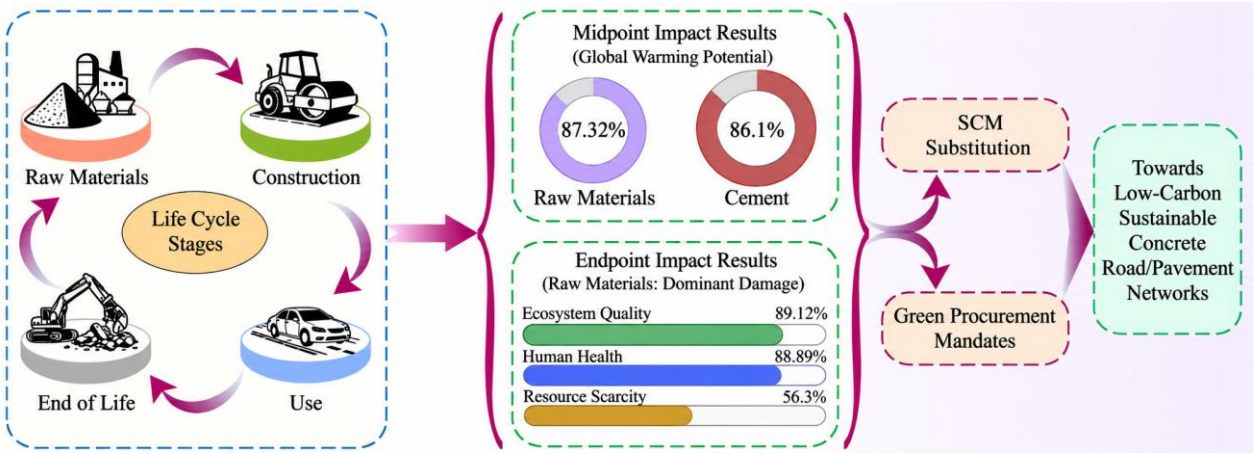
[a] ***ORCID:*** *0009-0009-1216-7485*; ***Email:*** *080msene003.astha@pcampus.edu.np*

[b] ***ORCID****: 0009-0001-3624-3130*; ***Email****: 079msene019.sahil@pcampus.edu.np*

Corresponding author:** Sahil Shrestha; ***Email: 079msene019.sahil@pcampus.edu.np; **Telephone:** +977-9861448239

Graphical Abstract

Nepal's infrastructure surge relies on durable concrete rigid pavements to reshape thousands of kilometres of national roadways. This research uses a cradle-to-grave life cycle assessment (C2G-LCA) to evaluate a 1 km rigid pavement. The findings revealed that material production—mainly cement—drives 87.32% of lifecycle global warming potential (711.27 tons CO_2 eq.) and approximately 89% of endpoint damages to ecosystem and human health damage, with cement being the major contributor to the material-phase impacts. By mandating low-carbon cement and embodied carbon thresholds in road contracts, Nepal can substantially decarbonize its expanding transport network.



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Abstract: Despite the rapid expansion of rigid road pavements in Nepal, their lifecycle environmental impacts remain largely unquantified. This study presents a cradle-to-grave Life Cycle Assessment (C2G-LCA) of a 1-km concrete pavement section along the Gwarko-Lamatar-Dahaltar (NH15) corridor. Results reveal that the material production phase dominates overall environmental burdens, accounting for roughly 89% of endpoint damages to human health and ecosystem quality, while cement production contributes 86.1% of material-phase global warming potential (GWP). These findings emphasize an urgent need to incorporate supplementary cementitious materials (SCMs), such as fly ash and ground granulated blast furnace slag (GGBS), into regional pavement designs and green procurement policies, while examining their availability, substitution rates, and cost-carbon trade-off. This research establishes a strong foundation for practical, evidence-based planning for low-carbon infrastructure, directly supporting Nepal's decarbonization and climate resilience targets under Nationally Determined Contribution (NDC) 3.0.

Keywords: *Life cycle assessment, Global warming potential, Concrete Pavements, Material production.*

Introduction

Transportation infrastructure is fundamental to national economic development, enhancing regional connectivity, facilitating trade, and improving access to essential services, including healthcare, education, and markets. Roads, being the most extensively used mode of transport in developing countries, contribute directly to multiple Sustainable Development Goals (SDGs), such as poverty reduction, economic growth, and climate action [1]. Concrete pavements have gained increasing significance owing to their higher structural strength, longer service life, lower maintenance frequency, and better performance under heavy traffic loading, making them the preferred choice in both new construction and rehabilitation projects [2]. But, the material production and processing, construction, operation, and end-of-life management of these concrete pavements impose significant environmental burdens throughout their life cycle, including greenhouse gas emissions, particulate matter formation, land use, and ozone depletion [3]. Thus, as global demand for transport mobility continues to rise alongside increasing commitments to climate change mitigation, the environmental performance of such concrete pavement systems has become a critical concern for engineers, policymakers, and researchers alike.

Various tools have been developed to investigate the environmental impacts of engineering systems and processes, among which Life Cycle Assessment (LCA) has emerged as the internationally recognized analytical tool for systematically quantifying such impacts. Standardized under ISO 14040 and ISO 14044, LCA evaluates impacts across all stages of a product or system's life cycle-from raw material extraction and production to construction, operation, maintenance, and end-of-life. Specifically, in the context of concrete pavements, LCA enables a comprehensive assessment of impacts, such as greenhouse gas emissions, energy consumption, and resource depletion associated with each life cycle phase, identifies environmental hotspots, and supports more sustainable material and design choices.

Although numerous pavement LCA studies have been conducted in North America, Europe, and China, evidence from developing countries remains comparatively limited [6,7]. For instance, in Nepal, the Strategic National Highway (SNH) envisions the addition of approximately 33,000 km of new two-lane paved national and provincial highway by 2043, reflecting the country's ambitious development goals [6]. Disaggregated data on the concrete versus flexible pavement share of this network are not readily available, but recent Nepalese road projects indicate growing interest in concrete pavement as an alternative to asphalt, particularly for sections exposed to heavy traffic, water seepage, steep gradients, and unstable ground conditions [7].

Despite this uptake, quantitative assessment of the environmental performance of concrete pavements under Nepal-specific conditions remains limited—including local construction

practices, material supply chains, transportation distances, and national electricity mixes. Therefore, direct application of international LCA models is inappropriate as these parameters differ substantially from those in high-income countries.

Several prior LCA studies have examined pavement systems but with notable limitations. Sreedhar *et al.* (2016) assessed the carbon footprint of pavement systems in India, which was scoped to material production and construction stages without adopting a complete cradle to grave approach that would include traffic-use and end-of-life demolition phases [8]. Likewise, Santero *et al.* (2011) and Zhao *et al.* (2015) concluded cement-dominated Global Warming Potential (GWP) profiles for concrete pavements, yet their findings were anchored in construction contexts (USA and China only) that differed from Nepal in terms of energy mix, transportation, and material sourcing [3,11]. In Nepal's context, Khanal *et al.* (2025) estimated the carbon footprint adopting Gate-to-Gate (G2G) approach; but the analysis was limited to the construction stage, excluding material production, use, and end-of-life stages [11]. Moreover, many pavement LCA studies emphasized climate change and greenhouse gas emissions, whereas comparatively fewer studies assess a broader range of midpoint and endpoint environmental impact categories [11,12]. Thus, a Cradle-to-Grave (C2G) approach is crucial for concrete pavements, as it captures environmental burdens throughout their service life, including maintenance and end-of-life phases, providing a more comprehensive basis for environmental decision-making than partial approaches such as cradle-to-gate [14]. Further, to the best of our knowledge, no study has yet applied a C2G-LCA framework to concrete road pavements under Nepal-specific conditions—encompassing the full suite of ReCiPe 2016's midpoint and endpoint impact categories. There is a research gap.

Accordingly, this study presents the first case-specific C2G-LCA of a concrete pavement in Nepal's hilly terrain: the Gwarko-Lamatar-Dahaltar Road section, offering a locally grounded evidence base rather than relying on factors and inventories drawn from international pavement LCA literature. The study aims to quantify environmental impacts across all 18 midpoint and 3 endpoint categories of ReCiPe 2016, identifying hotspots throughout the pavement's life cycle phases. The assessment adopts a C2G system boundary, drawing on primary data from local material suppliers and construction records combined with secondary background databases.

Results reveal that the material phase dominates the pavement's overall environmental footprint, with cement production alone representing the most critical hotspot across the pavement's lifecycle. These findings provide a quantitative foundation for prioritizing the substitution of supplementary cementitious materials (SCM) and embodied-carbon considerations within Nepal's road procurement policies. Future research should critically examine regional, SCM-blended binders for road construction under similar hilly-terrain conditions, while incorporating social and

economic life cycle dimensions to support holistic, climate-resilient, and low-carbon road sustainability strategies aligned with Nepal's Nationally Determined Contribution (NDC 3.0) targets.

Methodology

The present study adopts a C2G-LCA approach, conducted in accordance with the principles and framework outlined in ISO 14040:2006 and ISO 14044:2006, which provide internationally recognized guidelines for performing (LCA) of road pavement systems [14]. This LCA methodology comprises four phases: (i) goal and scope definition, (ii) life cycle inventory (LCI) analysis, (iii) life cycle impact assessment (LCIA), and (iv) Result interpretation.

Goal and scope definition

The goal and scope definition phase, as mandated by ISO 14040:2006, is foundational to LCA methodology. It establishes the system boundaries, functional unit, and impact assessment scope that collectively determine the validity, reproducibility, and comparability of the entire LCA. Within this context, the goal is to analyse environmental life-cycle impacts of concrete pavement under Nepal-specific conditions, while evaluating its potential impacts on human health, ecosystem and resource scarcity.

The Gwarko-Lamatar-Dahaltar Road (NH15)—a Hilly Terrain road, originating from Gwarko [16]— was selected for this study, with specific focus on its Namobuddha section located 37.5 km from Gwarko. The selected pavement section comprises a 7 m wide, 25 cm thick carriageway constructed with M25-grade Ordinary Portland Cement (OPC) concrete.

The functional unit was defined as 1 km of concrete road pavement with a 7 m wide carriageway and a design life of 20 years. Within the framework, the system boundary is defined as C2G with different lifecycle phases, including: (i) raw material (cement, coarse aggregates, fine sand, reinforcing steel) extraction, production, and transportation to construction site; (ii) on-site construction activities, including concrete mixing using a drum-type mixture, paving, and vibration; (iii) the use phase, comprising fuel (diesel and petrol) consumption associated with vehicular traffic over the 20-years design life; and (v) end-of-life demolition. Activities excluded from the system boundaries are therefore identified as limitations of this study, include subgrade, subbase and base preparations, road marking materials, cutting and filling earthworks, vegetation clearing, and maintenance overlays, the last of which was excluded on the assumption that no major rehabilitation would be required for rigid pavement within the 20-year design life. Recycling of

demolished concrete at the end-of-life was not modelled due to the absence of local recycling facility data.

Life cycle inventory analysis

The Life Cycle Inventory (LCI) is the systematic quantification of all material inputs, energy flows, and transportation inputs of each life cycle stage of the selected pavement system within the defined system boundary. For this, both primary and secondary data sources were used.

Site-specific primary data were acquired from the Road division offices and relevant project documentation—including bills of quantities (BoQs), cost estimates, mix design reports, and construction records. Secondary data were obtained from Norms for Rate Analysis of Road and Bridge Works—published by the Department of Roads (DoR), Nepal [17]—along with equipment hire rate, published reports, literature, and available databases such as Ecoinvent v.3.11 [18]. The detailed inventory used for this study is provided in **Table 1**.

Table 1. LCI data LCA-C2G for the 1-km concrete pavement section along the Gwarko-Lamatar-Dahaltar (NH15) road (per functional unit)

Life Cycle Phase	Inventory Item	Quantity	Unit	Data Source	Remarks
Material Production	Cement	736.75	Tonne	Mix Design	
	Sand	1063	Tonne	Mix Design	
	Aggregates	1860	Tonne	Mix Design	
	Reinforcing steels	35.03	Tonne	Estimated	
	Water	372	Kg	Mix Design	
Transportation of Material	Cement	300	Km	Site Engineer	Cement factory to site
	Sand, Aggregates	15	Km	Site Engineer	Crusher to site
	Reinforcing Steels	300	Km	Site Engineer	Factory to site
Construction	Diesel for Concrete Mixture	1190	Kg	DoR Hire Rate	
	Diesel for Vibrator	31	Kg	Specification of Needle Vibrator	
Use	2- wheeler	145415	No.		Projected no. of vehicles at the end of 20 years.
	Cars (Petrol)	25510	No.		
	Cars (Diesel)	2834	No.		
	Trucks and Tractors	1905	No.		
	Bus	4689	No.		
End-of-Life	Demolition fuels	10220	Kg.	DoR Hire Rate	

Material input considered in the LCA included cement (OPC 53-grade), sand, aggregates, and reinforcing steels (Fe500), were derived from mix designs and were calculated for 1 km functional unit. Transport distances from material sources, such as cement factories, crusher sites, and steel suppliers, to the construction sites were estimated as per the supplier locations and site information given by the respective site engineers.

For the construction phase, machinery requirement was identified from the DoR norms for road works. Similarly, fuel consumption by on-site drum type concrete mixer and needle vibrator were estimated from the DoR's Norms of Plants and Machinery. The operational stage of the considered road was then modelled based on traffic related fuel consumption with traffic volume forecasted for 20 years applying a 6% growth rate [19]. Furthermore, the traffic in this study included two-wheelers, diesel cars, petrol cars, buses, and trucks with 90% of cars assumed to be Petrol and 10% to be Diesel [20]. End of life stage considers the fuel consumed in the machinery (air compressor, concrete joint cutter, tractor trolley) used in the dismantling and transportation of debris to the nearest dumping site.

Life cycle impact assessment

The Life Cycle Impact Assessment (LCIA) evaluates the significance of potential environmental impacts and links inventory data to specific environmental impact categories in order to assess their potential environmental impacts. In this study, the ReCiPe 2016 Hierarchist impact assessment method was adopted. It is the most widely applied characterization method in infrastructure and pavement-related LCA studies [18,19]. The ReCiPe 2016 Hierarchist perspective adopts a 100-year time horizon, balancing short-term and long term environmental concerns, and is recommended as the default perspective for comparative studies [21].

LCIA was conducted using SimaPro software (version 10.2.0.2) and the consequent results were analysed at both the midpoint and endpoint levels, as described earlier. Midpoint analysis was prioritized as the primary basis for interpretation, as it provides a more transparent link between emissions and environmental mechanisms and also lower uncertainty [21]. In addition, endpoint impacts were evaluated to support decision-making by aggregating emissions into damage-oriented categories. The ReCiPe 2016 method covers 18 midpoint impact categories and three endpoint categories [21]. Table 2 shows the different types of impact categories considered in the study, along with their corresponding sub-categories. In accordance with ISO standards, the LCIA phase includes classification, characterization, normalization, and weighting. Classification assigned inventory flow to relevant impact categories based on their environmental effects. Characterization was performed by multiplying classified inventory quantities by their respective characterization

factors. Normalization and subsequent weighting of those diverse numerical scores were excluded from the study, as ISO 14044 considers both as optional elements of LCIA. Normalization was avoided as reference values are often outdated or not specific to Nepal, which could thereby distort the results. Sousa *et al.* (2021) noted that external normalization factors are almost exclusively compiled by a small number of data-rich nations, leaving many countries without a representative dataset of their own, and ISO 14044 itself lists geographical and temporal representativeness among its core data quality criteria [23]. Likewise, weighting was avoided because of its dependency on subjective judgements about which impact matters more. Notably, ISO 14044 states that this is not scientifically reliable and does not allow it in public comparison studies—a view also supported by Pizzol *et al.* [20,21].

Table 2. Impact categories assessed under ReCiPe 2016 Hierarchist midpoint and endpoint framework [21]

Category Types	Categories	Unit
Midpoint Categories	Global warming	Kg CO_2 eq.
	Stratospheric ozone depletion	Kg CFC^{-11} eq.
	Ionizing radiation	KBq Co-60 eq.
	Ozone formation, human health	Kg NOx eq.
	Fine particulate matter formation	Kg PM2.5 eq.
	Ozone formation, terrestrial ecosystem	Kg NOx eq.
	Terrestrial acidification	Kg SO_2
	Freshwater eutrophication	Kg P eq.
	Marine eutrophication	Kg N eq.
	Terrestrial ecotoxicity	Kg 1,4-DCB
	Freshwater ecotoxicity	Kg 1,4-DCB
	Marine ecotoxicity	Kg 1,4-DCB
	Human carcinogenic toxicity	Kg 1,4-DCB
	Human non-carcinogenic toxicity	Kg 1,4-DCB
	Land use	m^2 year
	Mineral resource scarcity	Kg Cu eq.
	Fossil resource scarcity	Kg oil eq.
	Water consumption	m^3
Endpoint Categories	Damage to human health	DALY
	Damage to ecosystem	Species.yr.
	Damage to resource scarcity	USD

Note: 1,4-DCB: 1,4-dichlorobenzene; CFC^{-11}: Chlorofluorocarbon-11; Co-60: Cobalt-60; CO_2: Carbon Dioxide; Cu: Copper; DALY= Disability-Adjusted Life Year; eq.: equivalent; KBq: kilobecquerels; Kg: Kilogram; N: Nitrogen; NOx: Nitrous Oxides; P: Phosphorus; PM2.5: Particulate Matter (<2.5µm); SO_2: Sulphur Oxides; USD: United States Dollar; yr.: Year.

Results and Discussion

The C2G-LCA results for the Namobuddha concrete pavement section—1-km functional unit, 7 m carriageway, and 20-years of design life—are presented in terms of midpoint and endpoint environmental impacts as discussed below. The relative contribution for the road in terms of mid-point and endpoint environmental impacts on every impact category of each life cycle phase has been shown in Figure 2 and Figure 3, respectively.

Midpoint impact assessment

Across the majority of ReCiPe midpoint impact categories (16 of 18), the material extraction and production phase was found to be the dominant contributor, consistent with previous pavement LCA studies that identified material production as the primary source of environmental burden in the concrete road system [24,25]. For the concrete pavement section under study, the total GWP over the 20-year life cycle was found to be 814.52 tonne CO_2-eq. per kilometre. Most of the total GWP came from the material production phase, which made up 87.32% of the overall contribution. In contrast, material transportation was responsible for 6.98%, and the use phase contributed 4.22%. The remaining phases had a much smaller effect, with the end-of-life phase accounting for 1.3% and the construction phase making up just 0.167%. These phase-wise contributions were broadly consistent across other midpoint categories—confirming the dominant environmental significance of upstream material production in concrete pavement systems, with the exception of terrestrial and marine ecotoxicity, where transportation emerged as the leading contributor. Transportation was the leading contributor to terrestrial ecotoxicity (8.17×10^5 kg 1,4-DCB, compared to 6.45×10^5 kg 1,4-DCB from material production) and contributed marginally more than material production to marine ecotoxicity (589 vs. 586 kg 1,4-DCB). This departure from the material-dominant pattern reflects the distinct impact pathway of transportation emissions relative to material extraction and processing, closely aligning with the comparative pavement LCA studies that identified material transportation as a disproportionate contributor to metal-related midpoint categories [28].

Through the contribution analysis feature in SimaPro, it was found that the cement production alone accounted for 86.1% of total material phase GWP—equivalent to approximately 610 tonne CO_2-eq. (0.831 tonnes CO_2-eq. per tonne of cement—as demonstrated in Figure 1. These findings confirmed its role as the principal environmental hotspot within the pavement system, aligning with the findings from Ma *et al.* (2016) and Rangelov *et al.* (2022) who reported cement production contributing approximately 90% of material phase emission in Chinese and US pavements, respectively [25,26]. Likewise, the calculated GWP intensity of 0.831 tonnes CO_2-eq per tonne of cement aligns closely with Nepal-specific studies, where 26 cement industries across the country

were studied and consequently, an average intensity of 0.739 tonne of CO_2-eq per tonne was assessed [31]. Similarly, a cradle-to-gate LCA of Nepalese cement production using SimaPro reported GWP values of approximately 0.88 tonne CO_2-eq per tonne for OPC, identified as the dominant emission hotspot, contributing over 91% of total impacts [32]. This dominance of cement can be attributed to the energy intensive nature of cement manufacturing, which requires high-temperature rotary kiln operations (exceeding 1450 $^{\circ}$C) and generates substantial CO_2 emissions through fuel combustion and the calcination of limestone [33]. On average, 30-40% of these direct emissions are attributable to the combustion of fuels required to attain the necessary kiln temperature; the remaining 60-70% arise from the calcination of limestone to calcium oxide—the chemical precursor to the calcium silicate responsible for cement's binding strength [34].

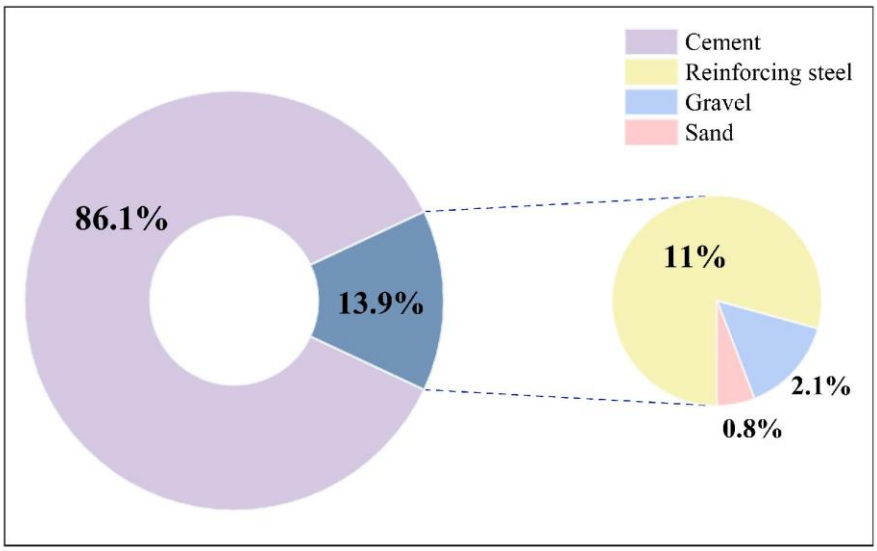


Figure 1. Contribution of individual material to GWP during their production stage for 1-km rigid concrete pavement of the selected section.

Reinforcing steel bars represented the second largest contribution of 11% of material-phase GWP (Figure 1). The calculated GWP intensity for reinforcing steel was 2.24 tonnes CO_2-eq per tonne. This value is consistent with reported intensities for India's blast furnace-basic oxygen furnace (BF-BOF) steel sector, which range from 2.2 to 2.6 tonne CO_2-eq. per tonne depending on plant age and efficiency [35]. The result is consistent with the global BF-BOF route average of approximately 2.3 tonnes CO_2-eq. per tonne of crude steel, which accounts for the majority (~70%) of world crude steel production [36]. Although the steel production (2.24 tonnes CO_2-eq/tonne) exhibits a substantially higher GWP intensity per unit mass than cement (0.831 tonnes CO_2-eq/tonne), its overall contribution to the total pavement carbon footprint remains lower, owing to cement's considerably greater mass share within the pavement system (Table 1). This demonstrates that the total material-phase emissions are governed not solely by per-unit emission intensity, but

by the combined effect of intensity and quantity. Coarse aggregates (gravel) and fine aggregates (sand) contributed the least to material-phase GWP—at 2.07% and 0.81%, respectively (Figure 1). This comparatively minor contribution reflects the mechanical nature of their processing—including scooping, crushing, screening, and transport— with no accompanying chemical transformation, unlike the energy- and process-intensive chemistry of cement production. Sand's marginally lower contribution relative to coarse aggregate further reflects this mechanical basis, since aggregates require the additional crushing step to achieve the required size gradation, which sand does not. This finding is consistent with the findings of Pizon *et al.* (2026), who demonstrated that aggregate and sand production contributes marginally to overall LCA impacts [37].

In contrast, the construction phase contributed 0.17% of total GWP and less than 5% of all the midpoint categories (Figure 2). This aligns with the literature, which states that on-site construction activities are consistently found to contribute a comparatively minor share of the total life cycle emissions relative to upstream material production and transport [38]. The low contribution of the construction phase reflects the actual construction practices adopted in the case study: a diesel-powered drum-type concrete mixture and a diesel-powered needle vibrator were the only equipment used on the site.

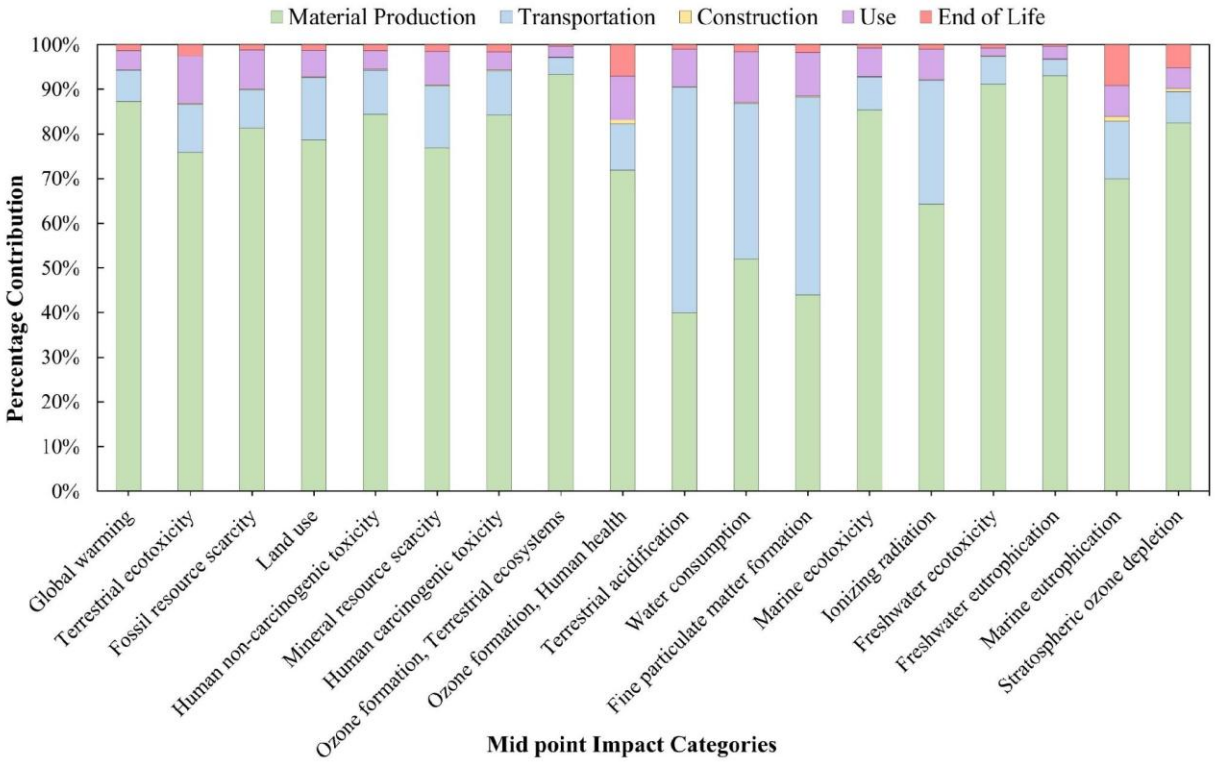


Figure 2. Percentage contribution of different life-cycle stages with respect to the 18 ReCiPe 2016 midpoint impact categories for 1 km of rigid concrete pavement.

Endpoint impact assessment

The endpoint LCIA results (Figure 3) demonstrate midpoint impacts into three damage categories, providing an integrated perspective on the overall severity of environmental consequences. For both human health and ecosystem quality, the material production phase was the dominant contributor to total lifecycle damage, accounting for 88.8% of human health damage and 89.1% of ecosystem quality damage. Within this phase, cement production was identified as the primary driver, contributing 80.5% of human health damage and 82.2% of ecosystem quality damage among material inputs—consistent with ReCiPe 2016 endpoint assessments of cement production, which similarly identified the clinkering stage as the dominant contributor to both damage categories [39]. Likewise, global warming (Human health) and particulate matter formation were the principal midpoint drivers within the human health endpoint, together accounting for the majority of the damage score. Conversely, within the ecosystem quality endpoint, global warming (terrestrial ecosystems) emerged as the leading contributor, responsible for roughly 69% of the total damage score. Land use and terrestrial acidification followed at a comparable level, each accounting for about 11%, closely followed by ozone formation (terrestrial ecosystem) (9%). This pattern is consistent with comparisons across different LCIA methods, which similarly identify climate change and land use as the principal global drivers of ecosystem quality damage, and climate change and particulate matter formation as the principal driver of human health damage [40].

The high contributions of global warming, human health and particulate matter formation to human health damage reflect the cumulative effect of cement manufacturing emissions across multiple endpoint pathways [41]. GHG emissions from cement production contribute to climate change that damages human health through climate sensitive disease including malaria, diarrhoeal diseases, malnutrition, and cardiovascular conditions, simultaneously contributing to ecosystem disruption through habitat loss and biodiversity decline [21]. The WHO has attributed over 150,000 deaths and approximately 5 million DALYs annually to climate change impacts globally [42]. Likewise, fine particulate matter (PM2.5) released during clinker production, grinding, and material handling is a major contributor to this burden. For instance, a case study of communities near a major cement facility in Brazil found PM2.5 exposure accounted for 3.5% of the total years of life lost from all causes, corresponding to 0.23 years lost in life expectancy, with additional attributable increase in cardiovascular and respiratory disease incidence [43]. The dominant contribution of the material phase to ecosystem quality damage (89.1%) reflects multiple midpoint impact pathways associated with raw materials extraction and processing.

Quarrying operations for limestone, aggregates, and sand directly damage terrestrial habitat, as the harvesting of raw materials degrades the surrounding landscape that constitutes the natural habitat of flora and fauna, resulting in biodiversity loss. In addition, cement production releases sulphur dioxide and nitrogen oxides that form acid rain upon atmospheric reaction, acidifying soil and fresh water systems and disrupting aquatic and terrestrial flora. Heavy metals released during clinker production and kiln operation, particularly copper, further contribute to this damage through terrestrial ecotoxicity. Cement production has been reported to generate 0.438 kg 1,4-DCB equivalent per kg of OPC, of which 61.5% is attributable to copper emissions alone [44].

Similarly, reinforcing steel production emits copper and zinc, key contributors to terrestrial, freshwater, and marine ecotoxicity, and lead is the dominant contributor to human toxicity [45]. This is consistent with a ReCiPe 2016 endpoint assessment of reinforcing bar manufacturing, which identified heavy-metal contamination during melting as the primary driver of human health damage, and heavy fuel combustion during billet reheating as the major contributor of ecosystem quality damage [46].

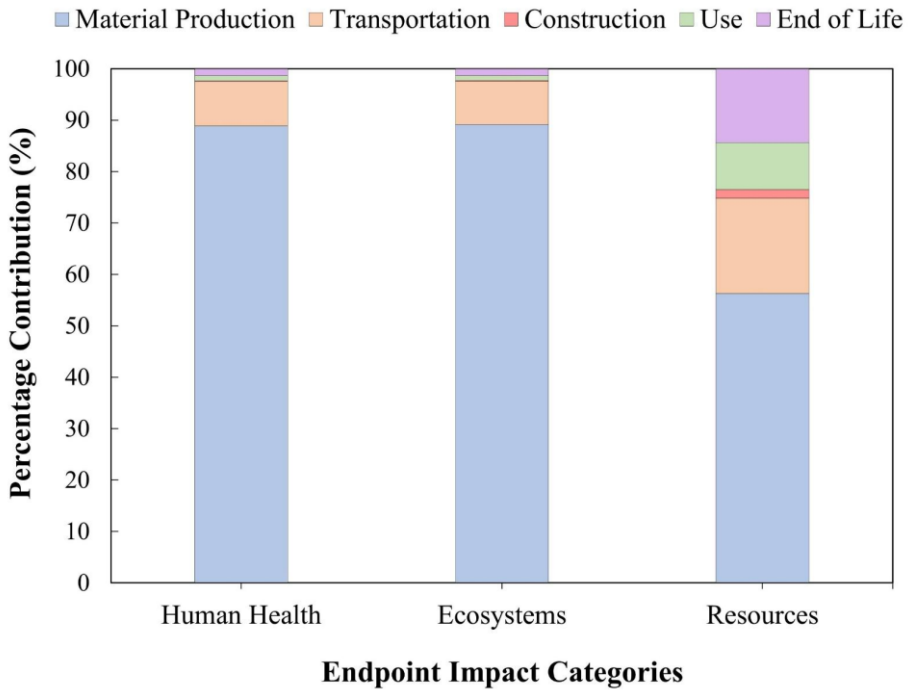


Figure 3. Relative contribution of different life-cycle phases to the ReCiPe 2016 endpoint impact categories for 1 km of rigid concrete pavement.

Unlike human health and ecosystem quality, the resource scarcity category shows a different distributed profile—with 56.3% contribution by raw material production phase, 18.48% by transportation, 1.73% by construction, 9.1% by use phase, and 14.37% by end of life. In ReCiPe method, resource scarcity endpoint measures the surplus costs of future mineral and fossil

extraction (expressed in USD), capturing depletion-driven increase in extraction costs rather than present day scarcity. The endpoint comprises two sub-categories: mineral resource scarcity, accounting for the depletion of metals and minerals, and fossil resource scarcity, representing the depletion of coal, oil, and natural gas. Both are expressed in USD per kilogram of resource extracted [21]. The results are observed to be consistent with prior ReCiPe endpoint assessment of cement production, in which fuel usage rather than raw material extraction accounted for 96% of total resource damage [39]. They are further supported by pavement-specific studies, which identify crude oil consumption during material production, together with diesel use in transport and mobile equipment, as the dominant driver of resource depletion across road life cycles [47]. The findings highlight the significance of local material sourcing and optimizing the transportation logistics which can simultaneously reduce transportation related impacts and fossil resource consumption [48].

Resource scarcity contributed 14.37% of End-of-life (EoL) phase because fossil fuel was used on demolition and transporting debris. This study did not model the EoL recycling of demolished concrete because local data were unavailable. If concrete recycling had been included and used as recycled aggregates for sub base or fill, the resource scarcity score would likely be lower. This points to a limitation of the current study and suggests that future evaluations creating recycle-inclusive EoL scenarios for Nepal's concrete pavements would provide a more complete picture of the environmental trade-offs associated with material recovery strategies.

Environmental implications and mitigation pathways

The results of midpoint and endpoint categories clearly illustrate that cement production is the key area to focus on for lowering the environmental impact of concrete road pavements in Nepal. This finding carries direct implications for sustainable pavement design and supports Nepal's NDC 3.0 goals to reduce greenhouse gas emissions from the road transport and construction sectors, as well as the global push toward net zero emissions [49]. The findings suggest several evidence-based mitigation pathways, as discussed below.

The most effective approach in existing construction practice is the partial replacement of OPC with supplementary cementitious materials (SCMs)—such as fly ash, ground granulated blast furnace slag (GGBFS), and silica fume [50]. Studies have shown that partial replacement of cement with fly ash (FA) or ground granulated blast furnace slag (GGBS) at 40-65% can reduce GWP by 54-61% while maintaining structural performance [51]. Locally available pozzolanic materials like calcined clay, rice husk ash could provide feasible alternatives to industrial by-products such as fly ash and GGBS, which are less abundantly available in Nepal owing to the limited presence of coal

fired power plants and blast furnaces [52]. Limestone Calcined Clay Cement (LC3) has been demonstrated in the South Asian context and is a particularly promising option, reducing CO_2 emissions by about 30% and conserving more than one-third of the energy compared to OPC [44,45].

Optimizing the logistics for material transportation falls onto second place as a priority. This is particularly relevant in Nepal's mountainous topography, where road networks are characterized by winding alignments, switchbacks, and elevation changes; this means that actual travel distances between material sources and construction sites are often substantially longer than straight-line distances would suggest, making the environmental benefits of logistics optimization disproportionately large relative to the modest cost of supply chain planning. Therefore, procuring aggregates and sand from sources near the construction sites and negotiating cement supply from the nearest factory, would directly decrease the haulage distance, diesel consumption, and the associated emissions. Moreover, transportation's dominant ecotoxicity contribution, reported, is consistent with the broader freight-transport LCA literature, which identifies brake and tyre wear alongside fuel combustion itself as significant sources of toxic heavy metals such as copper and zinc [55]. This indicates that the logistic optimization would deliver ecotoxicity co-benefits alongside its resource-scarcity and GWP benefits. Reducing the haulage distance would reduce both fuel-related emissions and cumulative wear-related releases associated with longer transport routes.

The implementation of EoL concrete recycling during the demolition phase, for example, using demolished concrete as recycled coarse aggregate in sub-base layers or fill applications, would decrease the virgin material requirement for future road construction and reduce the burden of resource scarcity endpoint [56]. To realize this potential in Nepal, specific measures would be needed including the establishment of centralized crushing and recycling facilities near major urban centres. In addition, the development of national technical standards governing the use of recycled aggregates in sub-base and fill applications would be necessary, alongside procurement policies that require use of recycled material content in publicly funded road projects. The growing volume of ageing road infrastructure reaching end of life presents an emerging opportunity to pilot such interventions and build the technical capacity needed to support material recovery at scale.

These mitigation pathways support Nepal's NDC 3.0 goals, which targets a 26.8% reduction in net GHG emissions by 2035 relative to the business-as-usual scenario. NDC 3.0 also calls for reducing transport-sector emissions through fuel efficiency improvement, electrification, and low-carbon construction materials—including 90% of public transport sales to be electric, reducing coal use through bioenergy, and better kiln efficiency [49]. Ultimately, these findings provide clear, data-

based evidence required to support this goal. The cement-related interventions are the most cost-effective way to achieve climate-resilient, sustainable, and low-carbon road infrastructure in Nepal.

Conclusions

As Nepal rapidly expands its road network across varied topography, engineers increasingly favour concrete pavements for their long lifespan and minimal maintenance requirements. Decisions on material selection, sourcing, and construction practice are rarely informed by environmental data specific to Nepal. To bridge these gaps, for the first time, this study performed a C2G-LCA of a 1 km concrete pavement section at chainage 37+500 on Nepal's NH15, located along the Gwarko-Namobuddha stretch in Bagmati province, using the ReCiPe 2016 Hierarchist method in SimaPro software, per ISO 14040/44. Here, the material production phase dominated most of the impact categories—accounting for 16 of the 18 ReCiPe 2016 midpoint accessed—contributing 87.32% of the total lifecycle GWP. Likewise, cement alone was responsible for 86.1% of this impact, driven by clinker calcination and high-temperature kiln combustion.

Transportation was the leading contributor to terrestrial ecotoxicity and contributed marginally more than material production to marine ecotoxicity, reflecting diesel combustion over Nepal's long, hilly haul distances. At the endpoint level, the material production stage prevailed: this phase is found to be responsible for 88.8% of the damage to Human Health (DALYs) and 89.1% of Ecosystem Quality (species.year). These findings highlight the point that cement mitigation would improve both climate and public health. Resource scarcity was found to be more evenly distributed; notably, transportation accounted for 18.48% because of the extended haulage in hilly terrain, underscoring the critical need for localized sourcing and supply chain optimization. In contrast, construction stage remained a minor contributor. Mitigation interventions targeting only on-site construction operations would achieve marginal gains relative to upstream material production approaches.

These findings identify cement production as the critical leverage point for decarbonizing Nepal's road sector. Material-level strategies offer far greater potential than construction-level ones.

In order to meet Nepal's NDC 3.0 target of a 26.8% reduction in the national GHG emissions by 2035, future research and policy should prioritize the partial substitution of the OPC with supplementary cementitious materials (SCMs), alongside broader adoption of the blended cements (such as LC3), that can cut production stage CO_2 emissions by up to 30%. Optimizing local material sourcing to minimize the transportation-related emissions and embedding embodied-carbon thresholds into procurement and pavement design policy would further support this target.

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Ethics Approvals: This study was conducted in full accordance with ethical principles. The overall cradle-to-grave life cycle assessment (C2G-LCA) was conducted in compliance with ISO 14040 and ISO 14044.

Data Availability: The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Code availability: Not applicable

Conflict of interest: The authors declare that they have no conflict of interest.

References

[1] Kaiser, N., & Barstow, C. K., 2022, Rural transportation infrastructure in low- and middle-income countries: a review of impacts, implications, and interventions. *Sustainability* **14**(4), Article 2149. https://doi.org/10.3390/su14042149

[2] Anastasiou, E. K., Liapis, A., & Papayianni, I., 2015, Comparative life cycle assessment of concrete road pavements using industrial by-products as alternative materials. *Resources, Conservation and Recycling* **101**, 1-8. https://doi.org/10.1016/j.resconrec.2015.05.009

[3] Gouveia, B. G., Donato, M., & Da Silva, M. A. V., 2022, Life cycle assessment in road pavement infrastructures: a review. *Civil Engineering Journal* **8**(6), 1304-1315. https://doi.org/10.28991/CEJ-2022-08-06-015

[4] Guerrero-Bustamante, O., Camargo, R., Duque, J., Martinez-Arguelles, G., Polo-Mendoza, R., Acosta, C., & Murillo, M., 2025, Designing sustainable asphalt pavement structures with a cement-treated base (CTB) and recycled concrete aggregate (RCA): a case study from a developing country. *Designs* **9**(3), Article 65. https://doi.org/10.3390/designs9030065

[5] Polo-Mendoza, R., Mora, O., Duque, J., Turbay, E., Martinez-Arguelles, G., Fuentes, L., Guerrero, O., & Perez, S., 2023, Environmental and economic feasibility of implementing perpetual pavements (PPs) against conventional pavements: a case study of Barranquilla city,

Colombia. *Case Studies in Construction Materials* **18**, Article e02112. https://doi.org/10.1016/j.cscm.2023.e02112

[6] National Planning Commission (NPC), 2020, *The Fifteenth Plan (Fiscal Year 2019/20-2023/24)* (Kathmandu, Nepal: National Planning Commission, Government of Nepal).

[7] Chhetri, N. P., Jaiswal, R., & Poudel, R., 2024, Resilient roads in challenging terrain: a case study of Siddhartha highway in Nepal. *Discover Civil Engineering* **1**(1), Article 76. https://doi.org/10.1007/s44290-024-00079-7

[8] Sreedhar, S., Jichkar, P., & Biligiri, K. P., 2016, Investigation of carbon footprints of highway construction materials in India. *Transportation Research Procedia* **17**, 291-300. https://doi.org/10.1016/j.trpro.2016.11.095

[9] Santero, N. J., Masanet, E., & Horvath, A., 2011, Life-cycle assessment of pavements. Part I: critical review. *Resources, Conservation and Recycling* **55**(9-10), 801-809. https://doi.org/10.1016/j.resconrec.2011.03.010

[10] Zhao, L. L., Wang, Z. H., Liu, Y., Gong, X. Z., Gao, F., Cui, J. P., Jiang, Q., & Ma, L. P., 2015, Analysis on the global warming potential of cement concrete pavement in China. *Materials Science Forum* **814**, 418-424. https://doi.org/10.4028/www.scientific.net/MSF.814.418

[11] Khanal, S., & Dongol, R., 2025, Carbon footprint estimation in road construction: a case study of Pokhara-Mugling road, Nepal. *Everest Advances in Science and Technology* **1**(1), 1-14. https://doi.org/10.3126/east.v1i1.88054

[12] Aryan, Y., Dikshit, A. K., & Shinde, A. M., 2023, A critical review of the life cycle assessment studies on road pavements and road infrastructures. *Journal of Environmental Management* **336**, Article 117697. https://doi.org/10.1016/j.jenvman.2023.117697

[13] Huang, X., Huang, Z., Zhou, Y., Hu, R., & Hu, B., 2025, Life cycle assessment and cost analysis of LC3 concrete considering sustainability and uncertainty. *Journal of Building Engineering* **102**, Article 111960. https://doi.org/10.1016/j.jobe.2025.111960

[14] Fan, H., Yu, H., Ma, H., Chen, X., Li, L., Du, Q., Zhang, M., Ma, H., & Wu, C., 2025, Refinement and application of life cycle assessment (LCA) for concrete: Development of a carbon emission metric normalized by salt-freezing durability and its use in designing high-durability, low-carbon, high-performance concrete. *Sustainable Materials and Technologies* **45**, Article e01622. https://doi.org/10.1016/j.susmat.2025.e01622

[15] Bureau of Indian Standards, 2006, *IS/ISO 14040: Environmental Management - Life Cycle Assessment - Principles and Framework* (New Delhi, India: Bureau of Indian Standards).

[16] Department of Roads (DoR), 2023, *Statistics of National Highway (SNH) 2022/23* (Kathmandu, Nepal: Department of Roads, Government of Nepal).

[17] Department of Roads (DoR), 2018 AD, *Norms for Works: Road and Bridges* (Kathmandu, Nepal: Department of Roads, Government of Nepal).

[18] Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B., 2016, The Ecoinvent database version 3 (part I): overview and methodology. *International Journal of Life Cycle Assessment* **21**(9), 1218-1230. https://doi.org/10.1007/s11367-016-1087-8

[19] Department of Roads (DoR), 2021, *Rigid Pavement Guideline 2021* (Kathmandu: Department of Roads, Government of Nepal).

[20] Karn, S., Jha, A. K., Maharjan, A., & Darlami, H. B., 2023, "Impact of electric vehicle on energy demand in Nepal using a scenario-based approach." Presented at the 14th *IOE Graduate Conference, Institute of Engineering, Pulchowk, NP*, 29 November-1 December.

[21] Huijbregts, M. A. J., Steinmann, Z. J. N., Elshout, P. M. F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., & van Zelm, R., 2017, ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. *International Journal of Life Cycle Assessment* **22**(2), 138-147. https://doi.org/10.1007/s11367-016-1246-y

[22] Hoxha, E., Vignisdottir, H. R., Barbieri, D. M., Wang, F., Bohne, R. A., Kristensen, T., & Passer, A., 2021, Life cycle assessment of roads: exploring research trends and harmonization challenges. *Science of the Total Environment* **759**, Article 143506. https://doi.org/10.1016/j.scitotenv.2020.143506

[23] Sousa, S. R., Soares, S. R., Moreira, N. G., Severis, R. M., & De Santa-Eulalia, L. A., 2021, Internal normalization procedures in the context of LCA: a simulation-based comparative analysis. *Environmental Modeling & Assessment* **26**(3), 271-281. https://doi.org/10.1007/s10666-021-09767-5

[24] Pizzol, M., Laurent, A., Sala, S., Weidema, B., Verones, F., & Koffler, C., 2017, Normalisation and weighting in life cycle assessment: quo vadis? *International Journal of Life Cycle Assessment* **22**(6), 853-866. https://doi.org/10.1007/s11367-016-1199-1

[25] Bureau of Indian Standards, 2009, *IS/ISO 14044: Environmental Management - Life Cycle Assessment - Requirements and Guidelines* (New Delhi, India: Bureau of Indian Standards).

[26] Loijos, A., Santero, N., & Ochsendorf, J., 2013, Life cycle climate impacts of the US concrete pavement network. *Resources, Conservation and Recycling* **72**, 76-83. https://doi.org/10.1016/j.resconrec.2012.12.014

[27] Singh, A., Vaddy, P., & Biligiri, K. P., 2020, Quantification of embodied energy and carbon footprint of pervious concrete pavements through a methodical lifecycle assessment framework. *Resources, Conservation and Recycling* **161**, Article 104953. https://doi.org/10.1016/j.resconrec.2020.104953

[28] Ivel, J., Watson, R., Abbassi, B., & Abu-Hamatteh, Z. S., 2020, Life cycle analysis of concrete and asphalt used in road pavements. *Environmental Engineering Research* **25**(1), 52-61. https://doi.org/10.4491/eer.2018.399

[29] Ma, F., Sha, A., Yang, P., & Huang, Y., 2016, The greenhouse gas emission from Portland cement concrete pavement construction in China. *International Journal of Environmental Research and Public Health* **13**(7), Article 632. https://doi.org/10.3390/ijerph13070632

[30] Rangelov, M., Dylla, H., Dobling, B., Gudimettla, J., Sivaneswaran, N., & Praul, M., 2022, Readily implementable strategies for reducing embodied environmental impacts of concrete pavements in the United States. *Transportation Research Record: Journal of the Transportation Research Board* **2676**(9), 436-450. https://doi.org/10.1177/03611981221086934

[31] K.C., A. K., Ghimire, A., Adhikari, B., Aryal, A., & Baral, B., 2025, Embodied energy and associated carbon emission of key building materials in Nepal. *Discover Environment* **3**(1), Article 15. https://doi.org/10.1007/s44274-025-00194-x

[32] Chaulagain, A., Lama, P., Adhikari, A., Mandal, S., & Uprety, B., 2025, Comparative life cycle assessment of decarbonization pathways for cement production in Nepal. *Energy Conversion and Management: X* **28**, Article 101284. https://doi.org/10.1016/j.ecmx.2025.101284

[33] Andrew, R. M., 2018, Global CO_2 emissions from cement production. *Earth System Science Data* **10**(1), 195-217. https://doi.org/10.5194/essd-10-195-2018

[34] International Energy Agency (IEA), 2018, *Technology Roadmap: Low-Carbon Transition in the Cement Industry* (Paris, France: IEA/World Business Council for Sustainable Development, Cement Sustainability Initiative).

[35] NITI Aayog, 2026, *Scenarios Towards Viksit Bharat and Net Zero - Sectoral Insights: Industry (Vol. 4)* (New Delhi: Government of India).

[36] International Renewable Energy Agency (IRENA), 2024, *Iron and steel* (Abu Dhabi, UAE: IRENA).

[37] Pizoń, J., Poranek, N., & Horňáková, M., 2026, Life cycle assessment of concrete containing crushed concrete paving blocks as a sustainable replacement for natural aggregates. *Sustainability* **18**(6), Article 2703. https://doi.org/10.3390/su18062703

[38] Koh, D., Tokbolat, S., & Blaauw, S. A., 2024, Life cycle assessment of pavement construction: a case study. *IOP Conference Series: Earth and Environmental Science* **1363**(1), Article 012065. https://doi.org/10.1088/1755-1315/1363/1/012065

[39] Ige, O. E., Duffy, K. J., Olanrewaju, O. A., & Collins, O. C., 2024, Measuring the environmental impact and uncertainty analysis of Portland cement production in South

Africa: a ReCiPe 2016 v1.04 endpoint method approach. In: V., Kumar (Ed.), Global Warming - A Concerning Component of Climate Change (IntechOpen). https://doi.org/10.5772/intechopen.1004055

[40] Bulle, C., Margni, M., Patouillard, L., Boulay, A.-M., Bourgault, G., De Bruille, V., Cao, V., Hauschild, M., Henderson, A., Humbert, S., Kashef-Haghighi, S., Kounina, A., Laurent, A., Levasseur, A., Liard, G., Rosenbaum, R. K., Roy, P.-O., Shaked, S., Fantke, P., & Jolliet, O., 2019, IMPACT World+: a globally regionalized life cycle impact assessment method. *International Journal of Life Cycle Assessment* **24**(9), 1653-1674. https://doi.org/10.1007/s11367-019-01583-0

[41] Wolde, M. G., Khatiwada, D., Bekele, G., & Palm, B., 2024, A life cycle assessment of clinker and cement production in Ethiopia. *Cleaner Environmental Systems* **13**, Article 100180. https://doi.org/10.1016/j.cesys.2024.100180

[42] Campbell-Lendrum, D., & Corvalán, C., 2007, Climate change and developing-country cities: implications for environmental health and equity. *Journal of Urban Health* **84**(S1), 109-117. https://doi.org/10.1007/s11524-007-9170-x

[43] Souza Zorzenão, P. C. D., dos Santos Silva, J. C., Bufato Moreira, C. A., Pinto, V. M., Tadano, Y. D. S., Yamamoto, C. I., & Godoi, R. H. M., 2024, Impacts of PM2.5 exposure near cement facilities on human health and years of life lost: a case study in Brazil. *Journal of Environmental Management* **370**, Article 122975. https://doi.org/10.1016/j.jenvman.2024.122975

[44] Olagunju, B. D., & Olanrewaju, O. A., 2021, Life cycle assessment of Ordinary Portland Cement (OPC) using both problem oriented (midpoint) approach and damage oriented approach (endpoint). In: A. Petrillo & F. De Felice (Eds.), Product Life Cycle - Opportunities for Digital and Sustainable Transformation (IntechOpen). https://doi.org/10.5772/intechopen.98398

[45] Zhou, X., Strezov, V., Jiang, Y., Yang, X., He, J., & Evans, T., 2020, Life cycle impact assessment of airborne metal pollution near selected iron and steelmaking industrial areas in China. *Aerosol and Air Quality Research* **20**, 1582-1590. https://doi.org/10.4209/aaqr.2019.10.0552

[46] Fente, T. E., & Tsegaw, A. A., 2024, Environmental impact assessment of steel reinforcing bar manufacturing process from scrap materials using life cycle assessment method: a case study on the Ethiopian metal industries. *Discover Applied Sciences* **6**(2), Article 53. https://doi.org/10.1007/s42452-024-05709-4

[47] Ding, C., Wang, Y., Tang, T., Mishra, S., & Liu, C., 2018, Joint analysis of the spatial impacts of built environment on car ownership and travel mode choice. *Transportation Research Part D: Transport and Environment* **60**, 28-40. https://doi.org/10.1016/j.trd.2016.08.004

[48] Nguyen, L., Moseson, A. J., Farnam, Y., & Spatari, S., 2018, Effects of composition and transportation logistics on environmental, energy and cost metrics for the production of alternative cementitious binders. *Journal of Cleaner Production* **185**, 628-645. https://doi.org/10.1016/j.jclepro.2018.02.247

[49] Ministry of Forests and Environment (MoFE), 2025, *Nepal's Third Nationally Determined Contribution (NDC 3.0)* (Kathmandu: Government of Nepal).

[50] Generowicz-Caba, N., & Kulczycka, J., 2025, LCA of cement with alternative additives: pathways to sustainable production. *Materials* **18**(13), Article 3057. https://doi.org/10.3390/ma18133057

[51] Orozco, C., Babel, S., Tangtermsirikul, S., & Sugiyama, T., 2024, Comparison of environmental impacts of fly ash and slag as cement replacement materials for mass concrete and the impact of transportation. *Sustainable Materials and Technologies* **39**, Article e00796. https://doi.org/10.1016/j.susmat.2023.e00796

[52] Tao, Y., Gautam, B. P., Pradhan, P. M., & Hu, C., 2022, Characterization and reactivity of Nepali clays as supplementary cementitious material. *Case Studies in Construction Materials* **16**, Article e00947. https://doi.org/10.1016/j.cscm.2022.e00947

[53] Scrivener, K., Martirena, F., Bishnoi, S., & Maity, S., 2018, Calcined clay limestone cements (LC3). *Cement and Concrete Research* **114**, 49-56. https://doi.org/10.1016/j.cemconres.2017.08.017

[54] Mostafa, A., Khater, H. M., Gharieb, M., & Anwar, M., 2025, Sustainable cement production: minimizing CO_2 by optimizing efficiency with LC3. *Discover Applied Sciences* **7**(7), Article 684. https://doi.org/10.1007/s42452-025-07298-2

[55] Osorio-Tejada, J. L., Llera-Sastresa, E., & Scarpellini, S., 2022, Environmental assessment of road freight transport services beyond the tank-to-wheels analysis based on LCA. *Environment, Development and Sustainability* **26**(1), 421-451. https://doi.org/10.1007/s10668-022-02715-7

[56] Kurda, R., Silvestre, J. D., & De Brito, J., 2018, Life cycle assessment of concrete made with high volume of recycled concrete aggregates and fly ash. *Resources, Conservation and Recycling* **139**, 407-417. https://doi.org/10.1016/j.resconrec.2018.07.004

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Impacts of the 2026 US-Iran War on Environmental Security in the Middle East

Salam Abdulqadir Abdulrahman *

College of Law and Politics, University of Human Development,

Sulaymaniyah 46001, Iraq

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Corresponding author:** Salam Abdulqadir Abdulrahman; ***Email: salam.abdulrahman@uhd.edu.iq; salam.abdulrahman@gmail.com; **Telephone:** +964-750-307-3111 or +964-770-140-6479

Graphical Abstract

Modern warfare not only causes human casualties but also degrades the environmental systems essential for daily life; the 2026 US-Iran conflict has severely threatened regional ecosystems through attacks on critical infrastructure, oil and gas facilities, and natural resources. These impacts extend into urban areas, endangering civilian populations and ecological stability while creating long-term environmental insecurities that may persist far beyond the end of hostilities.



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Abstract: Modern warfare does not merely inflict human casualties; it also degrades the environmental systems vital for daily life. The 2026 US-Iran conflict poses a severe threat to regional ecosystems, as belligerents deliberately target critical infrastructure and weaponize natural resources to secure military advantages or compel concessions. Oil and gas tankers in the Strait of Hormuz, alongside refineries and energy installations throughout Iran and the Arab Gulf states, have emerged as primary targets. This destruction extends rapidly into urban areas, presenting catastrophic risks to both civilian populations and ecological stability. Wartime environmental destruction triggers long-term insecurities that far outlast any formal peace agreement.

Keywords: *2026 US-Iran war, Environmental security, Insecurities, Iran, Arab Gulf states.*

Introduction

On February 28, 2026, the United States and Israel launched a major, widespread offensive against Iran. They targeted military and non-military infrastructure, including air defence bases, missile launch pads, buildings suspected of housing regime figures, oil facilities, and civilian infrastructure. The US codenamed its offensive 'Operation Epic Fury,' and Israel designated its campaign 'Operation Roaring Lion.' Iran responded by firing missiles at US and Israeli military bases while also targeting non-military infrastructure across the region, including within the Arab Gulf states. Following more than five weeks of hostilities, the parties agreed to a temporary ceasefire. Later, on June 17, they remotely signed a diplomatic agreement called the Islamabad Memorandum—negotiated by Pakistan to end the war and reopen the Strait of Hormuz. But, hostilities resumed on July 8, driven by a lack of progress in negotiations and mutual accusations regarding attacks on ships in the Persian Gulf [1-3].

Like many conflicts that endanger ecosystems through the use of destructive, chemically loaded weapons—such as the war in Ukraine, where new findings suggest 20 per cent of the land suffers from chemical contamination—the US-Iran conflict has targeted environmental infrastructure from its very outset [4]. The warring parties use these tactics to undermine their opponents' combat capabilities while simultaneously weaponizing the environment itself, as demonstrated in the Strait of Hormuz. This war raises heightened environmental concerns because it unfolds in a region that supplies 20% of global oil consumption, represents over 13% of the global natural gas export market, and contributes significantly to the global fertilizer supply. The area is densely packed with dozens of oil rigs, refineries, gas-related installations, power plants, and commercial transport hubs. Furthermore, because both the Arab Gulf states and Iranian coastal cities rely heavily on seawater desalination for domestic fresh water, these critical facilities have increasingly become military targets.

Donald Trump has repeatedly threatened to strike civilian infrastructure, which would cause catastrophic consequences for both people and the environment. During a Fox News Radio interview with Brian Kilmeade on March 13, 2026, he threatened to destroy power and water desalination plants, stating, 'I could take out things within the next hour—power plants that create the electricity, that create the water. They have desalinisation all over the place. We could do things that would be so bad they could literally never rebuild as a nation again.' He then escalated his rhetoric; in April 2026, he threatened to wipe out the entire Iranian civilisation. Stating that strikes would send the country back to the 'Stone Ages' (sic) and that it would 'never be brought back again,' he warned that these actions would follow if an agreement was not reached and his terms were not accepted. His terms have not been accepted. The war he launched drags on. The United

States has become trapped in a situation like the Vietnam War. For its part, Iran promised 'irreversible destruction' if the US carried out its threats [5-9].

The US and Israeli militaries have previously struck nuclear power plants, energy installations, industrial complexes, transport networks, and water infrastructure. Iran claims that these attacks destroyed 'dozens of water transmission and treatment facilities and parts of critical water supply networks.' Meanwhile, Iran has targeted desalination plants, power stations, commercial ships, energy facilities, and digital infrastructure across Gulf states aligned or cooperating with the US. These attacks are likely to intensify whenever the conflict resumes, further undermining regional environmental security [10-15].

This paper highlights the environmental dimensions of the 2026 US-Iran conflict by examining it through a security lens. It provides a detailed review of environmental infrastructure targets and their implications for water security, air quality, and soil health in Iran and the Arab Gulf states. By addressing environmental security directly, the paper argues that the conflict poses an immediate threat to—and has severely undermined—the region's ecological stability. Furthermore, it posits that environmental insecurity carries long-term consequences for human well-being and planetary health that will persist far beyond any immediate truce or formal end to hostilities. The paper concludes that profound ecological damage has already occurred, and the longer the war continues, the more compromised regional environmental security will become.

Examining the environmental dimensions of military conflict offers a new perspective in which to see the reality of human aggression. This approach by no means diminishes the significance of human casualties or the destruction of homes; rather, it highlights the profound damage inflicted upon the ecosystems that support the life and prosperity of all species. Hence, within the context of this paper, environmental security refers to safeguarding three primary environmental components—water (including the Persian Gulf), air, and soil—to protect both the environment itself and the populations whose lives and well-being rely on its health.

Water security

Water infrastructure is highly vulnerable to attacks during military conflicts. Critical assets—including waterways, natural water sources, storage facilities, lakes, reservoirs, pumping stations, distribution networks, treatment plants, and desalination facilities—face significant threats. International law prohibits damage to the environment and essential civilian systems, but enforcing these rules remains a challenge. Legally, states are obligated to protect the environment from harm and ensure that weapons and tactics do not target natural ecosystems or critical infrastructure, as human survival and planetary health depend entirely on these protections. In an anarchical

international system, conflicting parties often operate with perceived impunity [16,17]. Consequently, environmental infrastructure across Iran and the Arab Gulf states faces a severe threat of destruction, with the desalination plants along the Arabian Gulf coastline being particularly at risk.

The Arab Gulf states are the world's most dependent consumers of desalinated seawater, which serves as the region's civilian and economic lifeline. Nations like Kuwait, Qatar, Bahrain, and the UAE rely almost entirely on processed seawater to meet domestic needs; by constructing over 400 advanced plants along their coastlines, they have made themselves easy targets for an Iranian attack. These facilities convert seawater into freshwater by removing salt and minerals—a process critical for the survival of Arab Gulf nations, which (except for Oman) possess virtually no other natural water sources. Collectively, the Persian Gulf states produce nearly 40 per cent of the world's desalinated water. These facilities, which process billions of litres of water daily to sustain millions of people, create a false sense of water security [14,18-24].

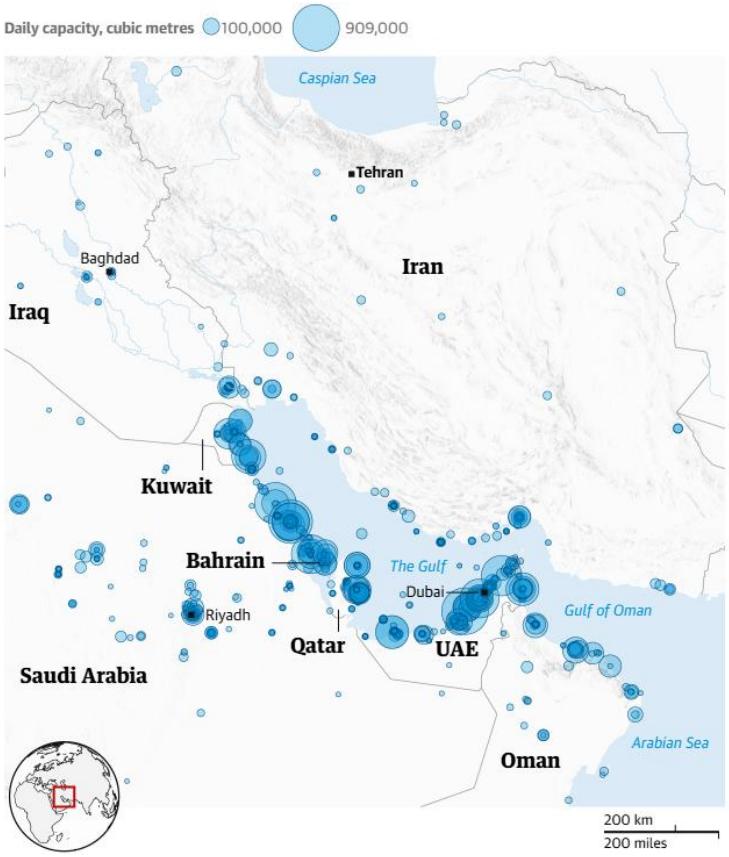


Figure 1. Numerous desalination plants across the Persian Gulf region could become military targets for belligerent parties. Desalination plants and water infrastructure are protected under international law, but the current state of international relations allows states to violate these laws and evade accountability for their actions.[1]

[1] Source: *The Guardian*, March 11, 2026. Available online at: https://www.theguardian.com/world/2026/mar/11/severe-water-stress-why-desalination-plants-are-gulf-greatest-weakness (accessed 8 August 2026).

Desalination plants are easy military targets because their large, fixed, and complex footprints leave them virtually defenceless against modern electronic and conventional warfare. They are highly vulnerable to drone strikes, missile attacks, cyber warfare, and other advanced weapon systems. A leaked document from the US State Department in 2009 stated that ‘an attack on Saudi Arabia's desalination plant in Jubail would force the entire population of Riyadh to evacuate 'within a week', as the plant delivers over 90% of the city's drinking water.’ The desalination plant in Jubail is called Ras al-Khair, which is the world's largest plant of its kind. It has a daily production capacity of over one million cubic metres. Military attacks on civilian infrastructure are highly likely given that the US has already targeted bridges, food factories, and schools in Iran. Furthermore, the US has threatened to destroy desalination plants in Iran if a deal is not reached. In response, Iran has promised mirrored retaliation and has already targeted several civilian infrastructure sites across the Arab Gulf states. Israel, which initiated the war and drew the US into it, has an undeniable record of striking civilian infrastructure in Gaza and elsewhere, has executed similar attacks in Iran, and may intensify these actions [25].

Recent events have highlighted the fragility of the seawater desalination system, demonstrating how rapidly cities like Dubai and Doha could run out of water; indeed, many Arab Gulf cities hold strategic reserves lasting just about one week. Because this infrastructure lies within easy reach of enemy missiles, it faces the dual threats of direct destruction and severe environmental contamination. Furthermore, many of these facilities are adjacent to power plants. This proximity offers a reliable electricity supply and effectively uses waste heat for desalination while simultaneously using water to cool the power plants. Thus, these desalination facilities are highly vulnerable if the power plants are attacked. Additionally, strikes on desalination plants can release chemicals used in the water purification process—such as sodium hypochlorite, ferric chloride, and sulphuric acid—into Gulf waters. Furthermore, strikes on nearby oil tankers or the use of heavy ordnance can pollute water intake zones with toxic chemical residues, instantly threatening the region's primary water source [19-22,26].

Several water desalination plants on both sides of the Persian Gulf have come under attack: desalination plants on Qeshm Island and in Assaluyeh, for which the US and Israel are accused; the Muharraq facility in Bahrain; and two desalination plants in Kuwait. Additionally, the Fujairah F1 power and water plant in the UAE was attacked, for which Iran is accused. These strikes forced an immediate halt to operations at the affected sites. Tehran had previously warned that it would target regional desalination plants if its own fuel and energy infrastructure were attacked. These incidents raise grave concerns about the vulnerability of this vital resource—especially since these

states hold minimal strategic water reserves—and constitute a direct, existential threat to water security, particularly for the Arab Gulf states [22,23,27-29].

The security of many other sectors is tied to the stability of the freshwater supply. Any disruption to this flow would be catastrophic for households, hotels, agriculture, industries, businesses, public facilities, and recreational sectors. Such an event would cause massive economic losses with severe consequences for the country's future. Furthermore, attacks on desalination plants can directly affect power generation because national electricity grids are integrated into these facilities. Consequently, 'damage could cascade into city-wide power outages or necessitate complete evacuations [24]'.

Israel relies on desalinated water for 80 to 85 per cent of its domestic and drinking needs, as well as for replenishing depleted aquifers and maintaining water levels in the Galilee reservoir; meanwhile, its agriculture and industry sectors depend mainly on recycled wastewater. Largely arid or semiarid, the country operates five massive desalination plants along its Mediterranean coast that collectively generate 600 million cubic metres of freshwater annually. Through partnerships with private companies, Israel aims to increase annual production to 2.3 billion cubic metres by 2050 and 2.75 billion cubic metres by 2075 [30-32]. Surprisingly, these desalination plants remained undamaged during the first phase of the war (February 28 to April 7, 2026), which was the most intensive and devastating period. Given the highly unpredictable nature of warfare, this temporary safety does not guarantee the future security of Israel's water infrastructure [33].

Iran's reliance on seawater desalination is very low compared to its Arab neighbour states on the other side of the Persian Gulf. Desalinated water accounts for only 2 to 3 per cent of its supply, and this capacity is heavily concentrated in its southern provinces. Nevertheless, Iran's traditional water sources are under immense pressure, mainly because of decades of over-extraction and multi-year droughts. This escalating crisis was raised multiple times by Iranian President Masoud Pezeshkian, who suggested that the capital may need to be relocated to a southern coastal province where it can rely directly on desalinated seawater. Furthermore, Iran's water, electricity, and energy infrastructure have been targeted by the US and Israel during the recent conflict, and further attacks are highly likely to occur, severely undermining the nation's broader water security, and worsening social stability [34].

The demand for desalinated water in the Arab Gulf states is projected to rise significantly because of population growth, climate change, high water consumption, and expansions in agriculture, industry, and recreation. The Arab Gulf states' average per capita daily water consumption of 560 litres is among the highest globally. As the world's most water-scarce region, the Middle East faces an expanding population alongside growing water requirements for agriculture, industry,

commerce, and recreation—particularly in the UAE. This strain is compounded by accelerating climate change, which is warming the region at nearly twice the global average rate and severely impacting water availability. Consequently, Arab Gulf nations plan to invest billions of dollars in future desalination projects to increase significantly daily production from its current 20 million cubic metres to a much higher capacity by 2050. A portion of these funds will likely be allocated to defence mechanisms to protect these critical facilities from attacks [35-38].

The 2026 US-Iran war is not the first conflict to threaten regional water infrastructure. During the 1990 Iraqi invasion, Kuwait's desalination plants suffered severe attacks, and Iraqi forces contaminated the Persian Gulf by releasing an estimated 11 million barrels of oil. This environmental damage rendered desalination impossible in certain areas, including along the Saudi coastline. A study conducted 12 years after the war concluded that traces of oil residue still lingered along Saudi Arabia's coast [39]. More recently, in 2022, the Houthis in Yemen targeted several of Saudi Arabia's facilities. The current US-Iran war presents a uniquely severe challenge to regional water security because it risks escalating into a full-scale water war. The conflict involves advanced, precision-guided weaponry and places all Arab Gulf states in the crosshairs. Actual and potential attacks on desalination infrastructure on both sides of the Persian Gulf pose an existential threat to the water security that Arab states have long worked to achieve. Furthermore, potential oil leaks or spills into the Gulf from attacked tankers could clog membranes and pumps, leaving desalination plants completely unable to produce drinking water [17,18,40,41].

Desalination plants are massive facilities integrated with fossil-fuel power grids, making them highly flammable. Furthermore, their coastal locations leave them highly vulnerable as accessible targets for Iranian strikes. Desalination plants had previously guaranteed future water security for both the Arab Gulf states and coastal Iranian cities. Because seawater is an infinite resource, technology seamlessly facilitated its large-scale purification for all civilian and industrial needs. The war has shattered this conviction. Insecurity in the freshwater supply automatically translates to instability across all sectors of society, forcing states reliant on desalination to rethink their guarantees for future water availability [24].

Gulf water security and the closure of the Strait of Hormuz

The Persian Gulf is a semi-enclosed sea located in the Middle East, in Western Asia. As an extension of the Indian Ocean, it is bordered by Iran to the northeast and the Arabian Peninsula to the southwest. The Gulf is approximately 1,000 kilometres long, with a width that varies from 340 kilometres at its widest point to just 39 kilometres (24 miles) at the Strait of Hormuz. It is a very shallow body of water, averaging only 35 metres in depth. The nations of the Arabian Peninsula that border the Gulf include Iraq, Kuwait, Bahrain, Qatar, Saudi Arabia, the United Arab Emirates

(UAE), and Oman. The Gulf's narrow opening at the Strait of Hormuz limits the water exchange. The Gulf is therefore one of the saltiest bodies of water in the world; yet, it concurrently serves as a critical habitat for several endangered species. This restricted water exchange also makes the Gulf highly vulnerable to pollution and other ecological catastrophes [42].

The Strait of Hormuz is a narrow waterway connecting the Persian Gulf with the Gulf of Oman and the Arabian Sea. The strategic importance of the strait stems from the fact that it is the sole maritime exit for oil and gas exports from the Persian Gulf states. Including Iran, these nations account for roughly 35% of global crude oil exports and 20% of global liquefied natural gas (LNG) trade. Additionally, one-third of the world's fertilizers pass through this strait [43,44].



Figure 2. The 2026 US-Iran conflict has affected the Persian Gulf, with Iran occupying the eastern and southeastern shores, and US-allied Arab states occupying the western and southwestern regions. As a vital maritime corridor, the Persian Gulf remains critical for the global economy.[2]

The Strait of Hormuz has emerged as the epicentre of the 2026 US-Iran war. Following a Pakistani-mediated temporary truce, the conflict is now mainly referred to as the US-Iran war. Although

[2] Source: *Australian National University*. Available online at: https://openresearch-repository.anu.edu.au/server/api/core/bitstreams/f8808efb-fc31-4a2f-aea1-e2152488e89e/content (accessed 3 August 2026).

Israel remains involved, the second phase of the war has concentrated on the Persian Gulf, where Israeli forces lack a physical presence. Amid bilateral negotiations for a potential diplomatic deal, Iran closed the strait to international navigation. In response, the United States imposed a naval blockade to restrict Iranian control over the waterway. Although traffic has resumed during occasional, temporary openings for authorized vessels, the Strait of Hormuz remains largely closed [45,46].

The closure of the Strait of Hormuz could trigger a global ecological catastrophe in international seas and oceans. Marine organisms in the Persian Gulf—such as microorganisms, algae, plants, and invertebrates—can attach to idle ships in a process known as biofouling. When these vessels finally move, they transport these species into international waters. Ships are usually coated with protective anti-fouling paint to prevent marine growth; but, after prolonged idleness, like that experienced in the Persian Gulf since the war began in February 2026, these protective layers degrade. As a result, the species attaching to the hulls can no longer be easily removed [47,48].

Over 1,500 ships are currently idle in the Persian Gulf, with hundreds more in the Gulf of Oman as of late July 2026. These vessels are highly likely to transport marine organisms from the Persian Gulf to various ports around the world. Because the Persian Gulf is one of the saltiest and warmest bodies of water on Earth, its native marine species are exceptionally resilient. They routinely survive extreme salinity and temperatures, giving them a high probability of thriving and multiplying in more temperate climates. As these invasive species spread, they can alter ecosystems, disrupt commercial operations like aquaculture and fisheries, and cause economic damage costing millions of dollars [47].

The Persian Gulf is isolated from the rest of the world's seas and oceans, connected only through the narrow chokepoint of the Strait of Hormuz. This isolation has created a unique, self-contained environment with fragile ecosystems hosting over 700 species of fish and some of the planet's most resilient, yet sensitive, fauna and flora. Attacks on oil and gas tankers, as well as on the hundreds of maritime and coastal fossil fuel facilities, will significantly increase the risk of oil spills and marine pollution. Oil spills and the release of toxic substances can also destroy critical habitats like seagrass beds, mangroves, and nearshore reefs [49]. Early reports on the war indicated that at least 12 merchant ships were struck in ports or within the Persian Gulf [50]. Such events could lead to an environmental catastrophe—endangering the survival and reproduction of the ecosystem and causing biodiversity loss—with impacts that may last for decades [49.51].

Air and soil security

'Modern warfare is a chemical event. Every missile, every bomb, every burning fuel depot releases its payload of toxic compounds into the air people breathe. The difference is whether we choose to count it,' says Narges Bajoghli, Professor of Middle East Studies at the School of Advanced International Studies, Johns Hopkins University. Bajoghli added that just within the span of two weeks of the US-Iran war, 5 million tonnes of greenhouse gas emissions were released, something that would be equivalent to the combined emissions of 84 countries over a year [52,53].

Military operations typically generate massive amounts of greenhouse gas emissions. The deployment and maintenance of fighter jets, aircraft carriers, missile and drone launchers, naval fleets, and armoured vehicles—alongside military logistics transport—consume vast amounts of fossil fuel, releasing these gases directly into the atmosphere. These activities drive severe environmental degradation, most notably air pollution and desertification. In Iraq, accelerating desertification is tied closely to decades of continuous military conflict. The heavy movement of armoured vehicles and machinery erodes critical topsoil, a process that triggers dust storms and creates shifting sand dunes [54]. This destruction is compounded by the immense volume of fossil fuels burned by modern war machinery.

While the true number and types of weapons used in the 2026 US-Iran are not known, probably because of military intelligence restrictions, reports indicate that thousands of missiles, drones, and projectiles have been used by the warring parties: the US-Israel coalition versus Iran. These weapons have carried and released chemicals, toxic gases, and hazardous materials into the areas where they exploded. In addition, buildings, refineries, oil depots, ammunition stockpiles, factories, various facilities, and vehicles have been damaged, destroyed, or have caught fire as a result of the attacks. Trees, forests, and wild grass have also caught fire and burned because of the explosions. All of these factors combined have catastrophic consequences for millions of civilians, as well as for the quality of the air, water, and soil.

In the opening days of the war, airstrikes on Tehran caused severe oil leaks in the streets and sent massive plumes of smoke into the atmosphere, blanketing large sectors of the city. Because many modern oil facilities are situated within densely populated urban zones, military strikes against them inflict significantly more severe impacts on public health and community well-being. In the following days, toxic black rain fell across Tehran and its adjacent areas. Officials in the Iranian government's Department of Environment advised people to stay indoors as much as possible (even though this provides limited protection during severe pollution events), avoid using air conditioners, and refrain from going out immediately after the rainfall. Additionally, the country's Red Crescent warned that 'toxic chemicals in the air could lead to acid rain, which can cause skin

burns and serious lung damage.' This environmental crisis has detrimental effects on air quality, as well as food and water security [26,39].

Acid rain is a form of precipitation that has higher levels of nitric and sulphuric acids than normal rain. One major cause is explosions, which release sulphur dioxide and nitrogen oxides into the air. The environmental impacts of acid rain include washing away aluminium from the soil and stripping vital nutrients from it. This process leads to the acidification of surface water and groundwater, which is harmful to aquatic life, as well as to trees, crops, and vegetables. Additionally, acid rain can cause severe respiratory issues in humans. It can also cause eye and skin irritation, headaches, and an increased long-term risk of cardiovascular disease, cancer, and cognitive dysfunction [49,55]. Some of these health problems have already appeared and will become more apparent in the future. Following initial air strikes on Tehran by Israel and the US, many residents reported 'difficulty breathing, burning eyes, sore throats, migraines, dizziness, and cardiac triggers,' and they face 'elevated risks of stroke, lung and other cancers… high blood pressure, and cognitive decline [56]'.

One major target in the US-Iran war has been fuel infrastructure, including production platforms, refineries, storage tanks, transfer centres, oil tankers, tanker trucks, and petrochemical plants. According to the UK-based Conflict and Environment Observatory (CEOBS), oil fires release 'a complex mix of pollutants with varying degrees of toxicity, including particulate matter, nitrogen oxides, nitrous acid, carbon monoxide, sulphur dioxide, and volatile organic compounds like formaldehyde, dioxins, furans, hydrocarbons, and polycyclic aromatic hydrocarbons.' These toxic substances pollute the air, soil, surface and groundwaters, travelling across borders to pose serious health risks to human beings, animals, and plants throughout the wider region. Oil fires also produce black carbon which 'absorbs solar radiation and accelerates atmospheric warming'. Information gathered up until mid-April indicates that more than 37 oil and natural gas sites have been hit by US and Israeli bombardments since the war began. If oil facilities targeted across the broader Middle East are included, that number rises to 80 [36,56-58].

Tehran, the capital of the Islamic Republic of Iran and home to nearly 10 million residents and 17 million in the wider metropolitan region, has been hit hard by US and Israeli strikes. Hundreds of buildings and facilities were targeted with heavy bombs, obliterating or severely damaging a vast amount of military and civilian infrastructure. In addition to thousands of human casualties, the strikes have generated large plumes of black smoke, severely impacting air quality, soil safety, and the immediate health of the population. This is taking place in a city that already suffers from poor air quality and numerous environmental problems. Surrounded by the Alborz Mountain range, the metropolitan area traps pollution, and its many high-rise buildings hinder wind movement and the

dispersion of airborne pollutants. Satellite data indicates that these plumes contained benzene, formaldehyde, polycyclic aromatic hydrocarbons, and fine particulate matter. These substances can penetrate deep into the human respiratory tract, aggravating respiratory and cardiovascular diseases. Continuous bombing and prolonged exposure to black plumes increase the risk of cancer and certain neurological disorders [50,59].

The same argument applies to areas within the Arab Gulf states, Israel, Jordan, and Iraq, where Iranian missiles have caused significant damage to buildings and both military and civilian infrastructure. Although the targeted countries usually report minor damage, evidence suggests that Iran has fired between 1,500 and 2,000 missiles—including ballistic and cruise missiles, and thousands of cross-border rockets and drones. Additionally, its proxies have launched thousands of rockets toward adversaries across the Middle East. Many of these attacks were deflected and the missiles intercepted, but a large number reached their targets. Beyond the immense human cost, these strikes have severely harmed the environment—not only in the targeted countries, but also in Iran. The mere launching of attacks from missile and rocket pads releases massive amounts of toxic gases into the air [33,50].

Iran's nuclear sites present another major concern for airborne toxic contamination. In fact, nuclear facilities pose a severe threat to environmental security. Because Iran has always kept its nuclear programme top-secret—even while claiming its activities are strictly for peaceful purposes like electricity generation—little information is available regarding the true scale of its operations or whether active enrichment is currently underway at its primary facilities in Natanz, Fordow, and Isfahan. Nevertheless, during the 12-Day War (June 13–24, 2025), the US and Israel heavily bombarded these three main sites. The attacks are believed to have caused massive structural damage. This probably explains why no further major strikes on nuclear infrastructure have occurred during the current war that began in February 2026. Although no significant radioactive leaks have been reported so far, radioactive release from damaged plants remains the most dangerous form of environmental pollution [50,60,61].

The 2026 US-Iran conflict also worsens global air pollution in two distinct ways: the rerouting of aviation and maritime shipping. Because of the closure and inherent danger of navigating airspace within reach of missiles and drones, numerous airlines must use longer alternative routes, resulting in increased travel times, fuel consumption, and emissions. Similarly, the closure of the Strait of Hormuz and threat of Houthi attacks in the Red Sea have forced many vessels to detour around the Cape of Good Hope rather than transiting the Suez Canal. Consequently, this shift has increased the global carbon footprint of these voyages by nearly 50 per cent [39]. Reconstruction efforts following the destruction of infrastructure and residential areas represent another growing source

of carbon emissions; cement and steel production are among the most carbon-intensive industrial processes in the world [62,63].

Modern weaponry used in combat disperses countless pollutants into the environment, with soil being the main recipient. Soil in bombed areas absorbs chemicals released from exploded munitions and structural debris. A wide array of hazardous chemicals is used in the construction of modern buildings. Recent studies conducted in Ukraine and the Gaza Strip detected industrial chemicals such as lead, cadmium, nickel, and chromium. These toxic substances gradually contaminate the food supply and cause severe, long-term soil degradation. Consequently, this form of contamination persists well beyond the active conflict, leaving lasting impacts on both the environment and public health [59]. The Gaza Strip has experienced unprecedented, large-scale destruction across all sectors by the Israeli military in reprisal for a major coordinated assault by the Palestinian militant group Hamas on October 7, 2023.

Finally, this paper has certain limitations. The primary constraint is the scarcity of comprehensive literature on the exact environmental impacts of the conflict, largely because the war is recent and it continues. The full facts of environmental damage and their effects on human health will require deep and long-term studies; like the effects of the nuclear bombs against Hiroshima and Nagasaki, and the effects of Russia's invasion and occupation of Ukraine. This data deficit exists partly because the warring parties and directly affected states are reluctant to highlight the environmental costs of the conflict, fearing it might galvanize domestic opposition or signal vulnerability to the international community. Furthermore, a prolonged internet shutdown in Iran severely restricted the outward flow of information. Nevertheless, considering the sheer volume and types of ordnance—including bombs, missiles, projectiles, and drones—it is evident that regional environmental security has been severely compromised. Another limitation is the lack of verified data regarding the true extent of the mutual damage inflicted by the warring parties, as this information directly impacts national security. Lastly, gathering firsthand empirical material is impossible, as the continuing volatile situation precludes safe fieldwork.

Conclusion

Various forms of security are deeply interconnected, including state, human, economic, societal, and environmental security. Environmental security affects all the others. We participate in our environment, affecting it and being affected by it. The health of our air, water, and soil, as well as the protection of ecosystems and planetary systems determines our own health as a species. Threats to the environment are threats to all other forms of security; they pose severe, existential risks to

the short- and long-term survival and well-being of human beings, animals, and plants. Furthermore, harms inflicted upon the environment will not disappear quickly. Described as 'slow violence', ecological destruction can persist for generations, or even permanently alter ecosystems beyond recovery [64].

Since the Industrial Revolution, mankind has behaved recklessly toward the environment. In particular, modern conflict has become catastrophic for nature. Equipped with advanced warfare technologies and highly destructive weaponry, modern wars inflict unprecedented damage on a scale the planet has never experienced. Today's conflicts have essentially become total wars against the environment itself, as warring parties show little to no consideration for the planet—including its flora, fauna, water, air, and soil. When armies bomb and burn everything in the heat of conflict, it is the environment that ultimately bears the long-term consequences.

Modern wars push the environment toward critical tipping points across numerous areas, sometimes past the point of no return. Driven by conflict, opposing sides treat everything as a legitimate target, regardless of international law. Because the conflicting parties do not fear prosecution by an international court, they believe they can get away with these actions. The massive destruction of water, oil, energy, civilian, and transportation infrastructure leaves landscapes devastated. As fire, toxic gases, and debris scatter, they pollute the air, soil, and waterways. This severely impacts human and animal health while disrupting the normal growth of crops and vegetation. The 2026 US-Iran war stands as a stark example of violating environmental security, with long-term, widespread impacts on all species and ecosystems across the region. Environmental safety in Iran, the Arab Gulf states, and the wider Middle East has been significantly compromised. As responsible state actors and global community members, the warring parties must immediately halt actions and alleviate the damage caused. All non-combatants are powerless, but all combatants are vulnerable also.

Warring parties must pay compensation for the harm they cause. Just as the UN mandated Iraq to pay $52.4 billion to Kuwait for environmental damage following its 1991 invasion, the US and Israel must be held liable for the environmental harm they have caused in Iran. Similarly, Iran must compensate for the damage it has inflicted on civilian and environmental infrastructure in the Arab Gulf states. This obligation to pay damages can serve as a powerful deterrent against future environmental aggression. The enforcement of law upholds ethics.

References

[1] The Editors of Encyclopaedia Britannica, 2026, *2026 Iran war*. Encyclopaedia Britannica October. https://www.britannica.com/event/2026-Iran-war

[2] American Jewish Committee (AJC), 2026, The Iran Strikes, Explained: How We Got Here and What It Means, 20 July. Available online at: https://www.ajc.org/news/the-iran-strikes-explained-how-we-got-here-and-what-it-means (accessed 1 August 2026)

[3] Council on Foreign Relations, 2026, *Iran's war with Israel and the United States*. Global Conflict Tracker, July 29. https://www.cfr.org/global-conflict-tracker/conflict/confrontation-between-united-states-and-iran

[4] Wirtu YD. and Abdela U., 2025, Impact of war on the environment: ecocide. *Frontiers in Environmental Science* ***13***, 1539520. https://doi.org/10.3389/fenvs.2025.1539520

[5] Senate Democrats, 2026, *Transcript: President Trump speaks with Brian Kilmeade of Fox News Radio interviews, 3.13.26,* March 13). https://www.democrats.senate.gov/newsroom/trump-transcripts/transcript-president-trump-speaks-with-brian-kilmeade-of-fox-news-radio-interviews-31326

[6] Amnesty International, 2026, *Iran: President Trump's apocalyptic threats of large-scale civilian devastation demand urgent global action to prevent atrocity crimes;* April 7. https://www.amnesty.org/en/latest/news/2026/04/iran-president-trumps-apocalyptic-threats-of-large-scale-civilian-devastation-demand-urgent-global-action-to-prevent-atrocity-crimes/

[7] Gritten, D., 2026, *Trump condemned over threat that Iran's 'civilisation will die'*. BBC News, April 7. https://www.bbc.com/news/articles/cwyk7xgkzvzo

[8] Roll Call, 2026, *Interview: Brian Kilmeade of Fox News Radio interviews Donald Trump for his radio show—March 13, 2026*. https://rollcall.com/factbase/trump/transcript/donald-trump-interview-brian-kilmeade-fox-news-radio-march-13-2026/

[9] Ellis-Petersen, H., 2026, *Why Iran's threat to destroy water facilities could spell disaster for Gulf countries*. The Guardian, March 23. https://www.theguardian.com/world/2026/mar/23/iran-threat-to-destroy-water-facilities-gulf

[10] Lawal, S., 2026, *What are 'civilian' sites in international law and where have US, Iran hit?* Al Jazeera, July 20. https://www.aljazeera.com/news/2026/7/20/what-are-civilian-sites-in-international-law-and-where-have-us-iran-hit

[11] Schmitt, M., 2026, *When civilian infrastructure becomes a lawful target*. Just Security, July 23. https://www.justsecurity.org/148907/civilian-infrastructure-becomes-lawful-target/

[12] Christou, W., 2026, *US hits civilian infrastructure as it expands strikes against Iran*. The Guardian, July 17. https://www.theguardian.com/world/2026/jul/17/us-marines-board-ship-gulf-oman-expanded-airstrikes-iran

[13] Lister, T., & Ebrahim, N., 2026, *Airports, plants and ports: The civilian targets increasingly under threat in the Middle East***.** CNN, March 30. https://edition.cnn.com/2026/03/30/world/middle-east-civilian-targets-iran-war-intl

[14] Magee, C., 2026, *Why is the US attacking southern Iran's civilian infrastructure?* Al Jazeera, July 17. https://www.aljazeera.com/news/2026/7/17/why-is-the-us-attacking-southern-irans-civilian-infrastructure

[15] The New Arab Staff & Agencies., 2026, *Iran minister says US, Israeli strikes caused 'heavy damage' to water, energy infrastructure*. The New Arab, March 22. https://www.newarab.com/news/heavy-damage-caused-iran-water-energy-infrastructure

[16] Geneva Environment Network, 2026, *Environmental impacts of the conflict in the Middle East*, May 30. https://www.genevaenvironmentnetwork.org/resources/updates/environmental-impacts-of-the-conflict-in-the-middle-east/

[17] Sajadian, A., & Leber, A., 2026, *In the war with Iran, targeting energy infrastructure has outsized impact on civilians*. Carnegie Endowment for International Peace, July 28. https://carnegieendowment.org/posts/2026/07/iran-war-energy-infrastructure-targets-environmental-harms

[18] Abdallah, S., 2026, *Desalination in a time of war*. Alhurra, March 6. https://alhurra.com/en/15587

[19] Jimmy, U. J., 2026, The American-Iran war and the collapse of Middle East water security. *African Water Security Studies (Environmental/Cross-disciplinary)* **1**(3). https://doi.org/10.5281/zenodo.21811954

[20] Maffly, B., 2026, *Gulf desalination plants in Iran's crosshairs*. The University of Utah, March 23. https://attheu.utah.edu/law-politics/gulf-desalination-plants-in-irans-crosshairs/

[21] Paddison, L., 2026, *There's a commodity even more vital than oil and gas in the Middle East—and it's at risk as war heats up*. CNN, March 11. https://edition.cnn.com/2026/03/11/climate/gulf-iran-war-water-desalination

[22] Reuters, 2026, *How vulnerable is the Gulf to attacks on desalination plants?*, July 21. https://www.reuters.com/sustainability/land-use-biodiversity/gulf-desalination-plants-lifeline-tens-millions-face-iran-threat-2026-07-21/

[23] Cafiero, G., 2026, *War and water in the Gulf*. Amwaj.media, August 5. https://amwaj.media/en/article/war-and-water-in-the-gulf

[24] Matchett, G., 2026, *Attacks on desalination plants in the Iran war forecast a dark future*. Atlantic Council, March 18. https://www.atlanticcouncil.org/dispatches/attacks-on-desalination-plants-in-the-iran-war-forecast-a-dark-future/

[25] Gayle, D., 2026, *Severe water stress': Why desalination plants are the Gulf's greatest weakness*. The Guardian, March 11. https://www.theguardian.com/world/2026/mar/11/severe-water-stress-why-desalination-plants-are-gulf-greatest-weakness

[26] Carroll, R., 2026, *Oil fires, toxic air and water risks: Environmental cost of Iran war expands to region*. Al-Monitor, March 14. https://www.al-monitor.com/originals/2026/03/oil-fires-toxic-air-and-water-risks-environmental-cost-iran-war-expands-region

[27] Mogensen, J. F., 2026, *War in Iran spotlights the risk to drinking water for millions in the Persian Gulf*. Scientific American, April 28. https://www.scientificamerican.com/article/war-in-iran-spotlights-the-risk-to-drinking-water-for-millions-in-the-persian-gulf/

[28] Kebebew, T., 2026, *Water under fire: The (il)legality of reprisals against desalination plants*. Opinio Juris, March 31. https://opiniojuris.org/2026/03/31/water-under-fire-the-illegality-of-reprisals-against-desalination-plants/

[29] Shehabi, M., 2026, *War on Iran: The dangers of attacking water desalination plants in the Gulf*. Arab Center Washington DC, April 28. https://arabcenterdc.org/resource/war-on-iran-the-dangers-of-attacking-water-desalination-plants-in-the-gulf/

[30] Ministry of Finance, 2021, *Background – Seawater desalination in Israel*. Government of Israel, January 26. https://www.gov.il/en/pages/project-water-desalination-background

[31] Bureau of Economic Geology, The University of Texas at Austin, 2023, *Importance of seawater desalination and wastewater reuse in Israel* [Audio podcast episode]. In *Water Resources Podcast*, September 7. https://wrp.beg.utexas.edu/node/31

[32] Jerusalem Post Staff, 2026, *Gov't approves plan to boost desalinated water production using private companies*. The Jerusalem Post, June 8. https://www.jpost.com/israel-news/article-898754

[33] Institute for the Study of War, 2026, *Iran update special report, April 8*. https://understandingwar.org/research/middle-east/iran-update-special-report-april-8-2026/

[34] Iran International, 2025, *Iran president says capital move now a necessity as water crisis deepens*, November 20. https://www.iranintl.com/en/202511209098

[35] Nature Index. (n.d.). *Climate change impacts and adaptation in the Middle East*. https://www.nature.com/nature-index/topics/l4/climate-change-impacts-and-adaptation-in-the-middle-east (accessed 7 August 2026).

[36] Ranjan, A., & Siddiqui, N., 2026, *The Iran war: Attack on thirsty nation*. Geopolitical Monitor, June 11. https://www.geopoliticalmonitor.com/the-iran-war-an-attack-on-thirsty-nation/ (accessed 7 August 2026).

[37] Demir, Ş., 2026, *How the Iran war expanded from military targets to critical infrastructure*. Anadolu Agency, August 7. https://www.aa.com.tr/en/middle-east/how-the-iran-war-expanded-from-military-targets-to-critical-infrastructure/4021273 (accessed 7 August 2026).

[38] Orto, N., 2024, *Desalination: Miracle or false hope for the water scarce Gulf countries?* Fanack Water, May 28. https://water.fanack.com/publications/desalination-miracle-or-false-hope-for-water-scarce-gulf-countries/ (accessed 8 August 2026).

[39] Daher, H., 2026, *Climate change: The silent casualty of war*. ORF Middle East, April 14. https://orfme.org/expert-speak/climate-change-the-silent-casualty-of-war/

[40] Cullinane, E., 2026, *Does the Iran war really threaten desalination in the Gulf?* Global Water Intelligence, March 12. https://www.globalwaterintel.com/articles/does-the-iran-war-really-threaten-desalination-in-the-gulf (accessed 8 August 2026).

[41] Fanack Water Editorial Team, 2026, *In the Gulf, water now matters more than oil*. Fanack Water, March 23. https://water.fanack.com/gulf-desalination-water-security-war-risk/ (accessed 8 August 2026).

[42] Australian National University. (n.d.). *Persian Gulf* [Map]. ANU Digital Collections. https://hdl.handle.net/1885/733721724 (accessed 3 August 2026).

[43] Institute for Energy Research., 2025, *Persian Gulf oil exports and the Strait of Hormuz*, June 30. https://www.instituteforenergyresearch.org/fossil-fuels/gas-and-oil/persian-gulf-oil-exports-and-the-strait-of-hormuz/ (accessed 3 August 2026).

[44] Reuters., 2026, *Explainer: What is the Strait of Hormuz and why is it so critical to the world?*, April 17. https://www.reuters.com/world/middle-east/what-is-strait-hormuz-why-is-it-so-important-oil-2026-04-17/ (accessed 3 August 2026).

[45] Hand, M., 2026, *Iran declares the Strait of Hormuz closed*. Seatrade Maritime News, June 20. https://www.seatrade-maritime.com/security/iran-declares-the-strait-of-hormuz-closed (accessed 4 August 2026).

[46] Al Jazeera, 2026, *Iran says Strait of Hormuz passage to be ensured after US pauses operation*, May 6. https://www.aljazeera.com/news/2026/5/6/french-container-ship-struck-in-latest-escalation-at-strait-of-hormuz (accessed 4 August 2026).

[47] ABC News, 2026, *Scientists warn of possible invasive species superspreader event due to stalling near Strait of Hormuz*, July 25. https://abcnews.com/International/scientists-warn-invasive-species-superspreader-event-due-stalling/story?id=135051186 (accessed 26 July 2026).

[48] Sankaran, V., 2026, *How the Strait of Hormuz closure could lead to the spread of invasive species*. The Independent, July 29. https://www.independent.co.uk/bulletin/news/strait-of-hormuz-closure-iran-war-mussels-barnacles-b3023557.html (accessed 4 August 2026).

[49] Mithika, D., 2026, *Assessing the environmental harm of the 2026 Iran war*. Development Aid, May 14. https://www.developmentaid.org/news-stream/post/206959/environmental-harm-of-the-2026-iran-war (accessed 10 August 2026).

[50] Conflict and Environment Observatory, 2026, *Operation Epic Fury: Emerging environmental harm and risks in Iran and the region*, March 2026. https://ceobs.org/operation-epic-fury-emerging-environmental-harm-and-risks-in-iran-and-the-region/ (accessed 13 August 2026).

[51] Leman, M., 2026, *The US-Israel war on Iran and how war and conflict are destroying the environment*. Greenpeace International, March 18. https://www.greenpeace.org/international/story/82201/iran-lebanon-war-environment-climate-impacts/ (accessed 16 August 2026).

[52] Al Jazeera English, 2026, *The Iran war's toll on public health and climate | UpFront* [Video]. YouTube. https://www.youtube.com/watch?v=11ivcDZOBz4&t=447s (accessed 29 July 2026).

[53] Mansour, O. W., 2026, *An analysis of the ecological repercussions of the 2026 Iran war on Iran and the Persian Gulf*, May 26. http://dx.doi.org/10.2139/ssrn.6832979

[54] Abdulrahman, S. A., 2025, Iraq's Desertification: The Complication of Environmental Security Issues. *Natural Built Social Environment Health* **1**(1), 83–103. https://doi.org/10.63095/NBSEH.25.720252

[55] U.S. Environmental Protection Agency, 2026, *What causes acid rain?* February 13. https://www.epa.gov/acidrain/what-acid-rain (accessed 10 August 2026).

[56] Gibson, K., Le, D., & Sharghi, A., 2026, *The human and environmental costs of the war in Iran*. Center for American Progress. https://www.americanprogress.org/article/the-human-and-environmental-costs-of-the-war-in-iran/ (accessed 11 August 2026).

[57] Kimball, S., 2026, *Iran war damaged as much as $58 billion of energy infrastructure, Rystad estimates*. CNBC, April 15. https://www.cnbc.com/2026/04/15/iran-war-energy-facilities-refinery-pipeline-lng.html (accessed 10 August 2026).

[58] M&S Research Hub, 2026, *War, environment, and data: Environmental impacts of the Iran–U.S.–Israel conflict and lessons from Gaza*, March 7. https://ms-researchhub.com/home/resources/the-global-economy-this-week/war-environment-and-data-environmental-impacts-of-the-iran-u.s.-israel-conflict (accessed 12 August 2026).

[59] Sénéquier, A., 2026, *The war in Iran: A conflict with lasting environmental and health consequences*. IRIS, March 13. https://www.iris-france.org/en/the-war-in-iran-a-conflict-with-lasting-environmental-and-health-consequences/ (accessed 12 August 2026).

[60] Lopez, C. T., 2025, *Historically successful' strike on Iranian nuclear site was 15 years in the making*. DOD News, June 26. https://www.war.gov/News/News-Stories/Article/article/4227082/historically-successful-strike-on-iranian-nuclear-site-was-15-years-in-the-maki/.

[61] International Campaign to Abolish Nuclear Weapons, 2025, *Israeli attack on Iranian nuclear facilities threatens to wreck diplomatic solution to nuclear proliferation challenges*, June 17. https://www.icanw.org/israeli_attack_on_iranian_nuclear_facilities_threatens_to_wreck_diplomatic_solution_to_nuclear_proliferation_challenges (accessed 14 August 2026).

[62] Horne, F., 2026, *The pollution that outlives war*. Al Jazeera, May 23. https://www.aljazeera.com/opinions/2026/5/23/the-pollution-that-outlives-war (accessed 17 August 2026).

[63] Masud, M.M., 2026, Geopolitical Conflict, Energy Shocks, and Global Sustainability: Development Implications of the Iran-Israel Conflict. *International Journal of Education Studies and Social Science Research* **1**(3), 34–55. https://ijesssr.com/pub/index.php/ijesssr/article/view/17

[64] Solaja, O., 2026, *War beyond the battlefield: Environmental and human security in Iran*. European Center for Populism Studies, March 9. https://www.populismstudies.org/war-beyond-the-battlefield-environmental-and-human-security-in-iran/ (accessed 19 August 2026).

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Failure of First-Generation GeneXpert MTB/RIF to Detect Rifampicin Resistance in Cutaneous Tuberculosis: A Case Report

Kholoud Maafi [1,2,3,a], Zakaria Asbai [1,b], Karim Souly [2,3,c], Souad Aboudkhil [1,d]

[1] *Laboratory of Biotechnology, Agri-Food, Materials and Environment,* Hassan II University of Casablanca

[2] *Ibn Sina University Hospital in Rabat ,Rabat, Morocco*

[3] *Faculty of Medicine and Pharmacy of Rabat, Mohamed V University , Rabat, Morocco*

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[a] ***ORCID:*** 0009-*0004*-8128-2149*;* ***Email:*** *kholoud.maafi@pasteur.ma*

[b] ***ORCID:*** *0000-0003-2748-3973****;*** ***Email:*** *zakaria.asbai@etu.fstm.ac.ma*

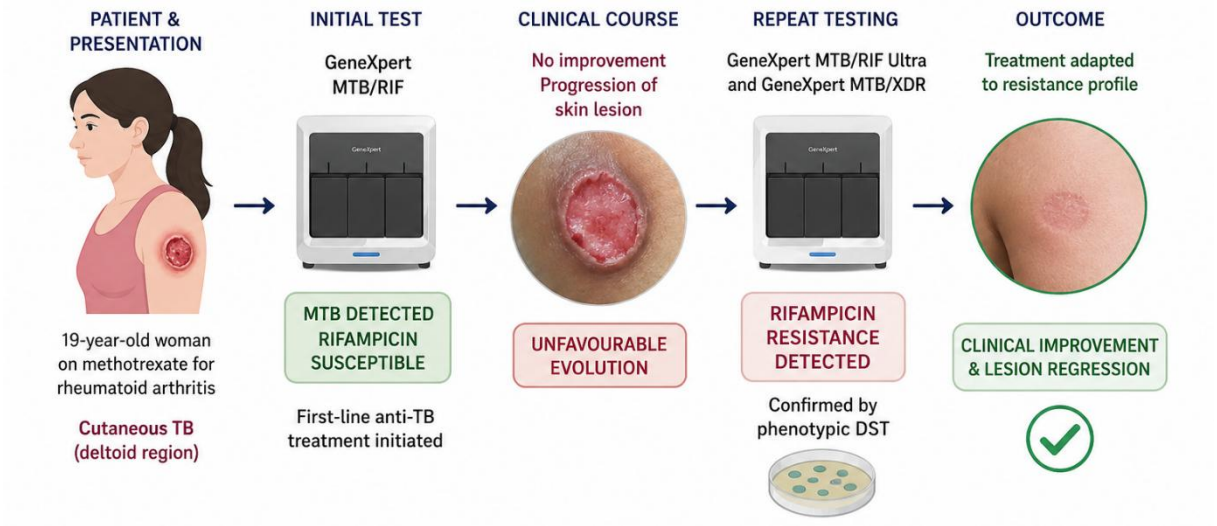
[c] ***ORCID:*** *****-****-****-****; **Email**: sl.karim@hotmail.fr*

[d] ***ORCID****: 0000-0001-5666-0970; **Email:** souadaboudkhil@gmail.com*

*** *Corresponding author :*** Kholoud Maafi ; ***Email*** : *Docteurmaafi@gmail.com*

Graphical Abstract

Cutaneous tuberculosis is a rare extrapulmonary form whose diagnosis remains challenging because of its low bacillary load. We report the case of a 19-year-old Moroccan woman receiving methotrexate for rheumatoid arthritis who developed deltoid cutaneous tuberculosis. Initial GeneXpert MTB/RIF detected *Mycobacterium tuberculosis* but failed to identify rifampicin resistance. GeneXpert MTB/RIF Ultra and GeneXpert MTB/XDR subsequently confirmed rifampicin monoresistance, allowing appropriate treatment modification and rapid clinical improvement. This case highlights the limitations of first-generation GeneXpert MTB/RIF in paucibacillary cutaneous tuberculosis and the value of next-generation molecular techniques for the early detection of drug resistance.



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Abstract: Cutaneous tuberculosis is a rare form of extrapulmonary tuberculosis. The diagnosis remains challenging because of its clinical polymorphism and low bacillary load. We report the case of a 19-year-old Moroccan woman receiving methotrexate for recently diagnosed rheumatoid arthritis who developed cutaneous tuberculosis in the deltoid region. Initial GeneXpert MTB/RIF analysis detected *Mycobacterium tuberculosis* without identifying rifampicin resistance, leading to first-line anti-tuberculosis treatment. Despite excellent adherence and multidisciplinary follow-up, the lesion progressively worsened. Repeat molecular testing with GeneXpert MTB/RIF Ultra and GeneXpert MTB/XDR revealed rifampicin monoresistance, subsequently confirmed by phenotypic drug susceptibility testing. Adjustment of the treatment regimen according to the resistance profile resulted in rapid clinical improvement and progressive lesion regression. This case highlights the diagnostic limitations of the first-generation GeneXpert MTB/RIF assay in paucibacillary cutaneous tuberculosis and emphasizes the value of next-generation molecular techniques for the early detection of anti-tuberculosis drug resistance, particularly in immunocompromised patients.

Keywords: *Cutaneous tuberculosis, Rifampicin resistance, GeneXpert MTB/RIF Ultra.*

Introduction

Tuberculosis (TB), one of the leading infectious diseases responsible for high global morbidity, remains the deadliest infectious disease, and is among the ten leading causes of death worldwide [1]. Although considerable progress has been made in its diagnosis and management, the World Health Organization (WHO) estimated that approximately 10.7 million people developed TB in 2024, resulting in nearly 1.25 million deaths [1,2]. The pulmonary form is predominant, but *Mycobacterium tuberculosis* (MTB) exhibits systemic tropism and can affect virtually any organ of the body, giving rise to a wide spectrum of clinical manifestations [1,2].

These various anatomical localizations, often characterized by a polymorphic clinical presentation and a low bacillary load (paucibacillary forms), are similar to numerous inflammatory, infectious, and neoplastic diseases. In addition to the considerable overlap between the clinical, radiological, and histopathological manifestations of extrapulmonary tuberculosis (EPTB) and those of many other diseases, the difficulty in obtaining representative clinical specimens and the variable performance of conventional microbiological techniques further complicate the diagnosis, making EPTB a major diagnostic challenge and justifying the use of rapid, accurate, and sensitive molecular methods [2–4].

In the Kingdom of Morocco, TB remains a major public health problem despite the efforts undertaken through the National Tuberculosis Control Programme (PNLAT). According to the World Health Organization (WHO), the estimated incidence has gradually declined over recent decades, from 115 to 92 cases per 100,000 population between 2000 and 2023. Nevertheless, the disease remains active, with approximately 33,000 new cases reported in 2024 [2]. The proportion of extrapulmonary tuberculosis (EPTB) has also increased, accounting for nearly half of all reported cases (49% in 2024), with lymph node (51%) and pleural (26%) forms being the most frequent [2] (Figure 1). This proportion exceeded 53% in 2025, according to the ministerial statement issued on the occasion of World Tuberculosis Day on 24 March 2026, in which the Minister of Health and Social Protection instructed that the screening and management of extrapulmonary tuberculosis (EPTB) should be strengthened [5].

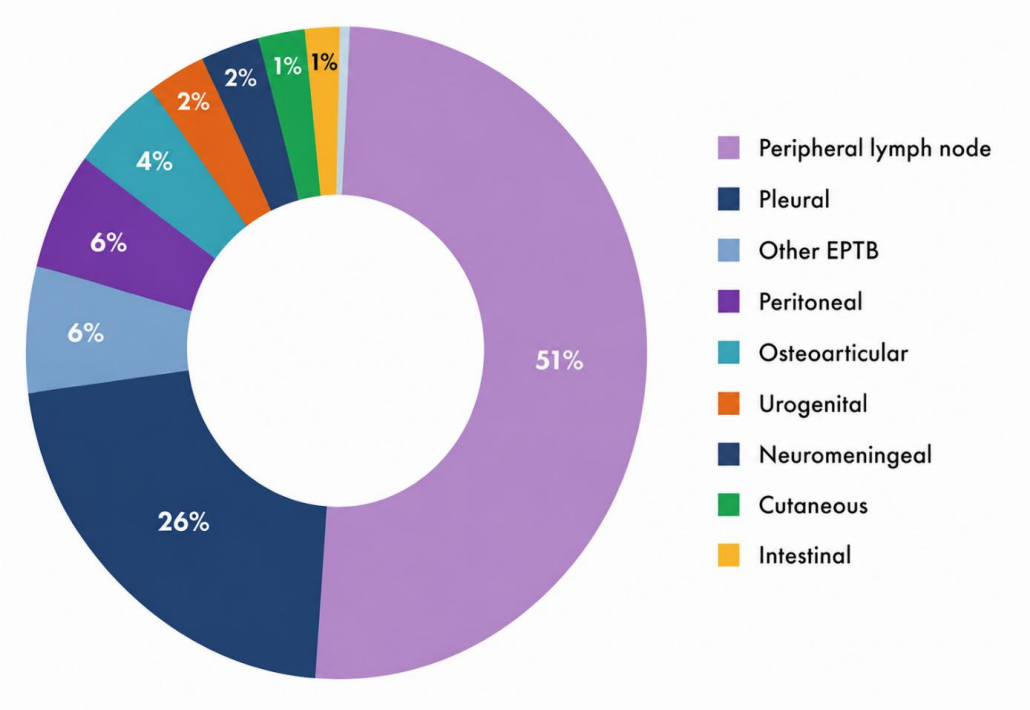


Figure 1. Distribution of newly notified extrapulmonary tuberculosis (EPTB) cases according to anatomical site in Morocco, 2024. *Source:* National Tuberculosis Control Guidelines, Ministry of Health and Social Protection (2025) [2]

Among the extrapulmonary tuberculosis (EPTB) localizations, the cutaneous form remains rare, accounting for approximately 1% of EPTB cases reported in Morocco [2,3] (Figure 1). Cutaneous tuberculosis (cutaneous TB) constitutes a distinct clinical entity, characterized by a wide diversity of dermatological manifestations, which may present as nodular, verrucous, ulcerative, or infiltrative lesions. Its rarity, frequently non-specific and atypical clinical presentation, together with the paucibacillary nature of cutaneous lesions, further delays and complicates the diagnosis [4,6].

This diagnostic difficulty may be worse in immunocompromised patients, particularly those living with HIV or receiving immunosuppressive therapy, in whom the risk of reactivation of latent tuberculosis infection or the development of atypical forms is higher. Furthermore, the emergence of drug-resistant *Mycobacterium tuberculosis* (MTB) strains, particularly rifampicin-resistant tuberculosis (RR-TB), represents an additional threat that may lead to treatment failure and prolonged clinical progression [1,4,7].

In this context, the rapid identification of MTB together with the early determination of the resistance profile is indispensable for the timely adaptation of the therapeutic regimen. Molecular techniques, particularly GeneXpert MTB/RIF, GeneXpert MTB/RIF Ultra, and GeneXpert MTB/XDR, have profoundly transformed the diagnostic approach by enabling the simultaneous

detection of mycobacterial DNA and mutations associated with resistance to anti-tuberculosis drugs, especially those active in rifampicin resistance through mutations in the *rpoB* gene [8].

These high-performance diagnostic tools are of crucial value in the diagnosis of paucibacillary extrapulmonary forms, in which conventional methods often lack sufficient sensitivity, and they allow earlier and more appropriate therapeutic decision-making [1,4,6]. In this report, we describe a rare case of rifampicin-monoresistant cutaneous tuberculosis (RR-TB), initially missed by first-line molecular testing (first-generation GeneXpert MTB/RIF), highlighting the importance of extended molecular diagnosis for revealing resistance profiles and optimizing therapeutic management.

Case Report

The patient was a 19-year-old female from the Kingdom of Morocco who had received Bacillus Calmette–Guérin (BCG) vaccination at birth in accordance with the National Immunization Programme (NIP). She was being followed in the Rheumatology Department for recently diagnosed rheumatoid arthritis (RA), and, in this context, her physician initiated immunosuppressive therapy with methotrexate (MTX), administered as subcutaneous injections as part of a chronotherapeutic treatment strategy, at the standard dose of 15 mg per week.

Four months after the initiation of this therapeutic regimen, the patient noticed the gradual appearance of a small cutaneous lesion over the right deltoid region. Initially, it presented as a small inflammatory nodule, slightly erythematous, mildly painful, and without discharge, with no associated systemic symptoms, including fever, deterioration of the general condition, night sweats, or weight loss. In view of the slow but progressive evolution of the lesion and its persistence despite topical treatment with an H1 antihistamine (chlorphenoxamine), a topical antibiotic (fusidic acid), and an antifungal agent (bifonazole), the patient consulted a dermatologist (Figure 2).

Dermatological examination revealed a well-defined, rounded subcutaneous nodular lesion with a firm inflammatory consistency, covered by stretched, slightly erythematous-violaceous skin, mildly raised and tender on palpation, with a non-specific appearance and measuring approximately 3 × 3 cm. The lesion was characterized by a small central blackish area suggesting early fistulization or superficial necrosis, with no discharge observed at the time of clinical examination (Figure 2).



Figure 2. Initial clinical appearance of cutaneous tuberculosis in a 19-year-old female patient receiving immunosuppressive therapy for rheumatoid arthritis, presenting as a small non-specific inflammatory nodule

Although several differential diagnoses were considered, including an inflammatory dermatosis or a chronic cutaneous infection (bacterial or fungal), the dermatologist rapidly suspected cutaneous tuberculosis based on the combination of several suggestive clinical and epidemiological findings. These included the patient's history of pulmonary tuberculosis (PTB) during childhood (at the age of 6 years, she developed PTB caused by rifampicin-susceptible *Mycobacterium tuberculosis* (MTB), which was treated with a standard first-line anti-tuberculosis regimen, resulting in complete recovery after six months of treatment, with no documented recurrence to date), the state of immunosuppression induced by the immunosuppressive therapy prescribed for the treatment of the autoimmune disease (RA), and the endemic nature of TB in the Kingdom of Morocco, despite the complete absence of clinical signs suggesting pulmonary tuberculosis at the time of consultation.

In this clinical context, a skin biopsy was performed and submitted to the Microbiology Laboratory of Ibn Sina University Hospital in Rabat for specialized mycobacteriological investigations in order to confirm biologically the suspected diagnosis of cutaneous tuberculosis before the initiation of an appropriate therapeutic regimen.

Direct bacteriological examination of the biological specimen by smear microscopy following modified Ziehl–Neelsen staining demonstrated the presence of acid-fast bacilli (AFB). In addition,

culture on a specific solid medium (Löwenstein–Jensen medium) revealed the presence of typical *Mycobacterium tuberculosis* colonies after two weeks of incubation at **37°C**.

Molecular diagnosis of the skin biopsy using the GeneXpert MTB/RIF assay, after homogenization of the biopsy specimen in a sterile mortar with sterile physiological saline in order to release the mycobacterial biological material, confirmed the presence of *Mycobacterium tuberculosis* (MTB) DNA, detected at a low level, corresponding to a Cycle Threshold (Ct) value ranging from 22 to 28, consistent with a moderate-to-low bacillary load. Parallel analysis of the probes targeting the rifampicin resistance-determining region (RRDR) of the *rpoB* gene did not reveal any detectable abnormality, leading to an initial interpretation in favour of a rifampicin-susceptible MTB strain.

On the basis of these biological findings, which were communicated to the dermatologist, the diagnosis of cutaneous tuberculosis was confirmed, and the patient was referred to a Centre for the Diagnosis and Treatment of Respiratory Diseases (CDTMR) in the city of Casablanca, where free first-line anti-tuberculosis treatment was prescribed and initiated in accordance with the national recommendations of the National Tuberculosis Control Programme (PNLAT).

The anti-tuberculosis treatment regimen consisted of a standard four-drug combination comprising rifampicin (R), isoniazid (H), pyrazinamide (Z), and ethambutol (E), prescribed for an initial period of two months (2RHZE), followed by a continuation phase consisting of rifampicin and isoniazid for four months (4RH), in accordance with the national recommendations for the management of drug-susceptible tuberculosis.

The patient adhered rigorously to the prescribed therapeutic regimen, with excellent treatment compliance throughout the course of therapy, ensured through the use of an electronic pill dispenser. She complied with the recommended administration schedule for the different medications (oral anti-tuberculosis drugs and systemic immunosuppressive therapy), particularly the recommended chronotherapeutic regimen, in order to optimize the efficacy of anti-tuberculosis treatment and minimize potential drug interactions. Given the concomitant administration of first-line anti-tuberculosis drugs together with methotrexate as immunomodulatory therapy for rheumatoid arthritis, particular attention was paid to the prevention of adverse drug reactions.

Coordination among the five specialists (the rheumatologist, dermatologist, physician from the National Tuberculosis Control Programme (CDTMR), pharmacist, and medical biologist) made it possible to adapt both the therapeutic and biological monitoring of methotrexate, given its potential hepatic and haematological toxicity, together with therapeutic drug monitoring (TDM) of the different anti-tuberculosis drugs and regular biochemical monitoring of renal function throughout the entire course of anti-tuberculosis treatment.

The Medical Biology Department ensured regular biological assessment through laboratory investigations, including a complete blood count (CBC), liver function tests (aspartate aminotransferase (AST), alanine aminotransferase (ALT), alkaline phosphatase (ALP), and bilirubin; together with monitoring of renal function (urea, creatinine, and estimated glomerular filtration rate (eGFR)). These biological parameters were also essential for monitoring anti-tuberculosis treatment because of its prolonged duration.

Despite this optimal management, including excellent treatment adherence without any reported interruption of therapy, avoidance of drug interactions between the prescribed anti-tuberculosis drugs and methotrexate, correct administration of all medications, and appropriate clinical and biological monitoring, the initial clinical course was unfavourable. At the end of treatment, the lesion had worsened. It was larger, more infiltrative, and more inflammatory, with no improvement after several weeks of therapy. This prompted the dermatologist to investigate an underlying microbiological cause, suspecting the presence of a drug-resistant *Mycobacterium tuberculosis* strain (Figure 3).



Figure 3. Clinical progression of cutaneous tuberculosis despite first-line anti-tuberculosis treatment initiated following an initial GeneXpert MTB/RIF result indicating rifampicin susceptibility (no mutation detected in the *rpoB* gene

A second skin biopsy was subsequently submitted to our laboratory, accompanied by a request for anti-tuberculosis drug susceptibility testing. This time, the GeneXpert MTB/RIF Ultra assay detected *Mycobacterium tuberculosis* at a medium level and also revealed rifampicin resistance (RR) through the detection of a mutation in the *rpoB* gene. In the context of suspected multidrug-resistant tuberculosis (MDR-TB), a GeneXpert MTB/XDR assay, allowing a more comprehensive

anti-tuberculosis drug susceptibility assessment, was also performed. This assay did not reveal resistance to the other anti-tuberculosis agents tested, including Group A fluoroquinolones, Group C second-line injectable agents (the aminoglycosides amikacin, kanamycin, and capreomycin), or the newer Group B anti-tuberculosis drugs (bedaquiline and linezolid), with the exception of rifampicin, thereby confirming a rifampicin-monoresistant tuberculosis (RR-TB) profile.

These molecular findings were subsequently confirmed by phenotypic drug susceptibility testing performed on mycobacterial colonies obtained after 10 days of incubation of the culture from the second biopsy on Löwenstein–Jensen solid medium. This anti-tuberculosis drug susceptibility study confirmed the resistance profile identified by the molecular approaches (RR-TB) by assessing the growth of *Mycobacterium tuberculosis* in the presence of the different anti-tuberculosis drugs tested. The concordance between the molecular and phenotypic findings further strengthened the reliability of the resistance diagnosis, allowing precise characterization of the susceptibility profile of the strain isolated from the cutaneous specimen and, consequently, appropriate guidance of therapeutic management.

These biological findings explained the initial therapeutic failure and demonstrated a diagnostic discrepancy between the first-generation GeneXpert MTB/RIF assay and the complementary analyses performed using GeneXpert MTB/RIF Ultra, GeneXpert MTB/XDR, and conventional phenotypic drug susceptibility testing. These mycobacteriological findings led to a reassessment of the therapeutic strategy in accordance with the national recommendations of the National Tuberculosis Control Programme (PNLAT), with the initiation of a new short-course treatment regimen adapted to the identified rifampicin-monoresistant (RR-TB) profile.

This new therapeutic regimen was based on a four-drug combination comprising three Group A anti-tuberculosis agents (bedaquiline (Bdq), linezolid (LZD), and the fluoroquinolone moxifloxacin (Mfx)), combined with pyrazinamide (Z), a Group C agent. This treatment regimen was prescribed for a duration of six months in our patient. Clinical evolution under this new therapeutic regimen was marked, from the first weeks after its initiation, by progressive clinical improvement, characterized by a reduction in local inflammation, decreased cutaneous infiltration, and gradual regression of the tuberculous lesion during medical follow-up (Figure 4).

This favourable outcome was achieved through appropriate and rigorous therapeutic management based on optimal treatment adherence, correct administration of the different anti-tuberculosis drugs, and strict compliance with the recommended chronotherapeutic regimen in order to optimize pharmacological efficacy and minimize potential drug interactions, particularly those related to the concomitant administration of methotrexate (MTX) prescribed for the underlying autoimmune disease.

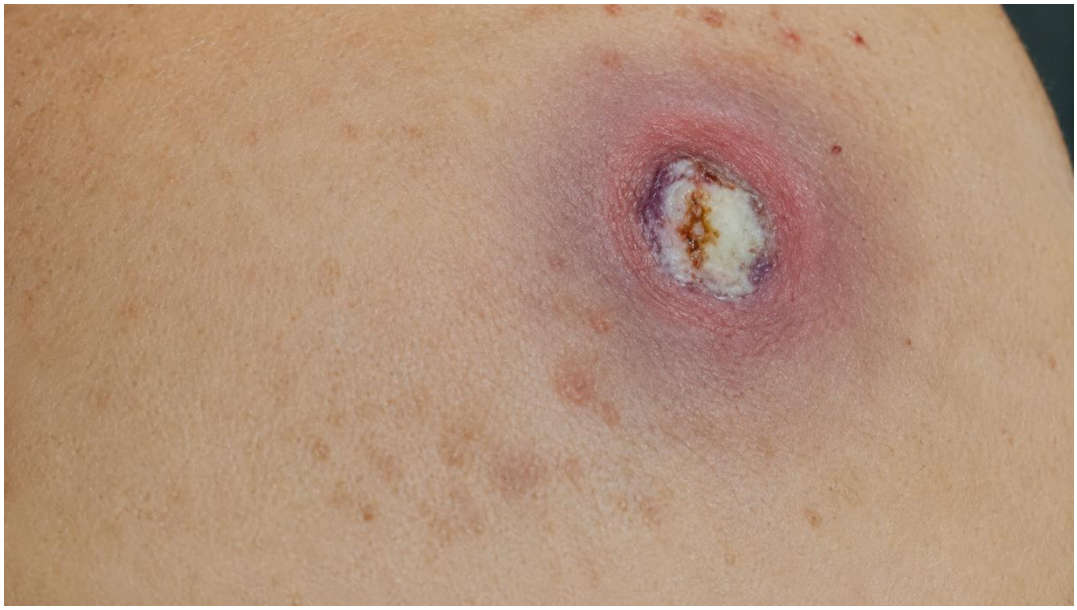


Figure 4. Progressive clinical regression of the cutaneous lesion one month after initiation of second-line anti-tuberculosis treatment

Discussion

Cutaneous tuberculosis constitutes one of the rare forms of extrapulmonary tuberculosis (EPTB), accounting for a small proportion of all extrapulmonary tuberculous manifestations [2,3]. Unlike pulmonary tuberculosis, whose clinical, radiological, and mycobacteriological presentation is generally better characterized and often typical, cutaneous localizations remain particularly difficult to diagnose because of their clinical polymorphism, low bacillary load, and resemblance to numerous dermatological diseases, including psoriasis, chronic eczema, fungal dermatoses, cutaneous sarcoidosis, cutaneous leishmaniasis, and cutaneous squamous cell carcinoma [9].

The skin represents a generally effective natural barrier against the penetration of the tubercle bacillus. But, when skin integrity is disrupted following a wound, trauma, ulceration, or even a surgical procedure, direct inoculation of *Mycobacterium tuberculosis* (MTB) may occur, resulting in cutaneous or mucocutaneous tuberculosis. In addition to direct inoculation, this form of EPTB may also result from contiguous spread or even haematogenous or lymphatic dissemination [6].

Cutaneous lesions may present with highly variable clinical appearances, ranging from an inflammatory nodule to a chronic ulcer, including verrucous or infiltrative forms, making clinical diagnosis frequently difficult and often insufficient [2,6,9]. In our case, the initial presentation as a small, isolated, atypical inflammatory cutaneous nodule, without constitutional symptoms or associated pulmonary manifestations, perfectly illustrates this diagnostic difficulty.

This can be increased in patients with pathological or iatrogenic immunosuppression. In our case, the patient was receiving methotrexate for the treatment of recently diagnosed autoimmune disease, a context known to favour opportunistic diseases such as the reactivation of latent tuberculosis infection and the emergence of atypical forms of the disease [2,10].

A recent meta-analysis published in 2026 confirmed that the introduction of biologic therapies (immunomodulatory treatments), including tumour necrosis factor-alpha (TNF-α) inhibitors, interleukin-17 (IL-17) inhibitors, and ustekinumab (an inhibitor of the p40 subunit shared by interleukins IL-12 and IL-23), which selectively target the immune system, increases the risk of tuberculosis associated with these therapies. This risk differs from that observed with conventional immunosuppressive agents and varies according to the different classes of biologic therapies [2,10].

In any patient receiving immunosuppressive therapy who presents with a chronic cutaneous lesion or a lesion resistant to conventional treatment (topical antifungal agents, H1 antihistamines, topical antibacterial agents, etc.), particularly when aggravated following the application of topical corticosteroids, cutaneous tuberculosis should remain a major differential diagnosis, even in the absence of concomitant active pulmonary tuberculosis, especially in an epidemiological context suggesting tuberculosis endemicity, such as that observed in Morocco.

The main originality of our clinical case lies in the demonstration of rifampicin resistance (RR) that was initially not detected by the first-generation GeneXpert MTB/RIF assay. Although this molecular technique has profoundly transformed the management of tuberculosis owing to its rapidity, sensitivity, and ability simultaneously to detect *Mycobacterium tuberculosis* complex DNA and mutations associated with rifampicin resistance (*rpoB* gene), certain analytical limitations persist. To overcome these limitations, a new version of the GeneXpert MTB/RIF assay was developed under the name **GeneXpert MTB/RIF Ultra**, with the aim of improving, on the one hand, the sensitivity for detecting *Mycobacterium tuberculosis* complex DNA, thereby reducing the limit of detection to **15.6 bacterial CFU/mL**, and, on the other hand, enhancing the sensitivity for detecting rifampicin resistance. The GeneXpert MTB/RIF Ultra assay incorporates an improved cartridge containing two different multicopy amplification targets (IS1081 and IS6110) [11].

The diagnostic performance of GeneXpert MTB/RIF Ultra and GeneXpert MTB/RIF for the detection of rifampicin resistance has been compared in several studies included in a Cochrane systematic review. Regarding GeneXpert MTB/RIF Ultra, five studies evaluated its ability to identify rifampicin resistance, reporting sensitivity values ranging from **50% to 100%**; specificity ranged from 93% to 100% (Table 1) [12].

Difference (Ultra − Xpert) In terms of clinical impact, the predictive analyses from this multicentre study showed that, in a hypothetical population of 1,000 patients, including 100 with rifampicin-resistant tuberculosis (RR-TB), the GeneXpert MTB/RIF Ultra assay would correctly identify all rifampicin-resistant cases without generating either false-positive or false-negative results, according to the estimates of the meta-analysis. By contrast, GeneXpert MTB/RIF would correctly identify the vast majority of rifampicin-resistant cases but could generate a small number of false-positive and false-negative results [12].

Overall, all the studies included in the meta-analysis provided evidence indicating that both assays have excellent diagnostic accuracy for the detection of rifampicin resistance. Although GeneXpert MTB/RIF Ultra demonstrated slightly superior performance in this study, no clinically significant difference was observed between the two techniques [12]. The principal advantage of GeneXpert MTB/RIF Ultra remains its improved detection of *Mycobacterium tuberculosis*, particularly in specimens with a low bacillary load, especially in extrapulmonary tuberculosis, rather than a substantially better identification of rifampicin resistance [12]. Both GeneXpert MTB/RIF and GeneXpert MTB/RIF Ultra exhibit excellent technical performance, with comparable sensitivity and specificity for the detection of rifampicin resistance. This meta-analysis also suggests that future researchers should consider the limitations of Löwenstein–Jensen culture as the reference standard for paucibacillary specimens and explore alternative approaches to overcome these limitations [12]. (Table 1)

A prospective multicentre study evaluating the diagnostic performance of GeneXpert MTB/RIF and GeneXpert MTB/RIF Ultra for the detection of rifampicin resistance (RR) showed that both molecular techniques exhibit excellent diagnostic accuracy and overall comparable performance. The authors reported a sensitivity of **95%** (95% CI: 91–98%) for both assays, together with a specificity of **98%** (95% CI: 96–99% for GeneXpert MTB/RIF and 97–99% for GeneXpert MTB/RIF Ultra) [13] (Figure 7). These findings indicate that the introduction of the Ultra technology has not significantly improved the performance of the assay for the identification of rifampicin resistance. Its principal contribution is that it increases the sensitivity for detecting the *Mycobacterium tuberculosis* complex, particularly in paucibacillary specimens. With regard to the detection of rifampicin resistance, both analytical methods provide equivalent diagnostic reliability and constitute effective tools for the early guidance of therapeutic management [36].

In contrast, a study investigating discordant rifampicin resistance detection between GeneXpert MTB/RIF and GeneXpert MTB/RIF Ultra demonstrated excellent reproducibility of both techniques for all isolates tested at moderate and low bacterial concentrations, with the exception

of two weakly enriched specimens. GeneXpert MTB/RIF Ultra produced a **"trace-positive"** result for one specimen harbouring the **H445D** mutation, thereby preventing determination of the melting temperature (Tm), whereas GeneXpert MTB/RIF failed to detect the *Mycobacterium tuberculosis* complex in another specimen carrying the **P439L** mutation [37] (Table 2).

Table 1. Forest plots comparing the diagnostic accuracy of GeneXpert MTB/RIF and GeneXpert MTB/RIF Ultra for the detection of rifampicin resistance. Each row represents an individual study. Blue squares indicate the estimated sensitivity or specificity, and horizontal lines represent the corresponding 95% confidence intervals. TP: true positive; FP: false positive; FN: false negative; TN: true negative.

Rifampicin resistance – Xpert MTB/RIF							
Study	**Year**	**TP**	**FP**	**FN**	**TN**	**Sensitivity (95% CI)**	**Specificity (95% CI)**
Biadglegne *et al.* [13]	2014	2	1	0	26	1.00 [0.16, 1.00]	0.96 [0.81, 1.00]
Dhasmana *et al.* [14]	2014	1	0	0	26	1.00 [0.03, 1.00]	1.00 [0.87, 1.00]
Bera *et al.* [15]	2015	1	0	0	1	1.00 [0.03, 1.00]	1.00 [0.03, 1.00]
Al-Ateah *et al.* [16]	2012	2	0	0	14	1.00 [0.16, 1.00]	1.00 [0.77, 1.00]
Hanif *et al.* [17]	2011	1	0	0	10	1.00 [0.03, 1.00]	1.00 [0.69, 1.00]
Friedrich *et al.* [18]	2011	1	0	0	4	1.00 [0.03, 1.00]	1.00 [0.40, 1.00]
Gu *et al.* [19]	2015	6	0	0	18	1.00 [0.54, 1.00]	1.00 [0.81, 1.00]
Nhu *et al.* [20]	2014	3	0	0	104	1.00 [0.29, 1.00]	1.00 [0.97, 1.00]
Meldua *et al.* [21]	2014	1	0	0	4	1.00 [0.03, 1.00]	1.00 [0.40, 1.00]
Wang *et al.* [22]	2020	5	0	0	21	1.00 [0.48, 1.00]	1.00 [0.84, 1.00]
Rufai *et al.* [23]	2015	1	0	0	17	1.00 [0.03, 1.00]	1.00 [0.80, 1.00]
Peter *et al.* [24]	2016	1	0	0	28	1.00 [0.03, 1.00]	1.00 [0.88, 1.00]
Rufai *et al.* [25]	2017	39	0	0	22	1.00 [0.91, 1.00]	1.00 [0.85, 1.00]
Vadwai *et al.* [26]	2011	39	5	1	80	0.97 [0.87, 1.00]	0.94 [0.87, 0.98]
Nataraj *et al.* [27]	2016	28	0	1	121	0.97 [0.82, 1.00]	1.00 [0.97, 1.00]
Sharma *et al.* [28]	2014	26	3	1	211	0.96 [0.81, 1.00]	0.99 [0.96, 1.00]
Li *et al.* [29]	2017	11	0	1	47	0.92 [0.62, 1.00]	1.00 [0.92, 1.00]
Du *et al.* [30]	2015	9	2	1	31	0.90 [0.55, 1.00]	0.94 [0.80, 0.99]
Ligthelm *et al.* [31]	2011	1	0	1	26	0.50 [0.01, 0.99]	1.00 [0.87, 1.00]
Rifampicin resistance – Xpert MTB/RIF Ultra							
Study		**TP**	**FP**	**FN**	**TN**	**Sensitivity (95% CI)**	**Specificity (95% CI)**
Wang *et al.* [32]	2019	6	0	0	23	1.00 [0.54, 1.00]	1.00 [0.85, 1.00]
Sun *et al.* [33]	2019	9	0	0	38	1.00 [0.66, 1.00]	1.00 [0.91, 1.00]
Wu *et al.* [34]	2019	4	0	0	23	1.00 [0.40, 1.00]	1.00 [0.85, 1.00]
Wang *et al.* [35]	2020	5	0	0	21	1.00 [0.48, 1.00]	1.00 [0.84, 1.00]

Reproduced from Kohli *et al.* [12]

Table 2. Comparison of the diagnostic performance of GeneXpert MTB/RIF and GeneXpert MTB/RIF Ultra for the detection of tuberculosis and rifampicin resistance. Adapted from Kohli *et al.* [36]

Assay	Sensitivity: All culture-positive	Sensitivity: Smear-negative	Sensitivity: HIV-negative	Sensitivity: HIV-positive	Specificity	Sensitivity for rifampicin resistance	Specificity for rifampicin resistance
Xpert MTB/RIF	83% (79–86; 383/462)	46% (37–55; 63/137)§	90% (84–94; 143/159)	77% (68–84; 88/155)	98% (97–99; 960/977)	95% (91–98; 167/175)	98% (96–99; 369/376)
Xpert MTB/RIF Ultra	88% (85–91; 408/462)	63% (54–71; 86/137)§	91% (86–95; 145/159)	90% (83–95; 103/115)	96% (94–97; 934/977)	95% (91–98; 166/175)	98% (97–99; 370/376)
Difference (Ultra − Xpert)	5.4% (3.3–8.0; 25/162)	17% (10–24; 23/137)	1.3% (−1.8 to 4.9; 2/159)	13% (6.4–21; 15/115)	−2.7% (−3.9 to −1.7; 36/977)	−0.6% (−3.2 to 1.6; 1/175)	0.3% (−0.7 to 1.5; 1/376)
Non-inferiority margin	Not predefined	−7%	Not predefined	Not predefined	Not predefined	−3%	−3%

Values are expressed as % (95% CI; n/N). CI, confidence interval; n, number of positive results; N, total number of samples

This study, based on the use of experimental **mock samples**, specifically evaluated the performance of rifampicin resistance (RR) detection, thereby further supporting the relevance of GeneXpert MTB/RIF Ultra in this context [14]. This improved version (GeneXpert MTB/RIF Ultra) showed a trend towards higher sensitivity than GeneXpert MTB/RIF in a high-resource setting with an intermediate incidence of tuberculosis, although this difference did not reach statistical significance. Its specificity was comparable to that of GeneXpert MTB/RIF, despite the occurrence of a small number of false-positive results among the **"trace-positive"** and **"very low-positive"** categories. Furthermore, certain mutations located within the region targeted by the **rpoB1** probe resulted in indeterminate rifampicin resistance results [37] (Table 3)

Table 3. Comparison of the performance of GeneXpert MTB/RIF and GeneXpert MTB/RIF Ultra for the detection of different *rpoB* mutations associated with rifampicin resistance [37]

rpoB mutation(s)	Phenotypic DST (RIF)	Xpert MTB/RIF	Xpert MTB/RIF Ultra
Q432P (Q513P)	R	Detected	Detected
D435Y (D516Y)	R	Detected	Detected
P439L (P520L)	S	Detected	Detected
H445D (H526D)	R	Detected	Detected
H445Y (H526Y)	R	Detected	Detected
S450L (S531L)	R	Detected	Detected
I491F (I572F)	R	Detected	Detected
D545E (D626E)	S	Detected	Detected
Q429H + H430P + H445Q	R	Detected	Detected
Q432K + H445D	R	Detected	Detected
D435N + H445N	R	Detected	Detected
Q432_D435delinsHI	R	Detected	Detected

Abbreviations: DST, drug susceptibility testing; RIF, rifampicin; R, resistant; S, susceptible.

The discordance observed in our clinical case between the results of GeneXpert MTB/RIF and GeneXpert MTB/RIF Ultra also raises the issue of the management of rare rifampicin-resistant strains. Resistance to this first-line anti-tuberculosis drug (R) is mainly caused (in approximately 95% of cases) by genetic variants within the rifampicin resistance-determining region (RRDR) of the *rpoB* gene, which encodes the β-subunit of RNA polymerase [38].

Rifampicin resistance is of particular importance because it constitutes an indirect marker strongly associated with multidrug-resistant tuberculosis. Early detection of rifampicin-

resistant tuberculosis (RR-TB) is therefore essential for the prompt adaptation of the therapeutic strategy, thereby avoiding the prolonged use of ineffective treatment regimens that may favour the acquisition of additional drug resistance while increasing the risk of adverse effects associated with anti-tuberculosis drugs administered for at least six months. In our case, the delayed identification of rifampicin resistance resulted in initial exposure to a treatment regimen to which the infecting strain was not susceptible, probably explaining the absence of clinical improvement despite appropriate therapeutic management based on the mycobacteriological findings obtained from the first biopsy

Conclusion

This case highlights the diagnostic challenges and potential limitations associated with cutaneous tuberculosis, a rare form of extrapulmonary tuberculosis whose atypical clinical presentation, often combined with a low bacillary load, frequently delays diagnosis. In patients receiving immunosuppressive therapy, the occurrence of chronic or unusual cutaneous lesions should raise suspicion of cutaneous tuberculosis, even in the absence of pulmonary manifestations, particularly in an endemic setting. This clinical case also illustrates that an initial rifampicin-susceptible result obtained by GeneXpert MTB/RIF does not definitively exclude rifampicin resistance when the clinical course is unfavourable. The use of next-generation molecular techniques, particularly GeneXpert MTB/RIF Ultra and GeneXpert MTB/XDR, combined with reference phenotypic methods, constitutes an essential strategy for the accurate and early identification of drug resistance profiles, thereby allowing prompt adaptation of the therapeutic regimen.

References

[1] World Health Organization, 2024, Global tuberculosis report 2020. World Health Organization (October, 2024). https://www.who.int/teams/global-programme-on-tuberculosis-and-lung-health/tb-reports/global-tuberculosis-report-2024

[2] Ministère de la Santé et de la Protection Sociale, 2025, Guide National de la lutte antituberculeuse au Maroc. Programme National de Lutte Antituberculeuse, Direction de l'Épidémiologie et de Lutte contre les Maladies. https://fr.scribd.com/document/939446213/Guide-du-PNLAT-2025-251008-095850

[3] Hailu, S., Hurst, C., Cyphers, G., Thottunkal, S., Harley, D., Viney, K., Irwin, A., Dean, J., & Nourse, C., 2024, Prevalence of extra-pulmonary tuberculosis in Africa: A

systematic review and meta-analysis. *Tropical Medicine & International Health* **29**(4), 257-265. https://doi.org/10.1111/tmi.13970

[4] Ministry of Health and Social Protection of Morocco, 2026, The Ministry of Health and Social Protection strengthens screening and management efforts for all forms of tuberculosis on the occasion of World Tuberculosis Day 2026 [Translated from the original French]. Ministerial communiqué. (Rabat: Ministry of Health and Social Protection). https://www.sante.gov.ma/Pages/communiqués.aspx?communiqueID=485&

[5] Jain R., Gupta G., Mitra D. K., & Randeep Guleria R., 2024, Diagnosis of extra pulmonary tuberculosis: An update on novel diagnostic approaches. *Respiratory Medicine* **225**, 107601. doi: 10.1016/j.rmed.2024.107601

[6] de Brito A. C., de Oliveira C. M., Unger D. A-A., & de Jesus Semblano Bittencour M., 2022, Cutaneous tuberculosis: epidemiological, clinical, diagnostic and therapeutic update. *Anais Brasileiros de Dermatologia* **97**(2), 129-144. https://doi.org/10.1016/j.abd.2021.07.004

[7] Qiu B., Wu Z., Tao B., Li Z., Song H., Dan Tian D., Wu J., Zhan M., & Jianming Wang Send J. W., 2022, Risk factors for types of recurrent tuberculosis (reactivation versus reinfection): A global systematic review and meta-analysis. *International Journal of Infectious Diseases* **116,** 14–20. https://doi.org/10.1016/j.ijid.2021.12.344

[8] World Health Organization, 2024, Manuel opérationnel de l'OMS sur la tuberculose. Module 3 : diagnostic - outils de diagnostic rapide pour le dépistage de la tuberculose. https://www.who.int/fr/publications/b/58221

[9] Mexico, U. C. A. A., González, J. F. M., González, A. L. R., Del Estado de Puebla Puebla Mexico, U. P. A., Servín, M. M., De Guadalajara Zapopan Mexico, U. A., Ávila, P. I. N., De Guadalajara Zapopan Mexico, U. A., Almanza, A. M., & De México Celaya Mexico, U. L., 2025), Cutaneous Tuberculosis : A Comprehensive Review of Etiopathogenesis, Clinical Subtypes, Diagnostic Modalities, and Contemporary Therapeutic Approaches. *International Journal of Medical Science and Clinical Research Studies* **5**(05). https://doi.org/10.47191/ijmscrs/v5-i05-06

[10] Kaixuan Liu K., Zeng Z., MD; Lu W., Yang Y., Lin T., 2026, Tuberculosis-Related Outcomes in Dermatologic Patients, Receiving Systemic Therapy A Systematic Review and Meta-Analysis. *JAMA Dermatology*. www.doi.org/10.1001/jamadermatol.2026.2365

[11] Jiang J., Yang J., Shi Y., Jin Y., Tang S., Zhang N., Lu Y., & Sun G., 2020, Head-to-head comparison of the diagnostic accuracy of Xpert MTB/RIF and Xpert MTB/RIF Ultra for tuberculosis: a meta-analysis. *Infectious Infectious Diseases* **52**(11):763-775. https://doi.org/10.1080/23744235.2020.1788222

[12] A. Kohli, M., Schiller, I., Dendukuri, N., Yao, M., Dheda, K., Denkinger, C. M., Schumacher, S. G., & Steingart, K. R., 2021, Xpert MTB/RIF Ultra and Xpert MTB/RIF assays for extrapulmonary tuberculosis and rifampicin resistance in adults. *Cochrane Database of Systematic Reviews* (1), CD012768. https://doi.org/10.1002/14651858.cd012768.pub3

[13] Biadglegne, F., Tesfaye, W., Sack, U., & Rodloff, A. C., 2013, Tuberculous Lymphadenitis in Northern Ethiopia : In a Public Health and Microbiological Perspectives. *PLoS ONE* **8**(12), e81918. https://doi.org/10.1371/journal.pone.0081918

[14] Dhasmana, D. J., Ross, C., Bradley, C. J., Connell, D. W., George, P. M., Singanayagam, A., Jepson, A., Craig, C., Wright, C., Molyneaux, P. L., Wickremasinghe, M., Lalvani, A., Cooke, G. S., & Kon, O. M., 2014, Performance of Xpert MTB/RIF in the Diagnosis of Tuberculous Mediastinal Lymphadenopathy by Endobronchial Ultrasound. *Annals of the American Thoracic Society* **11**(3), 392-396. https://doi.org/10.1513/annalsats.201308-250oc

[15] Bera, C., Michael, J. S., Burad, D., Shirly, S. B., Gibikote, S., Ramakrishna, B., Goel, A., & Eapen, C. E., 2015, Tissue XpertTM MTB/Rif assay is of limited use in diagnosing peritoneal tuberculosis in patients with exudative ascites. *Indian Journal of Gastroenterology* **34**(5), 395-398. https://doi.org/10.1007/s12664-015-0599-7

[16] Al-Ateah S. M., Al-Dowaidi M. M, El-Khizzi N. A., 2012, Evaluation of direct detection of Mycobacterium tuberculosis complex in respiratory and non-respiratory clinical specimens using the Cepheid Gene Xpert(R) system. *Saudi Medical Journal* **33** (10):1100-5. https://pubmed.ncbi.nlm.nih.gov/23047207/

[17] Hanif, S. N. M., Eldeen, H. S., Ahmad, S., & Mokaddas, E., 2011, GeneXpert® MTB/RIF for rapid detection of Mycobacterium tuberculosis in pulmonary and extra-pulmonary samples [Correspondence]. *The International Journal of Tuberculosis and Lung Disease* **15**(9), 1274-1275. https://doi.org/10.5588/ijtld.11.0394

[18] Friedrich S.O., Von Groote-Bidlingmaier F., & Diacon A. H., 2011, Xpert MTB/RIF assay for diagnosis of pleural tuberculosis. *Journal of Clinical Microbiology* **49**(12):4341-2. https://doi.org/10.1128/jcm.05454-11

[19] Gu Y., Wang G., Dong W., Li Y., Ma Y., Shang Y., Qin S., & Huang H., 2015, Xpert MTB/RIF and GenoType MTBDRplus assays for the rapid diagnosis of bone and joint tuberculosis. *International Journal of Infectious Diseases* **36**, 27-30. https://doi.org/10.1016/j.ijid.2015.05.014

[20] Nhu N. T., Heemskerk D., Thu do D.A., Chau T. T., Mai N.T., Nghia H. D., Loc P. P., Ha T. M., Merson L., Thinh T. V., Day J., Chau N. V., Wolbers M., Farrar J., & Caws M., 2014, Evaluation of GeneXpert MTB/RIF for diagnosis of tuberculous meningitis. *Journal of Clinical Microbiology* **52**(1):226-33. www.doi.org/10.1128/JCM.01834-13

[21] Meldau, R., Peter, J., Theron, G., Calligaro, G., Allwood, B., Symons, G., Khalfey, H., Ntombenhle, G., Govender, U., Binder, A., Van Zyl-Smit, R., Dheda, K., 2014, Comparison of same day diagnostic tools including Gene Xpert and unstimulated IFN-γ for the evaluation of pleural tuberculosis : a prospective cohort study. *BMC Pulmonary Medicine* **14**(1), 58. https://doi.org/10.1186/1471-2466-14-58

[22] Wang G., Wang S., Yang X., Sun Q., Jiang G., Huang M., Huo F., Ma Y., Chen X., Huang H., 2020, Accuracy of Xpert MTB/RIF Ultra for the diagnosis of pleural TB in a multicenter cohort study. *Chest* 157(2), 268-275. https://pubmed.ncbi.nlm.nih.gov/31437432/

[23] Rufai, S. B., Singh, A., Kumar, P., Singh, J., & Singh, S., 2015, Performance of Xpert MTB/RIF Assay in Diagnosis of Pleural Tuberculosis by Use of Pleural Fluid Samples. *Journal of Clinical Microbiology* **53**(11), 3636-3638. https://doi.org/10.1128/jcm.02182-15

[24] Peter JG, Zijenah LS, Chanda D, Clowes P, Lesosky M, Gina P, Mehta N., Calligaro G., Lombard C. J., Kadzirange G., Bandason T., Chansa A., Liusha N., Mangu C., Mtafya B., Msila H., Rachow A., Hoelscher M., Mwaba P., Theron G., Keertan Dheda K., 2016, Effect on mortality of point-of-care, urine-based lipoarabinomannan testing to guide tuberculosis treatment initiation in HIV-positive hospital inpatients: a pragmatic, parallel-group, multicountry, open-label, randomised controlled trial. *Lancet* **387**(10024):1187-97. https://pubmed.ncbi.nlm.nih.gov/26970721/

[25] Rufai, S. B., Singh, A., Singh, J., Kumar, P., Sankar, M. M., Singh, S., Nigam, K., Sharma, D., Gupta, A. K., &Rawat, V. S., 2017, Diagnostic usefulness of Xpert MTB/RIF assay for detection of tuberculous meningitis using cerebrospinal fluid. *Journal of Infection* **75**(2), 125-131. https://doi.org/10.1016/j.jinf.2017.04.010

[26] Vadwai V., Boehme C., Nabeta P., Shetty A., Alland D., & Rodrigues C., 2011, Xpert MTB/RIF: a new pillar in diagnosis of extrapulmonary tuberculosis? *Journal of Clinical Microbiology* **49**(7), 2540-5. https://pubmed.ncbi.nlm.nih.gov/21593262/

[27] Nataraj G., Kanade S., Mehta P., 2016, Xpert((R)) MTB/RIF for improved case detection of extra-pulmonary TB in a tertiary care setting in urban India. International *Journal of Tuberculosis and Lung Disease* **20**(7), 890-894. https://www.researchgate.net/publication/303892896_XpertW_MTBRIF_for_improved_case_detection_of_extra-pulmonary_TB_in_a_tertiary_care_setting_in_urban_India

[28] Sharma S. K., Kohli M., Chaubey J., Yadav R. N., Sharma R., Singh B. K., Sreenivas V., Sharma A., Bhatia R., Jain D., Seenu V., Dhar A., & Soneja M., 2014, Evaluation of Xpert MTB/RIF assay performance in diagnosing extrapulmonary tuberculosis among adults in a tertiary care centre in India. *European Respiratory Journal* **44**(4):1090-3. https://pubmed.ncbi.nlm.nih.gov/25063241/

[29] Li, Y., Pang, Y., Zhang, T., Xian, X., Wang, X., Yang, J., Wang, R., Chen, M., & Chen, W., 2017, Rapid diagnosis of extrapulmonary tuberculosis with Xpert Mycobacterium tuberculosis/rifampicin assay. *Journal of Medical Microbiology* **66**(7), 910-914. https://doi.org/10.1099/jmm.0.000522

[30] Du, J., Huang, Z., Luo, Q., Xiong, G., Xu, X., Li, W., Liu, X., & Li, J., 2015, Rapid diagnosis of pleural tuberculosis by Xpert MTB/RIF assay using pleural biopsy and pleural fluid specimens. *Journal of Research in Medical Sciences* **20**(1):26–31. https://pmc.ncbi.nlm.nih.gov/articles/PMC4354061/

[31] Ligthelm, L. J., Nicol, M. P., Hoek, K. G. P., Jacobson, R., Van Helden, P. D., Marais, B. J., Warren, R. M., & Wright, C. A., 2011, Xpert MTB/RIF for Rapid Diagnosis of Tuberculous Lymphadenitis from Fine-Needle-Aspiration Biopsy Specimens. *Journal of Clinical Microbiology* **49**(11), 3967-3970. https://doi.org/10.1128/jcm.01310-11

[32] Wang, G., Wang, S., Jiang, G., Yang, X., Huang, M., Huo, F., Ma, Y., Dai, G., Li, W., Chen, X., & Huang, H., 2019, Xpert MTB/RIF Ultra improved the diagnosis of

paucibacillary tuberculosis: A prospective cohort study. *Journal of Infection* **78**(4), 311-316. https://doi.org/10.1016/j.jinf.2019.02.010

[33] Sun, Q., Wang, S., Dong, W., Jiang, G., Huo, F., Ma, Y., Huang, H., & Wang, G., 2019, Diagnostic value of Xpert MTB/RIF Ultra for osteoarticular tuberculosis. *Journal of Infection* **79**(2), 153-158. https://doi.org/10.1016/j.jinf.2019.06.006

[34] Wu, X., Tan, G., Gao, R., Yao, L., Bi, D., Guo, Y., Yu, F., & Fan, L., 2019, Assessment of the Xpert MTB/RIF Ultra assay on rapid diagnosis of extrapulmonary tuberculosis. *International Journal of Infectious Diseases* **81**, 91-96. https://doi.org/10.1016/j.ijid.2019.01.050

[35] Wang, G., Wang, S., Yang, X., Sun, Q., Jiang, G., Huang, M., Huo, F., Ma, Y., Chen, X., & Huang, H., 2020, Accuracy of Xpert MTB/RIF Ultra for the diagnosis of pleural TB in a multicenter cohort study. *Chest* **157**(2), 268-275. https://pubmed.ncbi.nlm.nih.gov/31437432/

[36] Dorman, S. E., Schumacher, S. G., Alland, D., Nabeta, P., Armstrong, D. T., King, B., Hall, S. L., Chakravorty, S., Cirillo, D. M., Tukvadze, N., Bablishvili, N., Stevens, W., Scott, L., Rodrigues, C., Kazi, M. I., Joloba, M., Nakiyingi, L., Nicol, M. P., Ghebrekhristos, Y., Anyango, I., Murithi, W., Dietze, R., Peres, R. L., Skrahina, A., Auchynka, V., Chopra, K. K., Hanif, M., Liu, X., Yuan, X., Boehme, C. C., Ellner, J. J., & Denkinger, C. M., 2018, Xpert MTB/RIF Ultra for detection of Mycobacterium tuberculosis and rifampicin resistance: a prospective multicentre diagnostic accuracy study. *The Lancet Infectious Diseases* **18**(1), 76-84. www.doi.org/10.1016/S1473-3099(17)30691-6

[37] Suh, E., Jung, S., Lee, J., Jhun, B. W., Kim, T. Y., Huh, H. J., & Lee, N. Y., 2025, Prospective Comparative Evaluation of the Xpert MTB/RIF and Xpert MTB/RIF Ultra Assays for Detecting Mycobacterium tuberculosis and Rifampin Resistance in High-resource, Intermediate-burden Settings. *Annals of Laboratory Medicine* **45**(6), 583-590. https://doi.org/10.3343/alm.2025.0101

[38] Van Rie, A., Whitfield, M. G., De Vos, E., Scott, L., Da Silva, P., Hayes, C., Heupink, T. H., Sirgel, F. A., Stevens, W., & Warren, R. M., 2019, Discordances between molecular assays for rifampicin resistance in Mycobacterium tuberculosis: frequency, mechanisms and clinical impact. *Journal of Antimicrobial Chemotherapy* **75**(5), 1123-1129. https://doi.org/10.1093/jac/dkz564

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Factors Influencing the Care of Sick Prisoners by Healthcare Staff in Emergency Departments: The Case of the Emergency Reception Department at Ibn Rochd Hospital, Casablanca

Maria Mazouri [a*], Imane Tahiri [b], Sanaa Deblij [c], Bouchaib Bahlaouan [d]

Laboratory of Healthcare and Sustainable developement, 2S2D, Higher Institutes of the Nursing Professions and Techniques of Health ISPITS Casablanca, Casablanca, *Morocco*

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[a] ***ORCID***: *0009-0004-9552-7629* ; ***Email***: *m.mazouri@ispitscasa.ac.ma*

[b] ***ORCID***: *0009-0006-4463-5114* ; ***Email***: *imanetahiri34@gmail.com*

[c] ***ORCID***: *0000-0002-5147-982X* ; ***Email***: *deblijfstm@gmail.com*

[d] ***ORCID***: *0000-0002-0976-1274* ; ***Email***: *b.bahlaouan@ispitscasa.ac.ma*

Corresponding author:** Maria Mazouri; ***Email address: *mazourimariaispitsc@gmail.com*

Graphical Abstract

This study described factors influencing prisoner management by healthcare staff in the Emergency Reception Department at Ibn Rochd Hospital, Casablanca. The findings revealed poor awareness of prison healthcare regulations, frequent confidentiality breaches, and inadequate collaboration between prison and hospital services. They highlight the need for staff training, stronger institutional collaboration, and measures to ensure equivalent healthcare for prisoners.



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Abstract: This study aimed to describe the factors influencing the management of prisoners by healthcare staff in the Emergency Reception Department (ERD) at Ibn Rochd Hospital in Casablanca, Morocco. A Level 1 quantitative descriptive study was conducted among medical and nursing staff (n = 50) using an anonymous self-administered questionnaire. Thirty questionnaires were returned (response rate: 60%). The results showed that 86.66% of the staff were unaware of the regulations governing prisoner management, 73% changed their attitude towards prisoners, and 67% provided care in the presence of accompanying personnel, compromising professional secrecy and patient confidentiality. Overcrowding, stress, and workload were identified as the main influencing factors. These findings highlight the need to strengthen staff training, improve collaboration between prison and hospital teams, establish specialized secure units, and reduce prison overcrowding to ensure equivalent healthcare for prisoners.

Keywords: *Ill prisoner, Professional secrecy, Right to health.*

Introduction

Across the world, many prison systems are facing a state of crisis with harmful consequences for prisoners, their families, and society as a whole [1]. Prisons, because they are subject to the general law of a country, should be seen to be founded on legal principles and human rights, with prisoners benefiting from the fundamental right to receive healthcare of the same quality as that provided to the general public [2]. Imprisonment nevertheless poses a significant threat to health: overcrowding, confinement, poor hygiene, and violence contribute to the development and worsening of diseases, with a disproportionately high prevalence of infectious diseases (HIV, tuberculosis), chronic conditions, and mental disorders [3]. Globally, imprisonment rates range from 30 per 100,000 population in India to 750 per 100,000 in the United States [4]. In France, according to the General Inspectorate of Social Affairs, the prison population increased by 25% between 1997 and 2013, and the provision of healthcare in prisons remains uneven and inadequate [5]. In Morocco, the Moroccan Prison Observatory in 2015 reported a prison population of approximately 76,000 inmates distributed across 7 detention facilities, with particularly limited healthcare resources: one doctor for every 800 prisoners, one dentist for every 1,200 prisoners, and one nurse for every 190 prisoners [6].

In response to these challenges, Morocco has undertaken several reforms. The General Delegation for Prison Administration and Reintegration (DGAPR) has invested considerable resources to provide prisoners with healthcare services equivalent to those available to the general population [7]. Law No. 10-23 on the organization and operation of prison establishments, together with the 2011 Constitution (Article 23), has strengthened the fundamental rights of prisoners, including the right to healthcare. Nevertheless, the provision of healthcare to prisoners within public hospitals continues to be hindered by many factors. Hazan [8] highlights the failure to respect prisoners' dignity—who remain handcuffed and restrained during transfers and medical consultations—as well as breaches of medical confidentiality, with consultations taking place in the presence of security escorts.

A recent French administrative court decision reaffirmed that restraints used during medical transfers and consultations must be individually assessed and proportionate, and that security measures must preserve prisoners' dignity and the confidentiality of medical consultations [8-10]

The Emergency Reception Department (ERD) of Ibn Rochd University Hospital in Casablanca was one of the two referral emergency departments authorized to provide emergency care for prisoners in the Greater Casablanca area at the time of the study. According to internal hospital

statistics, 161 emergency transfers of prisoners were recorded in the Greater Casablanca area; 55 of these (34.2%) were managed by the ERD of Ibn Rochd Hospital. These figures indicate that the department managed a substantial proportion of prison-related emergency cases in the region, making it an appropriate setting for investigating healthcare professionals' experiences in caring for prisoners.

Prisoners may experience overlapping health, social and psychological difficulties that increase their vulnerability. In emergency departments, healthcare professionals must reconcile security requirements with their ethical and professional obligations, including respect for patients' rights, dignity and medical confidentiality. Insufficient knowledge of the relevant regulations, combined with the absence of clear care protocols, security procedures and arrangements for coordination between institutions, may complicate the provision of appropriate care to prisoners.

The limited number of Moroccan studies addressing these issues, together with observations made during a clinical placement in the ERD, motivated the present investigation. This study aimed to identify the factors influencing the care of prisoners by healthcare professionals in the Emergency Reception Department of Ibn Rochd Hospital in Casablanca and to formulate recommendations for improving the quality and continuity of care.

Methodology

Study Design

The present study was a Level 1 descriptive quantitative study, according to Fortin's classification [11]. It aimed to describe the factors influencing the management of prisoners by healthcare staff in the Emergency Reception Department (ERD), without manipulating variables or using a comparison group. This design provides an accurate description of the situation within a specific clinical setting and generates hypotheses for future research.

Study Setting

The study was conducted in 2018 in the Emergency Reception Department (ERD P29) of Ibn Rochd University Hospital (CHUIR) in Casablanca. At the time of the study, this department was known as the Emergency Reception Department (ERD P29). It has since been reorganized and is now designated as the Trauma Centre. A public institution with legal personality and financial autonomy, operating under the joint technical and financial supervision of the Ministry of Health and the Ministry of Finance, CHUIR has a capacity of 1,165 beds distributed across four facilities: Ibn Rochd Hospital, 20 August Hospital, the Children's Hospital, and the Dental Consultation and

Treatment Centre. The ERD provides uninterrupted 24-hour emergency care and comprises four functional units: reception, surgical consultation, medical consultation, and the resuscitation area. This department was selected because it is one of only two centres in the Greater Casablanca area authorized to provide care for prisoners, serves as a national reference centre for emergency care, and offers a sufficiently comprehensive database to investigate the research question.

Population and Sampling

The target population consisted of all medical and nursing staff working in the Emergency Reception Department of Ibn Rochd Hospital, comprising 50 healthcare professionals (31 nurses and 20 physicians, including emergency physicians, residents, and professors). Exhaustive sampling was used, with all staff members invited to participate. Fifty questionnaires were distributed, and 30 were returned, giving a response rate of 60%, which was considered acceptable for an exploratory descriptive study.

Data Collection Instrument

Data were collected using an anonymous self-administered questionnaire developed on the basis of the research problem and the literature review. The questionnaire comprised 23 items divided into four sections: (a) general characteristics (sex, age, and professional profile); (b) staff-related factors (experience in caring for prisoners, knowledge of regulations, management of restraints, presence of accompanying personnel, influence on attitudes, and behaviour adopted); (c) organizational factors (collaboration between prison services and the healthcare facility, and the perceptions of other patients); and (d) overall assessment of the quality of care and the main problems identified. The questionnaire included both closed-ended questions (single- or multiple-choice) and open-ended questions (free-text comments). Anonymity and confidentiality were guaranteed, and the participants' free and informed consent was obtained verbally before the questionnaires were distributed.

The questionnaire was designed to collect the perceptions, experiences, and opinions of healthcare professionals regarding the management of prisoners. It did not investigate the experiences or perceptions of prisoners or prison officers.

Data Analysis

The collected data were classified according to the main concepts of the study, then entered, analysed, and presented in tables (frequencies and percentages), before being interpreted in the light of relevant findings from the literature.

Ethical Considerations

In accordance with the ethical principles governing research on human participants [11], three principles were respected: (a) voluntary participation and informed consent; (b) strict confidentiality of the data collected; and (c) preservation of respondents' anonymity. No information that could identify the participants was collected.

Results

General Characteristics

Of the 50 questionnaires distributed, 30 completed questionnaires were returned and considered suitable for analysis, giving a response rate of 60%. The socio-demographic and professional characteristics of the sample are presented in Table 1. The majority of respondents (73%) were aged between 20 and 30 years, and the gender distribution was balanced (50% women and 50% men). State Registered Nurses (SRNs) represented the largest professional group (63%), followed by emergency physicians (17%), resident doctors (13%), and professors (7%). All respondents (100%) had previously provided care to at least one prisoner during their professional careers.

Table 1. Socio-demographic and Professional Characteristics of Healthcare Staff

Characteristic	**n**	**%**
Age		
20–30 years	22	73.33
30–40 years	6	20.00
40–50 years	1	3.33
50 years and over	1	3.33
Sex		
Female	15	50.00
Male	15	50.00
Professional Profile		
State Registered Nurse (SRN)	19	63.33
Emergency Physician	5	16.67
Resident Doctor	4	13.33
Professor	2	6.67

Source: Self-administered questionnaire, Emergency Reception Department, Ibn Rochd Hospital, 2018

Healthcare Staff-Related Factors

Table 2 summarizes the main findings relating to healthcare staff-related factors. Nearly nine out of ten respondents (86.66%) reported being unaware of the regulations governing the management of prisoners, whereas 70% expressed an interest in receiving training on this subject. Almost half of the respondents (46.66%) requested that prisoners remain handcuffed during treatment, and 67% provided care or performed examinations in the presence of accompanying personnel (law enforcement officers or prison security staff). Seventy per cent of participants reported feeling reassured by the presence of these accompanying personnel, although 67% acknowledged that their presence negatively affected compliance with professional secrecy and patient confidentiality. Furthermore, 73% stated that a patient's status as a prisoner influenced both their attitude and the care they provided. The most frequently reported behaviour was a feeling of insecurity (33.34%), followed by reduced empathy (16.67%) and fear (13.33%).

Table 2. Healthcare Staff-Related Factors Influencing the Management of Prisoners

Item	Yes, n (%)	No, n (%)
Aware of the regulations governing the management of prisoners	4 (13.34)	26 (86.66)
Wishes to receive training on the relevant regulations	21 (70.00)	9 (30.00)
Requests that prisoners remain handcuffed during treatment	14 (46.66)	16 (53.34)
Provides care in the presence of accompanying personnel	20 (66.67)	10 (33.33)
Feels reassured by the presence of accompanying personnel	21 (70.00)	9 (30.00)
Considers that the presence of accompanying personnel compromises professional secrecy	20 (66.67)	10 (33.33)
Changes attitude when the patient is a prisoner	22 (73.33)	8 (26.67)

Source: Self-administered questionnaire, Emergency Reception Department, Ibn Rochd Hospital, 2018.

Furthermore, when participants were asked to identify the factor that most influenced their attitude, stress and workload ranked first (42%), followed by department overcrowding (30%), the prisoner's criminal record (16%), and other factors such as the patient's behaviour or the nature of the illness (12%). These findings reflect the substantial impact of organizational conditions on the quality of the healthcare professional–patient relationship in an overcrowded emergency department.

Organisational and Environmental Factors

Table 3 presents the organizational factors identified. Sixty-seven per cent of participants considered the collaboration between prison services and their healthcare facility to be inadequate, reporting complex prison-to-hospital transfers, poor communication, and occasionally strained relationships between the two institutions. According to the healthcare staff, the presence of prisoners alongside other patients in the waiting area generated feelings of insecurity in 43.25% of cases, fear in 32.43%, and no particular feeling in 24.32%

Table 3. Organizational Factors and Overall Assessment of Prisoner Healthcare Management

Item	n	%
Collaboration between prison and hospital teams considered inadequate	20	66.67
Perceived impact of prisoners' presence among other patients:		
Insecurity	16	43.25
Fear	12	32.43
No particular feeling	9	24.32
Overall management of prisoners considered unsatisfactory	17	56.67
Staff identifying at least one problem hindering prisoner healthcare management	26	86.67

Source: Self-administered questionnaire, Emergency Reception Department, Ibn Rochd Hospital, 2018.

Overall, 56.67% of participants considered the healthcare management of prisoners in the Emergency Reception Department (ERD) to be unsatisfactory. They attributed this to department overcrowding, prolonged waiting times, the high prevalence of communicable diseases, the lack of training on the relevant regulations, poor organization between prison services and the hospital, and stigmatization by the general population. In addition, 86.67% (26/30) of respondents identified at least one problem hindering the management of prisoners within their healthcare facility.

Discussion

This descriptive study aimed to identify the factors influencing the management of prisoners by healthcare staff in the Emergency Reception Department of Ibn Rochd Hospital in Casablanca. The findings should be interpreted as reflecting the perceptions and professional experiences of the healthcare staff who participated in the survey rather than the experiences of prisoners or prison

officers. Although the findings cannot be generalized, they are consistent with observations reported in both the international and Moroccan literature and highlight several major structural and ethical challenges

Poor Knowledge of the Regulatory Framework Undermines the Healthcare Professional–Patient Relationship

The most striking finding concerns the widespread lack of awareness (86.66%) of the regulations governing the management of prisoners. This lack of legal knowledge prevents healthcare professionals from reconciling a patient's status as a prisoner with the provision of care that fully respects patients' rights and generates a sense of insecurity that influences their behaviour [10]. As McMillan [12] points out, it then becomes difficult to establish a relationship of trust between the healthcare professional and the patient, even though this relationship is fundamental to all healthcare practices. Ventéjoux and Hirschelmann [13] emphasize that professionals are confronted with a poorly defined situation for which no protocols exist, leading each individual to act according to personal judgement, thereby increasing inconsistencies in practice. It is unlikely that this will happen if the personnel in attendance are trained, as their *formation* is likely to be uniform.

This lack of awareness and training may be partly explained by the young age of the sample (73% aged 20–30 years), suggesting a large proportion of early-career professionals who may have had less exposure to the care of prisoners and received less training on their specific needs. Nevertheless, the strong interest expressed in receiving training (70%) represents an encouraging opportunity to strengthen both undergraduate and continuing professional education.

Professional Secrecy Compromised by the Presence of Accompanying Personnel

The fact that 67% of healthcare professionals provided care in the presence of accompanying personnel, and that 70% reported feeling reassured by their presence, whereas 67% acknowledged that this presence undermined professional secrecy and patient confidentiality, reflects a major ethical dilemma. On the one hand, the presence of security escorts responds to legitimate security concerns given the potential dangerousness of certain prisoners [14]. On the other hand, it infringes upon prisoners' privacy and hinders the establishment of a trusting relationship that enables patients to disclose their symptoms and healthcare needs [12].

These findings raise important ethical concerns regarding the balance between security requirements and prisoners' fundamental rights as patients. The British Medical Association [19] emphasizes that prisoners should receive healthcare equivalent to that available to the general population. Its guidance further establishes that prisoners should normally be examined and treated without restraints or prison officers present, unless an individual risk assessment identifies a substantial security threat.

These principles are particularly relevant to the present findings, as 66.67% of respondents reported providing care in the presence of accompanying personnel, and the same proportion acknowledged that this practice compromised professional secrecy. Although security precautions may be necessary in specific circumstances, they should be proportionate to the individual risk and should not unnecessarily interfere with clinical examinations, medical confidentiality or patient dignity.

The BMA guidance therefore provides a useful ethical framework for developing clear institutional protocols and improving collaboration between healthcare professionals and prison authorities. It should be considered that Britain's prison system is under great pressure and that there have been appalling cases of women prisoners giving birth while shackled in prisons in recent years.

It should be noted that the Emergency Reception Department investigated in the present study did not provide obstetric or maternity care. Women requiring childbirth were admitted directly to the maternity department. Consequently, situations involving women giving birth while restrained fell outside the scope of this study and were not encountered by the healthcare professionals surveyed.

The identification of stress and workload (42%) as the main factors influencing healthcare professionals' attitudes, followed by department overcrowding (30%), confirms that working conditions in the Emergency Reception Department (ERD) have a substantial impact on the quality of care provided to prisoners as well as to other patients. By its very nature, the ERD is an overcrowded department faced with a continuous influx of patients, and the admission of a prisoner under escort complicates procedures (patient movement, security, and confidentiality).

The inadequate collaboration between prison services and the healthcare facility, reported by 67% of participants, is consistent with the findings of Edge *et al*. [15], who highlighted that poor coordination and communication between prison and hospital services, together with the dominance of security requirements over clinical priorities, compromise confidentiality, patient

autonomy, and the continuity of care. Ventéjoux & Hirschelmann [13] emphasize that such tensions undermine institutional partnership and compromise established working procedures between the two institutions. Furthermore, the absence of a dedicated admission procedure exposes prisoners to public view in waiting areas, generating feelings of insecurity among other patients (43.25%) and **fear** (32.43%), which may result in discrimination and even prisoners refusing to accept healthcare.

Recommendations

In the light of the study findings and the literature reviewed, recommendations are proposed under four complementary areas. These recommendations are offered to inform decision-makers and encourage practical actions to improve the healthcare management of prisoners within public healthcare facilities.

Research

National multicentre studies on the healthcare management of prisoners should be supported and expanded across different types of healthcare settings (emergency departments, hospital wards, and prison healthcare facilities) in order to generate robust and comparable data. Qualitative research, particularly through in-depth interviews with healthcare professionals, prisoners, and prison staff, would provide a better understanding of the relational and organizational mechanisms. The establishment of a national database on medical transfers and the right to healthcare for prisoners would also facilitate the development and monitoring of public policies [2,16].

Education and Training

The inclusion, within the initial and continuing education of healthcare professionals (nurses, doctors, and healthcare assistants), of a dedicated module covering, among other topics, the regulations governing the management of prisoners, ethical principles (dignity, professional secrecy, and confidentiality), and communication skills specific to this population appears essential. The development of interprofessional training programmes for both healthcare and prison staff would promote mutual understanding and improve coordination. At the same time, the implementation of health education programmes for prisoners, particularly regarding hygiene, would help reduce the burden of disease within prison settings [17].

Practice

Several operational measures may be recommended: (a) modernizing the facilities and equipment of healthcare services providing care for prisoners; (b) establishing additional healthcare units within prison establishments, including specialist consultations to reduce the need for medical transfers [8,18]; (c) organizing prisoners' access to care within public hospitals through dedicated pathways that minimize public exposure; (d) allowing greater flexibility in certain security measures to facilitate the work of healthcare staff, particularly by removing handcuffs during treatment whenever the prisoner's level of risk permits [19]; and (e) ensuring that prisoners receive healthcare of a quality and continuity equivalent to that provided to the general public [20].

Management

At the institutional level, several actions should be prioritized: (a) establishing specialized secure units within public healthcare facilities, equipped with appropriate resources and staffed by personnel trained in the management of prisoners [20]; (b) developing a dynamic working protocol between prison services and hospital services to improve collaboration [16]; (c) introducing systematic screening on entry into prison for communicable diseases, including tuberculosis, sexually transmitted infections, and hepatitis B and C, given their high prevalence in prison settings [20]; and (d) addressing prison overcrowding, identified in the literature as the main risk factor for the deterioration of prisoners' health [17].

Conclusion

The evolution of the legal status of prisoners has led to the recognition of their fundamental rights, including the right to healthcare, the right to information, respect for medical confidentiality, and human dignity. Nevertheless, the present study demonstrates that, in practice, these rights continue to face numerous challenges within the Emergency Reception Department of Ibn Rochd Hospital in Casablanca. Healthcare staff's lack of knowledge of the relevant regulations, breaches of professional secrecy resulting from the presence of security escorts, the stigmatization of prisoners, and inadequate collaboration between prison and healthcare institutions all contribute to a standard of care considered unsatisfactory by more than half of the healthcare professionals surveyed.

These findings call for a multidimensional approach combining professional training, the development of interinstitutional protocols, the establishment of dedicated units, and measures to address prison overcrowding. The situation of ill prisoners will only become truly comparable to

that of patients in the community if progress is achieved within two cultures—healthcare and prison services—that have long remained at odds. Despite its limitations, the present study seeks to contribute to a better understanding of this issue and to encourage, at the national level, further research and practical initiatives.

Because this study explored only healthcare professionals' perspectives, future qualitative and mixed-methods studies should also investigate the experiences of prisoners and prison officers to provide a more comprehensive understanding of healthcare delivery in custodial settings. The right to healthcare for all applies to prisoners. Their rights as patients must not be diminished.

Reference

[1] Mulgrew, R., 2023, Prisoner lives cut short: The need to address structural, societal and environmental factors to reduce preventable prisoner deaths. *Human Rights Law Review* **23**(2), ngad006.

[2] Abouzahir, H., Nya, S., Belhouss, A., & Benyaich, H., 2020, Aspects éthiques et déontologiques de la médecine pénitentiaire. *Droit, Déontologie & Soin* **20**(3), 313–318. https://doi.org/10.1016/j.ddes.2020.07.012

[3] Alves da Costa, F., Verschuuren, M., Andersen, Y., Stürup-Toft, S., Lopez-Acuña, D., & Ferreira-Borges, C., 2022, The WHO Prison Health Framework: A framework for assessment of prison health system performance. *European Journal of Public Health* **32**(4), 565–570. https://doi.org/10.1093/eurpub/ckac020

[4] Wilper, A. P., Woolhandler, S., Boyd, J. W., Lasser, K. E., McCormick, D., Bor, D. H., & Himmelstein, D. U., 2009, The health and health care of U.S. prisoners: Results of a nationwide survey. *American Journal of Public Health* **99**(4), 666-672. https://doi.org/10.2105/AJPH.2008.144279

[5] Branchu, C., Guedj, J., Zientara-Logeay, S., De Blasi, M., Lopez, F., & d'Almeida, S. (2015). *Évaluation du plan d'actions stratégiques 2010–2014 relatif à la politique de santé des personnes placées sous-main de justice* (Rapport n° 2015-050R / IGSJ n° 58-15). Inspection générale des affaires sociales (IGAS) & Inspection générale des services judiciaires (IGSJ). Ministère de la Justice. https://www.justice.gouv.fr/sites/default/files/migrations/portail/art_pix/Evaluation-politique-de-sante-PPSMJ_Rapport%20definitif.pdf

[6] Alaoui, K., 2015, 3 novembre, *La prise en charge médicale en milieu carcéral, étudiée lors d'un colloque national à Rabat*. Maroc Hebdo. https://maroc-hebdo.com/article/la-prise-en-charge-medicale-en-milieu-carceral-etudiee-lors-dun-colloque-national-a-rabat

[7] Délégation générale à l'administration pénitentiaire et à la réinsertion., 2023, *Rapport d'activité 2023*. Royaume du Maroc. https://www.dgapr.gov.ma/publication/pdf/Rapport-activite%CC%81%20DGAPR%20fr.pdf

[8] Hazan, A., 2015, 16 juin, *Avis du 16 juin 2015 relatif à la prise en charge des personnes détenues au sein des établissements de santé*. *Journal officiel de la République française*, n° 162, texte n° 148. https://www.legifrance.gouv.fr/jorf/id/JORFTEXT000030891422

[9] Centre d'Études en Droits Humains et Démocratie, & Centre pour la Gouvernance du Secteur de la Sécurité, 2021, *La situation des prisons au Maroc à la lumière des standards internationaux, de la législation nationale et de la nécessité des réformes (2016–2020).* https://www.dcaf.ch/sites/default/files/publications/documents/La_situation_dans_les_prisons_au_Maroc.pdf

[10] Observatoire international des prisons – section française. (2010, avril). *Contribution de l'Observatoire international des prisons – section française sur le traitement des personnes détenues dans les établissements pénitentiaires français (44e session du Comité contre la torture des Nations Unies : Examen des 4e à 6e rapports périodiques de la France).* https://tbinternet.ohchr.org/_layouts/15/TreatyBodyExternal/DownloadDraft.aspx?key=MmP8u%2F8XcdZOpQI9pMq3zL41E81AbbUodVNx%2FbQ6KVJCM6n4lxgokkzZo8D8yBm9

[11] Fortin, M.-F., & Gagnon, J., 2016, *Fondements et étapes du processus de recherche : Méthodes quantitatives et qualitatives* (3e éd.). (Montréal, Québec, Canada: Chenelière Éducation).

[12] McMillan, J., 2022, Trust and medical ethics. *Journal of Medical Ethics* **48**(3), 153-153. https://doi.org/10.1136/medethics-2022-108199

[13] Ventéjoux, A., & Hirschelmann, A., 2014, Soins pénalement ordonnés et positionnements professionnels : Des pratiques au carrefour de la Santé et de la Justice. *Pratiques Psychologiques* **20**(2), 95–110. https://doi.org/10.1016/j.prps.2014.04.001

[14] Mendès-Leite, R., 2016, Publications de Rommel Mendès-Leite : 1985-2015. In: M. Banens (ed.), *Des mots, des pratiques et des risques*. (Lyon : Presses universitaires de Lyon). https://doi.org/10.4000/books.pul.24208

[15] Edge, C., Stockley, R., Swabey, L., King, E., Decodts, F., Hard, J., & Black, G., 2020, Secondary care clinicians and staff have a key role in delivering equivalence of care for prisoners: A qualitative study of prisoners' experiences. *eClinicalMedicine* **24**, Article 100416. https://doi.org/10.1016/j.eclinm.2020.100416

[16] Frank, J. W., Linder, J. A., Becker, W. C., Fiellin, D. A., & Wang, E. A., 2014, Increased hospital and emergency department utilization by individuals with recent criminal justice involvement: Results of a national survey. *Journal of General Internal Medicine* **29**(9), 1226–1233. https://doi.org/10.1007/s11606-014-2877-y

[17] World Health Organization Regional Office for Europe., 2023, *Principles for making prisons and places of detention resilient to infectious diseases, including epidemic and pandemic threats* (WHO/EURO:2023-8262-48034-71157). World Health Organization Regional Office for Europe. https://iris.who.int/handle/10665/373552

[18] Bengoa, A., Mateo-Abad, M., Zulaika, D., Vergara, I., & Arroyo-Cobo, J. M., 2018, Availability and use of healthcare resources in prisons according to the transference model: a comparative study in Spain. *Revista espanola de sanidad penitenciaria* **20**(1), 21–29. https://pmc.ncbi.nlm.nih.gov/articles/PMC7525130/pdf/main.pdf

[19] British Medical Association, 2025, *The medical role in restraint and control: Custodial settings: Guidance from the British Medical Association* (Originally published August 2009; revised March 2025). (London: British Medical Association). https://www.bma.org.uk/media/wffbkpyv/medical-role-in-restraint-updated-2025.pdf

[20] World Health Organization, 2021, *WHO consolidated guidelines on tuberculosis: Module 2: Screening – Systematic screening for tuberculosis disease*. (Geneva: World Health Organization). https://iris.who.int/handle/10665/340255

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Factors Governing Biofilm Formation in Drinking Water Networks: A General Survey

Mourad Elgoulli [a], Ikhlas Hani Chennoufi [b], Soukaina Mitro [c], Hafida Zahir [d], Mostafa Ellouali [e], Hassan Latrache [f]*

Industrial and Surface Engineering Laboratory, Team Bioprocesses and Biointerfaces, Faculty of Science and Techniques, Sultan Moulay Slimane University, BP 523 Beni Mellal, Morocco

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[a] **ORCID:** 0000-0002-2866-1367 ; **Email:** mouradelgoulli2015@gmail.com

[b] **ORCID:** 0000-0002-0532-9943 ; **Email:** ikhlashani86@gmail.com

[c] **ORCID:** 0000-0003-0049-5165 ; **Email** : mitrosoukaina@gmail.com

[d] **ORCID:** 0000-0001-8663-1775; **Email** : hafidazahir@yahoo.com

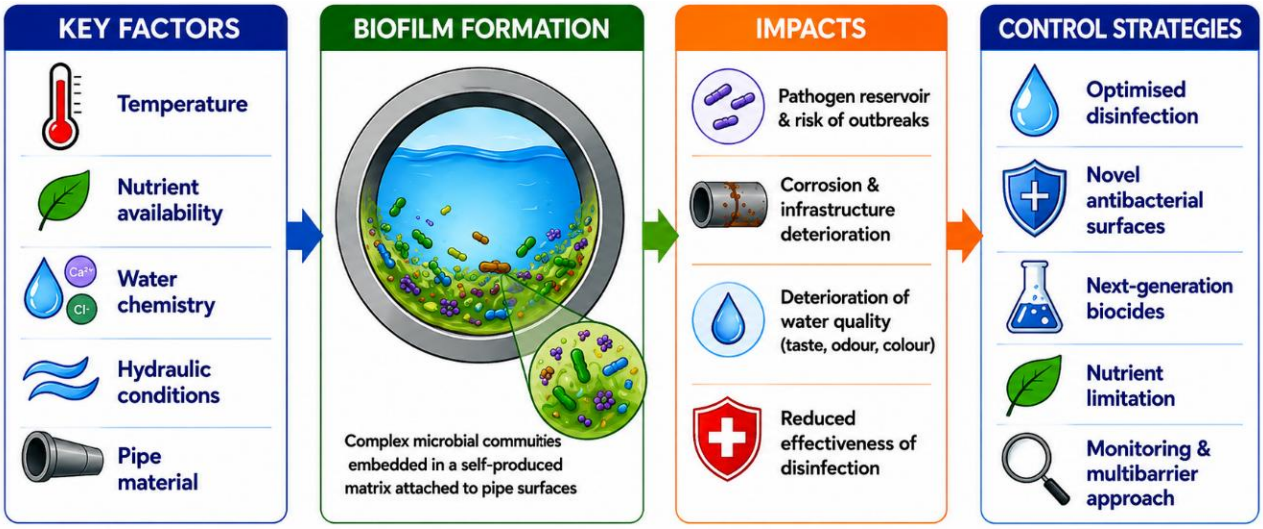
[e] **ORCID:** 0000-0002-1337-885X ; **Email** : m.ellouali@hotmail.com

[f] **ORCID:** 0000-0003-2297-9320 ; **Email** : latracheh@yahoo.fr

* ***Corresponding author:*** Hassan Latrache ; ***Email*** : latracheh@yahoo.fr ; Phone number: +212651732454

Graphical Abstract

The drinking water distribution system (DWDS) leads to the consumer's tap. Microbial biofilms can colonize pipe surfaces, act as reservoirs for pathogens, accelerate infrastructure decay, and degrade organoleptic water quality. Their resistance to conventional disinfection, including chlorine, together with their regenerative capacity, makes eradication difficult. Biofilm proliferation is governed by temperature, nutrient availability, water chemistry, hydrodynamics, and pipe material. Consequently, safeguarding water quality requires integrated multi-barrier strategies, including novel antibacterial surfaces, next-generation biocides, and stringent nutrient limitation to effectively control biofilm resilience and protect public health.



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Abstract: The drinking water distribution system (DWDS) is often threatened by the dangerous threat of biofilms as these intricate microbial consortia aggressively colonize pipe surfaces and act as reservoirs for pathogens which accelerate the infrastructure decay and degrade the organoleptic quality. Their resistance to conventional disinfection which includes chlorine, and their powerful regenerative capacity make eradication strategies ineffective. Environmental variables that govern biofilm proliferation include temperature, nutrient availability, water chemistry, and hydrodynamics, as well as the pipe material. The safeguarding of the water quality needs to be transformed by integrated and multi-barrier strategies. This necessitates also the implementation of advanced solutions like novel antibacterial surfaces, next-generation biocides, and stringent nutrient limitation to interrupt the resilience of biofilm and to protect public health.

Keywords: *Biofilm, Drinking water, Disinfection, Factors.*

Introduction

In a DWDS, the bacterial biomass is associated with biofilms (Figure 1) rather than being suspended in the water, where their structure is influenced by numerous factors (hydraulic conditions, pipe materials, etc.) [1]. Moreno *et al.* [2] estimate that 95 % of the total biomass is attached to the pipe walls, compared to only 5 % in the water (Figure 2).

Biofilms act as reservoirs for pathogens, giving rise to outbreaks of infection and incurring considerable healthcare costs [3]. Fragments of biofilm can break away and contaminate water, causing outbreaks of gastroenteritis and other diseases [4]. Studies have shown that a greater bacterial diversity was observed in biofilms compared to planktonic water, with the families *Pseudomonadaceae* and *Nitrospiraceae* being the most common [5]. Biofilms accommodate a variety of pathogens (*Vibrio cholerae*, *Salmonella spp.*, *Escherichia coli*, *Legionella pneumophila*, *Mycobacterium avium*, *Pseudomonas aeruginosa*) as well as antibiotic resistance genes [6], which are responsible for legionellosis, pneumonia and other diseases [7]. It has been suggested that bacteria present in the form of biofilms in the DWDS are metabolically active and culturable, being potentially able to contaminate water with pathogens [8].

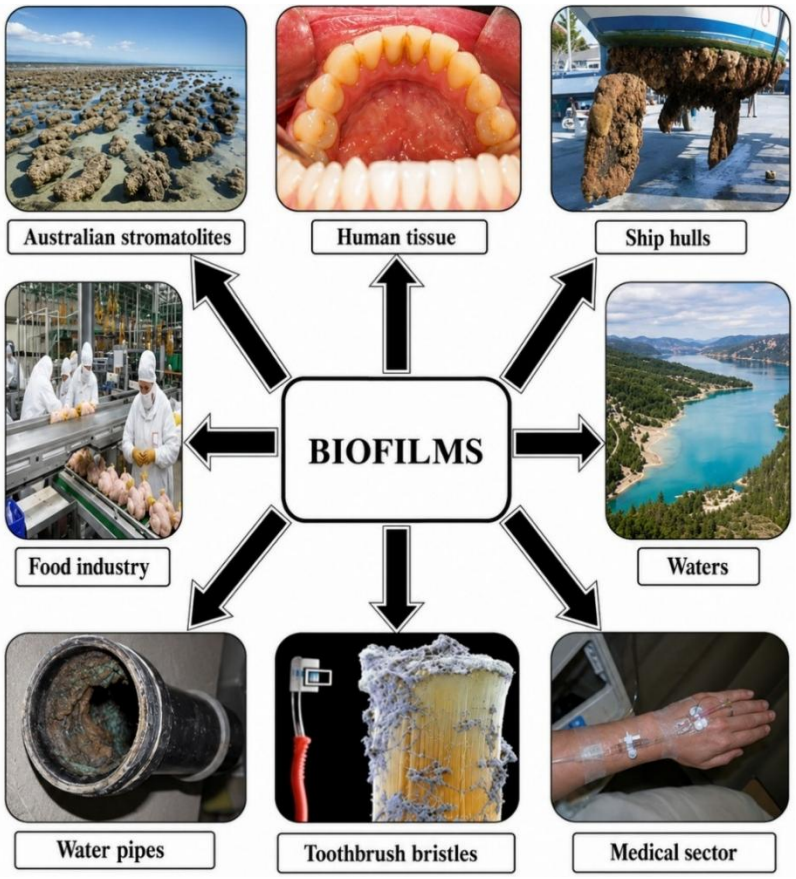


Figure 1. Representative environments where biofilms naturally develop and persist across environmental, industrial, domestic, and clinical settings

Studies note that biofilms are composed of metabolically heterogeneous populations; only some cells are highly active, and others have reduced or dormant metabolism controlled by gradients of oxygen, nutrients, and electron acceptors, determining specific physiological groups of bacteria in the biofilm [9,10]. Copper surfaces and copper-containing surfaces may also reduce the cultivability and metabolic activity of bacteria in biofilms by several orders of magnitude (or log) by eliminating viable and metabolically active cells from the biofilm through membrane damage and contact poison mechanisms [11]. Furthermore, the activity of biofilms can cause undesirable odours, tastes and discolouration in water through the accumulation of organic matter and metals [12].

The formation of biofilms in DWDS (Figure 3) creates technical (especially corrosion and clogging), economic, operational, and maintenance-related challenges [9]. First, biofilms may promote corrosion processes in iron pipes and cement-based materials through electrochemical interactions and the impact of metabolites and specific redox mechanisms [13]. For instance, bacteria can adhere to corroded areas and roughness on the surface of the pipe, leading to enhanced biofilm formation and localized corrosion [13-15]. Second, several studies have revealed that corrosion products from iron materials can facilitate biofilm development, diminishing disinfectant efficacy and promoting microbiologically influenced corrosion [12]. It is reported that such organisms contribute to the deposition of particles, scale, and suspended matter, resulting in clogging, discoloration, and, in extreme instances, total blockage [12]. Specifically, the adhesion of biofilms and inorganic material (e.g., iron and manganese) to the inner walls of the pipes decreases the lumen of the pipe, increasing the pressure while lowering the outflow [12,16]. Such impacts require extensive cleaning and replacement of the corroded and blocked pipes, incurring significant costs.

In addition, biofilm-covered stagnant water promotes poor water quality and encourages the proliferation of organisms [17,18]. The number of bacteria increases substantially following stagnation. For example, Li *et al.* [19] demonstrated that when exposed to stagnant conditions, bacteria grew rapidly in the pipe biofilm. Finally, the chemical composition of the material influences the characteristics of biofilm as well as the release of dissolved organic carbon into the water [20]. Rahmatika *et al.* [21] discovered that when compared to the initial content (<103 cells/mL), total cell counts (TCC) and dissolved organic carbon (DOC) values rose exponentially (6.0 × 105 cells/mL and 5.2 mg C/L, respectively) in the water stored inside the cross-linked polyethylene.

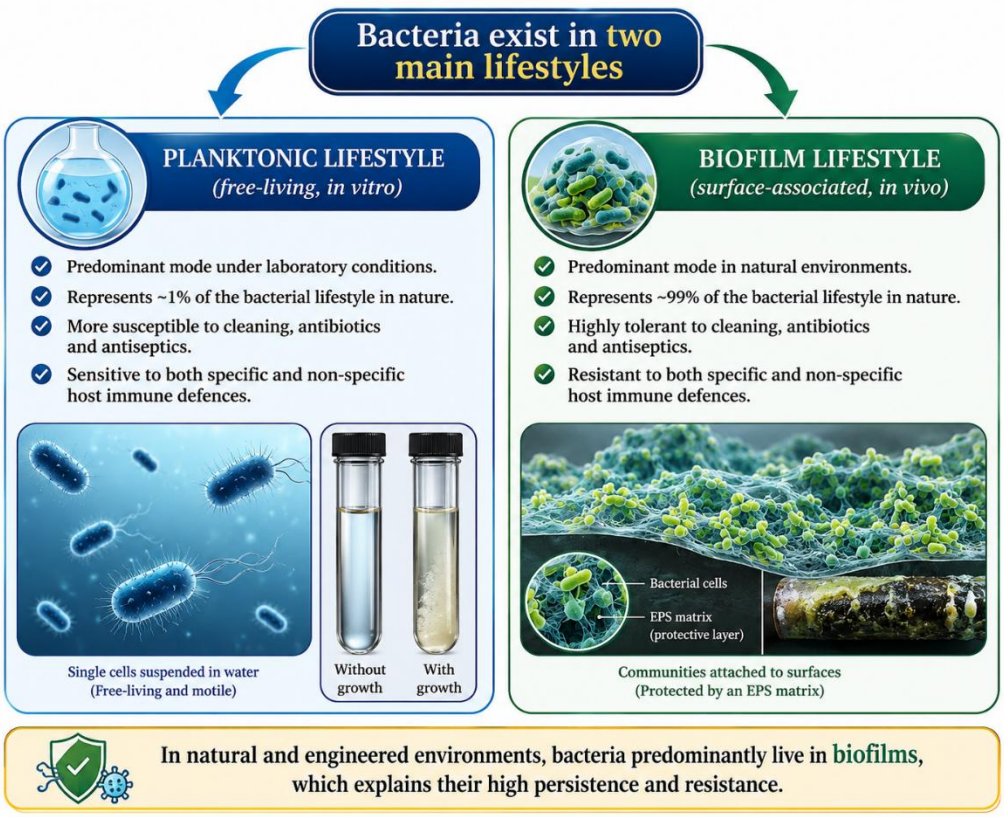


Figure 2. Comparison between planktonic and biofilm lifestyles of bacteria

Biofilms typically possess many defense mechanisms against environmental stress. Their exopolysaccharides (EPS: extracellular polymeric substances) have been shown to provide protection from disinfectants or osmotic stress [4,22]. For instance, biofilms can resist disinfectants such as chlorine in various ways including the EPS diffusion barrier [21], decreased metabolism of cells inside the biofilm [23,24], production of neutralizing enzymes [22,23]. This resistance includes interactions with protozoa that can shelter pathogens (e.g., *Legionella*) are also involved in this resistance [25]. Indeed, *Legionella* was even found to be ubiquitous in biofilms and source water which highlights its importance as an indicator of treatment efficacy [26,27]. Moreover, iron and steel metal pipes are commonly degraded by bacteria, which also decreases the efficiency of disinfectants through chlorine reaction with the metal surface [28]. As a result, biofilms resist the disinfectant action of chlorine and chloramines and other disinfectants allowing the proliferation of chlorine-resistant organisms such as *Mycobacterium spp.* or *Helicobacter pylori* [29]. Therefore, there is a disinfection dilemma with biofilms, as they can regrow even at high chlorine concentrations (10 mg/L).

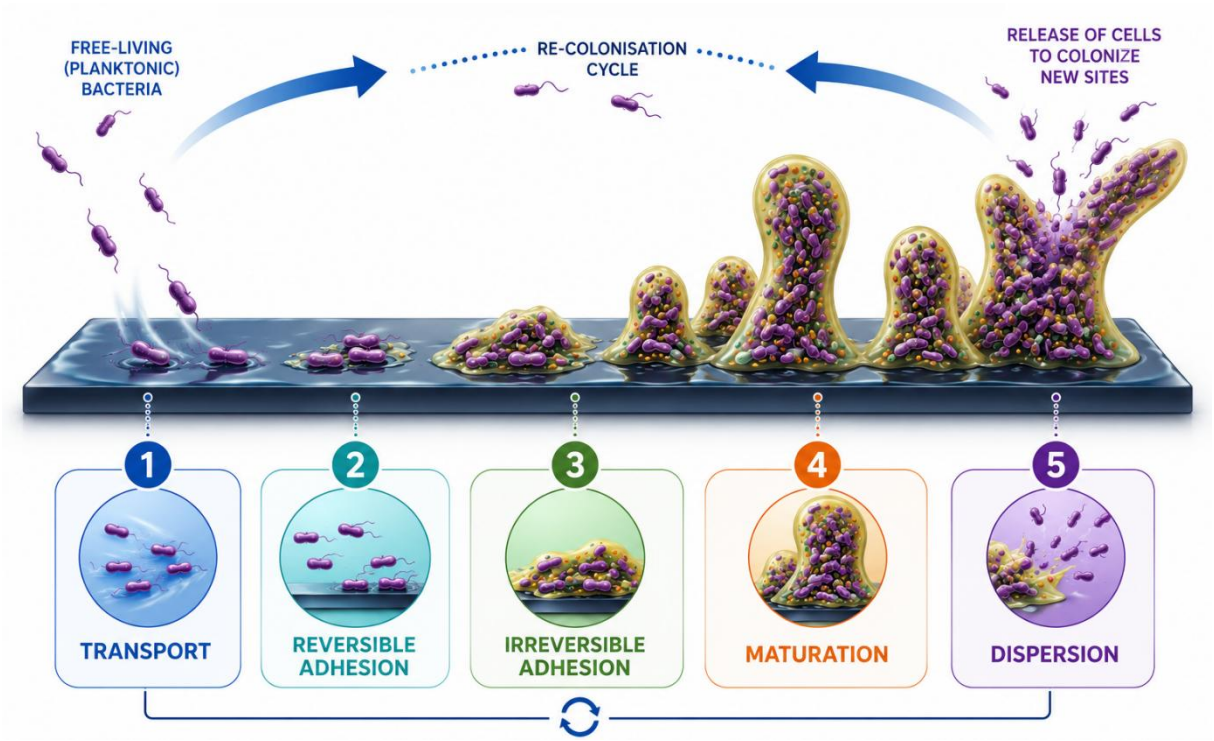


Figure 3. Schematic representation of the sequential stages of biofilm formation and development

Biofilms are a serious threat to public health and infrastructure. There is not enough study of the combined effect of environmental, technological and anthropogenic factors (temperature, chemical composition of water, nutrients, properties of the substrates, disinfectants, and hydrological characteristics) on their formation. Accordingly, this general survey offers a critical analysis of the factors influencing biofilm formation, supplemented by (i) a comparative assessment of recently developed innovative control strategies and (ii) a practical methodology for analysing distribution networks, intended for researchers and managers. The focus is on conventional drinking water systems, excluding industrial networks or domestic hot water systems, although certain principles may apply to them. Consequently, the central question is which factors are decisive for their prevention and control.

Factors governing biofilm formation

Physicochemical factors of water

Temperature

Temperature is a key variable governing biofilm dynamics and the microbiological integrity of water, yet it is not a mere growth promoter [30]. Indeed, it affects microbial communities in a non-

linear manner [31-33]. At the molecular level, it alters the physicochemical properties of the bacterial surface (hydrophobicity, electron-donating character) and directs metabolism towards the production of EPS, which is essential for the structure and resilience of the biofilm [30]. Responses vary by species: some pathogens (e.g. *Salmonella*) maximize biofilm formation at moderate temperatures (about 20–22°C); others (e.g. Vibrio) enhance it at cooler temperatures [34]. At the community level, warming restructures populations by favouring certain genera (*Pseudomonas*, *Fusarium*) and alters the viscosity of EPS, which may paradoxically lead to detachment and downstream dispersal [32,35].

Although health authorities recommend temperatures above 55–60°C to combat planktonic pathogens (notably *Legionella*), biofilms offer substantial protection against such temperatures [36]. The optimum temperature for biofilm growth is not certain. Some studies suggest >45°C, others a peak at 45°C, with these discrepancies attributable to the composition of the communities and the experimental contexts [34]. Furthermore, temperature acts indirectly by promoting the release of dissolved organic carbon (DOC) from pipework materials (notably a 7.2-fold increase in release at 60°C), thereby stimulating microbial regrowth and reducing the efficacy of disinfectants [32]. Figure 4 summarizes these multiple mechanisms.

Thermal management offers targeted solutions among control strategies. For example, Lamas *et al*. [34] demonstrated that maintaining a temperature of 45°C in shower heads effectively reduces active microbial populations and pathogens. But, the application of this approach to all DWDS networks is severely limited by (i) inevitable temperature fluctuations, particularly in secondary sections, and (ii) the complex and non-linear responses of multi-species biofilms to heat. Consequently, this approach is mainly relevant for domestic hot water systems in large buildings (hospitals, hotels) and is not a universal solution for cold-water networks, where temperature control is difficult.

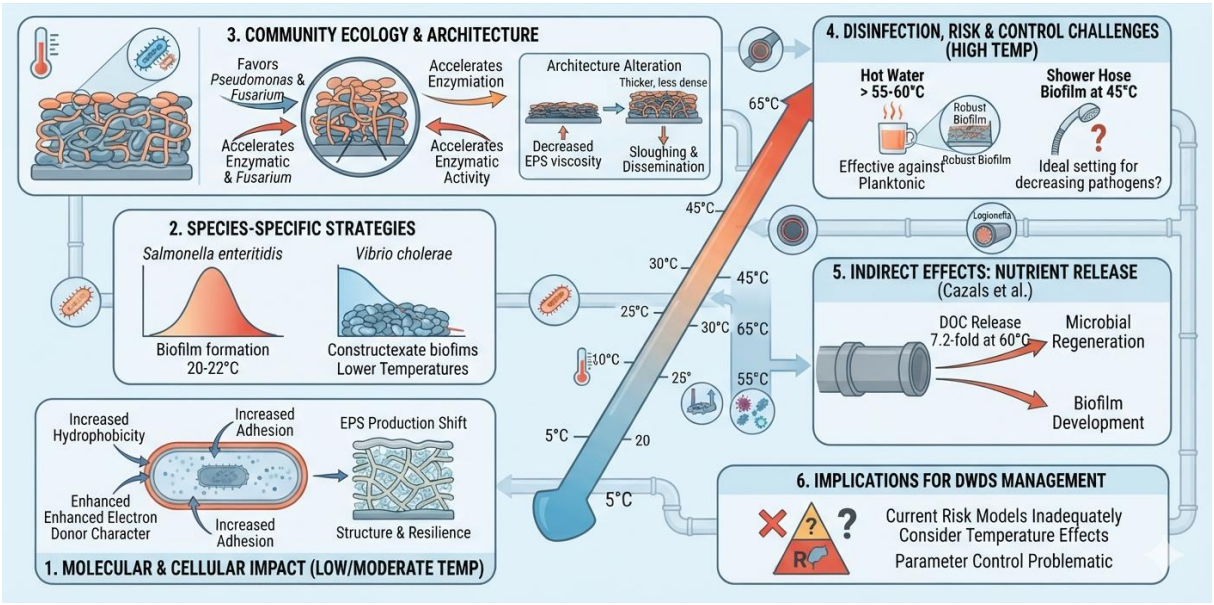


Figure 4. Temperature: a nuanced regulator of biofilm dynamics in drinking water

pH

pH is a key determinant of biofilm behaviour (Figure 5), integrating physicochemical and biological pathways [37]. By altering the electrostatic environment at solid–liquid interfaces, pH influences the chance of bacterial adhesion: as pH approaches the isoelectric point, electrostatic repulsion weakens, reducing the energy barrier to attachment and promoting early colonization [37]. Changes in pH alter surface hydrophobicity, making substrates more adhesive. These physicochemical effects interact directly with metabolic activity: conditions conducive to nitrification, for example, favour autotrophic populations but cause local acidification, which can, paradoxically, enhance adhesion to materials such as PVC [37,38]. This coupling is, however, bidirectional: changes in pH, particularly sudden or extreme ones, disrupt the structural integrity of mature biofilms by weakening the extracellular matrix, causing detachment with direct consequences for water quality [37,39].

Sensitivity to pH is particularly evident in the case of *Salmonella spp.*, where recent studies show that biofilm formation is optimal in a slightly acidic environment (pH 5.5–6.6), whereas extreme conditions (pH 4.4–4.5) completely inhibit it [40]. These findings contradict earlier studies which suggested there was no effect, and highlight the importance of the experimental context and the strains studied.

pH control can be used as a preventive measure. Indeed, Tran *et al.* [39] demonstrated that maintaining a slightly acidic pH of 5.5-6 inhibits formation of *Bacillus subtilis* biofilm, most likely

through altered EPS matrix production. Applicability in real drinking water systems is limited by two factors: (i) regulations call for a pH of 6.5-9.5, excluding too acidic solutions, and (ii) the acidic conditions accelerate corrosion of metal (cast iron, copper, steel) pipes which leads to metal leaching and infrastructure damage. Hence, this approach is restricted to specific applications, e.g., closed-loop industry circuits or pre-treatment steps.

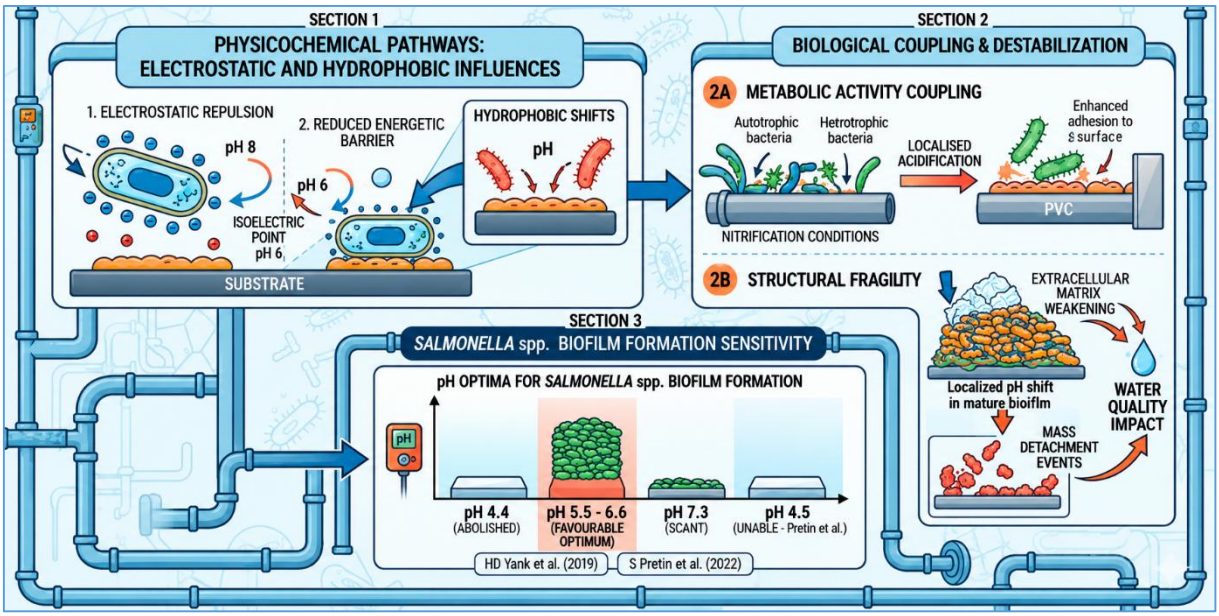


Figure 5. The critical role of pH in biofilm behavior

Nutrient availability

Nutrient availability is a major factor controlling biofilm formation in DWDS (Figure 6). Its role is often reduced to merely stimulating growth, but an approach based solely on the Redfield ratio (C:N:P) is too narrow to understand the mechanisms of microbial adaptation to different nutritional conditions [35,41]. Nutrient limitation does not necessarily reduce biofilm formation; on the contrary, it may select for stress-tolerant populations and favour species with an increased ability to colonize nutrient-rich surface niches [35]. Furthermore, high concentrations of ammoniacal nitrogen (NH_4^+) promote the growth of nitrifying bacteria, significantly altering the composition and biogeochemical functions of the community [38].

The interactions between nutrition and adhesion go beyond the mere supply of nutrients required for colonization. To illustrate, ions present in tap water alter the surface properties of bacteria (hydrophilicity, electron-donating character) and promote adhesion, irrespective of cell density or nutritional status [42,43]. The study by Montoya-Pachongo *et al*. [44] shows that nutritional deficiency reduces EPS production and the adhesive properties of biofilms, in line with the work of Zhang *et al*. [41] and Desmond *et al*. [24]. At the community level, nutrient gradients within the

biofilm allow the coexistence of microorganisms with opposing metabolisms (methanogens/methanotrophs), and the ability to use complex carbon sources (humic substances) via extracellular digestion confers resilience to fluctuations [23,41].

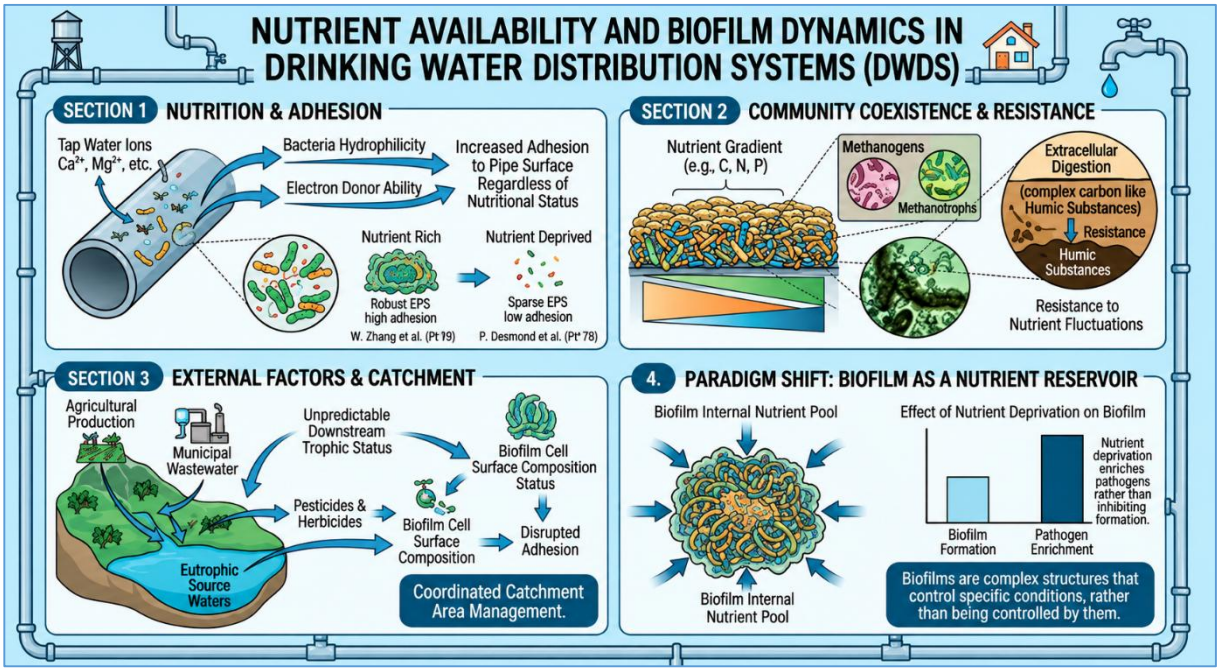


Figure 6. Nutrient availability and biofilm dynamics in DWDS

The nutrient load from source waters (eutrophication, agricultural discharges) directly influences the trophic status of downstream biofilms [42,43,45]. The intrusion of pesticides and herbicides into groundwater can also alter the chemical composition of cell surfaces and disrupt cell adhesion, highlighting the need for integrated catchment management [42,43,45]. Nutrient deficiency does not necessarily inhibit biofilm formation, but may promote the enrichment of pathogens, particularly as the biofilm itself acts as a nutrient reservoir regardless of the quality of the circulating water.

Limiting the availability of nutrients – though difficult to achieve in a DWDS – can be enhanced by careful choices of materials. The use of materials with low dissolved organic carbon (DOC) leaching is a promising avenue, as illustrated by Cazals *et al*. [32], who observed a 7.2-fold increase in DOC leaching at 60°C. Anti-leaching coatings, currently under development, could offer a complementary solution for reducing the bioavailability of carbon in pipes, although their durability and long-term effectiveness under real-world conditions remain to be demonstrated.

Operational and treatment factors

Water chlorination

Reliance on disinfectant residues as the primary barrier against microbial proliferation in DWDS ignores the adaptability of biofilms. The matrix of extracellular polymeric substances (EPS) greatly impedes the penetration of biocides [4,22]. Further, the natural degradation of disinfectants through reaction with organic matter and the biofilm itself makes regrowth inevitable [49]. The persistence of biofilms under continuous disinfection pressure, evidenced by recurrent deterioration in water quality (turbidity, colour, biocorrosion), exposes a fundamental flaw in strategies that treat bulk water chemistry as a substitute for microbial control of surfaces [46,47].

Disinfection procedures also have a selective effect on microbial communities: multi-species biofilms show greater tolerance to chlorine than pure cultures, probably through synergistic interactions [46]. Thus, monochloramine may promote the proliferation of opportunistic pathogens such as *Legionella spp.* or nitrifying bacteria, depending on the concentrations applied [47]. Chlorinated solutions, tend to homogenize the composition of microbial communities [26]. At sublethal concentrations (0.75–1 mg/L), chlorine can paradoxically stimulate the adhesion and cultivability of Pseudomonas aeruginosa, suggesting adaptive responses that precondition the cells for increased resistance [48,49]. Exposure to chlorine can induce antibiotic resistance through mutagenesis and horizontal gene transfer, or generate viable but non-cultivable (VBNC) forms capable of re-emerging at a later stage [50]. Finally, the formation of by-products and undesirable flavours may affect consumer confidence [16].

Disinfection reveals complex trade-offs: free chlorine and chlorine dioxide act quickly but have poor penetration; monochloramine penetrates better but is generally less effective [47]. Concentrations below 2 mg/L are insufficient, and changes in disinfectant (e.g. replacing chlorine with chloramine) can destabilize existing biofilms and mobilize contaminants and pathogens [51]. Furthermore, upstream treatments influence biofilm potential: coagulation and filtration reduce bacterial loads, but granular activated carbon (GAC) filters can enrich antibiotic resistance genes (ARGs) and biofilm-forming genera such as Pseudomonas, thereby seeding downstream systems [50,52].

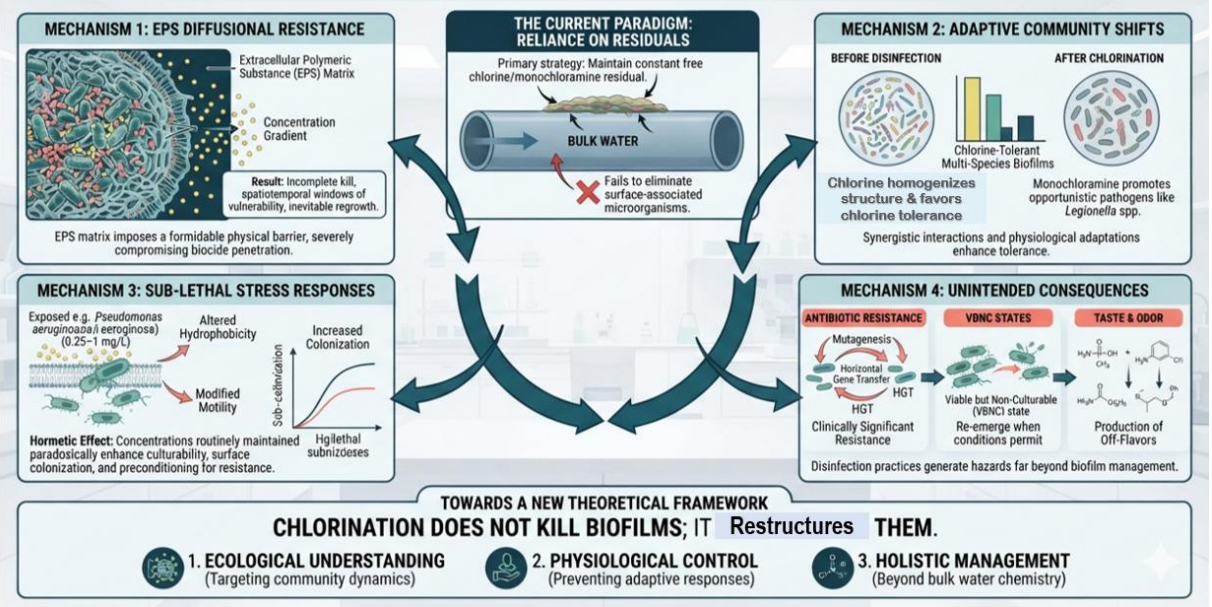


Figure 7. Rethinking disinfection: the paradox of biofilm adaptation in drinking water systems

Beyond traditional biofilm-control strategies, a paradigm shift is needed. Rather than seeking to 'kill' biofilms, emerging approaches aim to weaken them or prevent their formation. Table 1 shows that, to date, no innovative strategy (Advanced physical disinfection (UV-LED, cold plasma, electroporation), Combined disinfection approaches (alternating chlorine/monochloramine, chlorine + UV)) offers a universal solution. Their effectiveness, often demonstrated in the laboratory, has yet to be validated under real-world network conditions, where the diversity of strains, the presence of organic matter and hydraulic fluctuations complicate the results. These approaches should be regarded as complements to basic treatment, rather than as alternatives. Figure 7 summarizes this paradox: disinfection, as currently practised, does not 'kill' biofilms but 'restructures' them, promoting the emergence of resistant strains and VBNC states, which necessitates a rethinking of control paradigms [6,52].

Hydrodynamics

Hydraulic conditions are the dominant physical driver of the ecology and integrity of biofilms in drinking water networks. The interaction between flow rate, pressure and flow regime determines the fundamental balance between biofilm accumulation and stability [53,54]. The shear stresses generated by turbulent flow exert a strict selective pressure, leading to compact and stable communities that are, however, more resistant to chemical removal [53]. Conversely, areas of low flow (end points of the network, dead spots) promote particle sedimentation and the accumulation

of nutrients, creating reservoirs of microbial proliferation that are protected from residual disinfection [17]. The decoupling of hydrodynamics from disinfectant transport makes these stagnant zones critical points for the regrowth of opportunistic pathogens.

The destabilizing impact of transient events (flushing, pressure surges, daily variations in flow rate) is underestimated. These disturbances can dislodge mature biofilms, causing detachments that are not limited to the resuspension of inert particles: they release metabolically active microorganisms into the water, directly compromising biological stability and manifesting as problems with turbidity and colour [63]. Hydraulic management therefore manifests competing effects: flow regimes that favour accumulation create the potential for subsequent severe mobilizations [54,55].

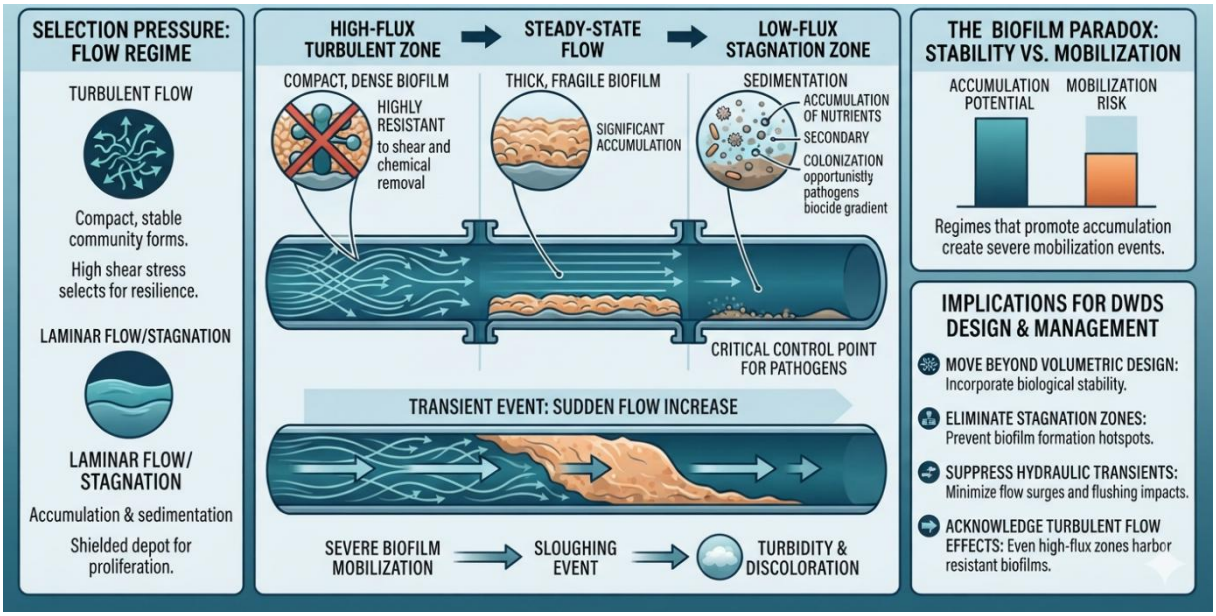


Figure 8. Hydraulic control: the dominant driver of biofilm ecology in DWDS

Recent advances in biofilm control have focused on active hydraulic management approaches. For example, Zeidan and Ostfeld [54] propose the use of scheduled flushing using controlled hydraulic transients to dislodge biofilms. This requires controlled variations in flow velocity, the kinetic energy of which detaches sessile communities without causing significant deterioration in water quality. The effectiveness of these approaches depends on the critical velocity specific to each type of biofilm and material, and their implementation requires accurate hydraulic modelling of the network to avoid excessive discharges or damage to infrastructure. These strategies have not yet been validated on a large scale.

Hydraulic design assumptions must incorporate biological stability criteria. The suppression of transients and the elimination of stagnation zones are key measures for reducing the risk of biofilm development, as summarized in Figure 8.

Material and infrastructural factors

The surface properties of pipes determine the structure of the ecological community [27,56]. Metal surfaces, because of conditions created by corrosion, promote greater bacterial growth that is qualitatively different from that observed on polymers [14]. The nodules formed on corroded metals provide favourable niches for long-term proliferation. Corrosion alters the physicochemical parameters of the water (disinfectant consumption, metal leaching) and promotes nitrification [15]. Conversely, polymer surfaces, although harbouring generally lower bacterial densities, can selectively enrich hydrophobic pathogens such as *Legionella*, whose adhesion is favoured by the surface chemistry [57]. The leaching of plasticizers and antioxidants can also provide nutritional resources for microbial communities [58]. Furthermore, the antimicrobial properties of copper are temporary: they reduce biomass in the short term, but bacteria such as *Pseudomonas aeruginosa* can enter a VBNC state and then re-emerge once the stress has been removed, and corrosion ultimately undermines this ability [11,22]. The age of infrastructure universally amplifies these effects, with corrosion products, organic deposits and mature biofilms creating heterogeneous environments that resist conventional measures [46,47]. Finally, surface roughness and the conditioning film interact with the material's properties to determine colonization, yet this film gradually masks the initial characteristics, rendering surface-level distinctions less relevant as the biofilm matures [26,56].

The selection of materials can therefore only be optimized in conjunction with active control strategies.

Anti-corrosion coatings with controlled release of biocides represent a promising control strategy. Emelyanenko *et al*. [59] demonstrated that copper- or silver-based coatings, deposited electrolytically, could reduce attached biomass by 2 to 3 logs under experimental conditions. Their main limitation remains ageing and the gradual loss of effectiveness, with performance declining after 1 to 2 years under real-world conditions. A promising approach combines these coatings with superhydrophobic surfaces that limit primary adhesion, but this technology still requires long-term validation before it can be widely adopted. The choice of materials for DWDS networks cannot be easily resolved, but rather requires a trade-off between different risks, influenced by the age of the infrastructure and the chemistry of the water (Figure 9).

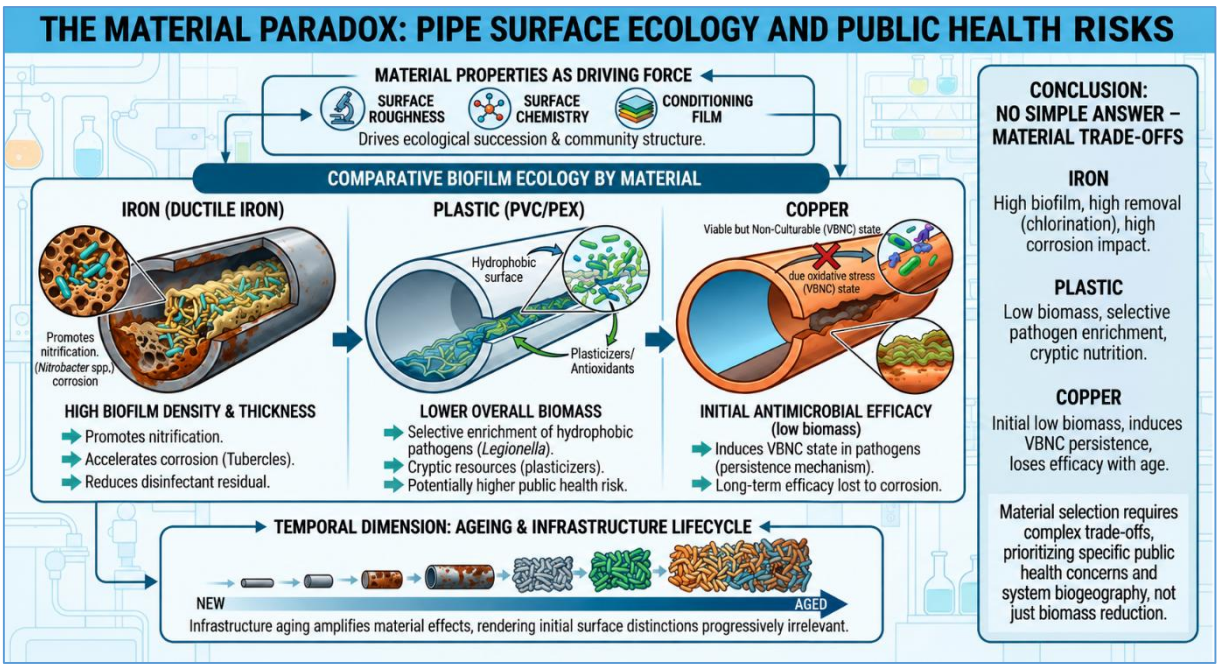


Figure 9. The material paradox: Pipe surface ecology and public health risks

Biological and ecological factors

Sensitive systems of intercellular communication govern the formation and structural dynamics of biofilms; e.g., quorum sensing, which regulates collective behaviour and community organization [60]. Extracellular polymeric substances (EPS) play a key role in providing a nutrient-rich habitat and enhancing the biofilm's resistance to environmental fluctuations [60,61]. Studies conducted on single-species biofilms limit our mechanistic understanding of EPS dynamics in a multi-species context, where bacterium-fungus interactions alter the physicochemical properties of the biofilm [62].

Biofilm maturity and species richness influence its tolerance to disinfectants, with mature biofilms being significantly more resistant than younger ones [63]. The physiological diversity of resident populations, including metabolically inactive and viable but non-cultivable (VBNC) cells, contrasts with studies relying on cultivability [10]. Furthermore, biofilms constitute a major reservoir of human pathogens and antibiotic resistance genes (ARGs), the spread of which via horizontal gene transfer remains poorly understood [52]. Interactions with higher trophic levels, notably grazing by protozoa, can increase the persistence of pathogens by creating conditions favourable to their development, as illustrated by the case of *Acanthamoeba* harbouring *Legionella pneumophila* and mycobacteria [64]. Finally, the presence of algae and invertebrates alters the structure of bacterial

communities and creates micro-scale heterogeneities that influence biogeochemical processes, suggesting that biotic interactions may, in some cases, override abiotic factors [10,62,63].

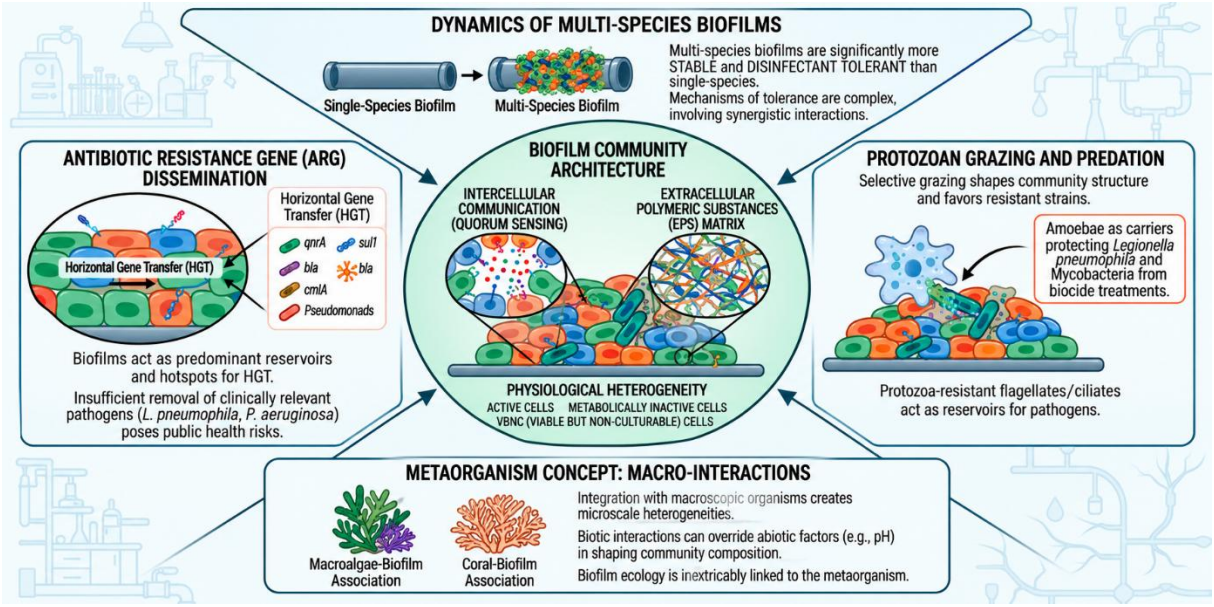


Figure 10. Complex biofilm ecology: From microscale interaction to multi-trophic dynamics

Targeting biotic interactions is an area yet to be explored. The use of predatory protozoa (e.g., *Tetrahymena* or *Acanthamoeba*) to control bacterial populations is discussed in the literature but their use is risky since some protozoa can be reservoirs of pathogens such as *Legionella*, which can worsen the health situation. On the other hand, the use of competing bacteria (probiotics) can lead to a preferential colonization of surfaces allowing for the diminishment of the potential for pathogens to colonize, as there are fewer available resources in terms of energy and space. This approach, which relies on community biology concepts, has not yet been tested in network settings where diversity leads to unpredictable results. Figure 10 summarizes the complexity of multi-trophic relationships which should not be overlooked in predictive biofilm formation models.

External environmental factors

Biofilm formation in DWDS is an adaptive and resilient process, resulting from the complex interaction between hydrogeochemical factors and anthropogenic influences. The quality of the source water is the main factor influencing the potential for microbial colonization, particularly in rural systems and small municipalities where treatment is less extensive [27]. The distinction between surface water and groundwater is not insignificant: systems supplied by surface water

harbour taxonomically richer and metabolically more diverse biofilms, highlighting the role of organic carbon availability as a selective pressure [65].

Climate change aggravates these effects by acting on physical and biological mechanisms. Warm water favours the proliferation of opportunistic pathogens and reduces disinfectant efficacy against *Legionella spp.* and non- tuberculous mycobacteria [66]. Warm water associated with lower rainfall and higher evaporation increases salinity, lowers dissolved oxygen levels and favours stagnation promoting biofilm formation and stabilization [61]. Extreme weather events (heavy rainfall, flooding) increase turbidity and the organic load, reducing the effectiveness of disinfectants but promoting bacterial colonization [67].

The chemical composition of water, which is determined by both natural processes and human activities, can have profound effects on the characteristics of biofilms. For example, mining activities alter the ionic composition of water, promoting colonization through changes in surface charge and adhesion [42,43]. Similarly, saline intrusion into coastal drinking water reservoirs affects the properties of biofilms forming on the surfaces of pipes [68]. Particulate matter and sediments constitute another underestimated factor: they provide both a habitat and a source of bacteria that are qualitatively different from those found in the water, enabling anaerobic processes to occur in an aerobic environment [56]. Furthermore, adsorbed pollutants (pesticides, heavy metals, toxins) can alter their morphology [22,45]. The protective effect of sediments and associated biofilms against disinfectants and predators is well established, but this resistance factor remains poorly accounted for in water quality management [45]. Conversely, factors such as such as pH and light, exert only a marginal influence in buried or opaque drinking water networks [27,56].

In the context of climate change, adaptation measures are being taken, such as increased chlorine dosing during warm periods or even the use of real-time sensors (turbidity, temperature, pH). These measures do not address the central issue of established biofilms, where viable microorganisms are sheltered. Thus, an integrated strategy, which considers upstream factors, active surveillance, and targeted intervention, is required to manage the impending challenges to water microbiology. Figure 11 shows the interrelationships between various processes, including the key role of source water quality and climate change in biofilm development, which are frequently overlooked in the context of drinking water management.

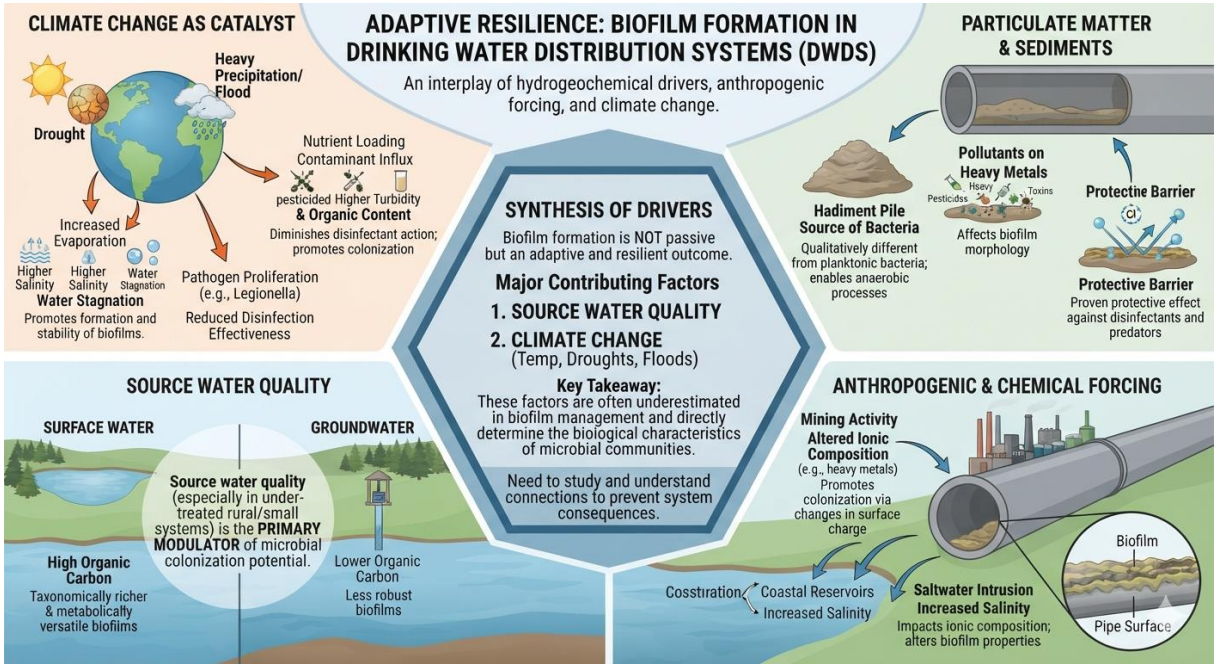


Figure 11. Adaptive resilience: Biofilms formation in DWDS

Simple visualisation

Table 2 shows the main factors influencing biofilms, summarizing their effect, whether or not the operator can control them, and the main known side effects. This simple guide makes it possible to prioritize the issues and highlight the importance of the synergistic interactions, which will be detailed in the following section.

Table 1: Summary of the main factors influencing biofilms in drinking water systems:

Factor	Effect on the biofilm	Can the operator control it?	Known side effect	Related Innovative Strategies	Intervention priority
Temperature	Strong, nonlinear	Difficult (except for water heaters)	Accelerated decline in chlorine levels	Pulsed heat treatment (45°C)	Medium (hot water systems)
pH	Moderate to strong, depending on the species	Yes (treatment)	Affects corrosion	Targeted adjustment (pH 5.5-6)	Low (regulatory constraints)
Nutriments (C, N, P)	Strong, but micro-niches	Partial (pre-treatment)	Eutrophication of springs	Low-release materials, pre-treatment	High (upstream)
Residual disinfectants	Moderate, selective	Yes, but limited	Selection of resistors, VBNC	Combined disinfection (chlorine + UV)	very high
Hydrodynamics	Very strong	Yes (network design)	Stagnation vs. shear	Scheduled purges, transient modeling	Very high (design)

Pipe material	Moderate to strong	During installation	Leaching, corrosion, aging	Antibacterial coatings, superhydrophobic surfaces	High (renovation)
Biological interactions (mixed cultures, VBNC, amoebae)	Very strong (often underestimated)	Not directly	Increased durability	Probiotics, dispersing enzymes	Low (Search)
Climate change	Indirect amplifier	No	Water source contamination	Adaptive strategies, enhanced monitoring	Low (Mitigation)

Interactions between factors and synergistic effects

The factors that influence formation and growth of biofilms in DWDS (water characteristics, materials, hydraulics) determine whether or not the biofilm will proliferate within the distribution network. Water quality parameters are synergistic, determining both the deficiency and the probability of survival of micro-organisms [27,56]. Seasonal variations in turbidity, pH and temperature actively compromise the disinfection barrier [69]. Exceeding the turbidity limit of 30 NTU protects bacteria from disinfectants, rendering the inactivation processes in treatment works ineffective [70]. This finding, combined with the fact that seasonal changes in water chemistry require a significant adjustment to the disinfection regime, argues against the adequacy of the current approach.

Although it is established that higher temperatures accelerate microbial growth, the direct link with the threshold at which pathogens emerge is less clear. For example, a water temperature below 18°C does not allow sufficient growth of *Legionella pneumophila* to pose a significant health threat; it is only at higher temperatures that the bacterium proliferates intensively [71]. Furthermore, rising temperatures promote corrosion and the inactivation of chlorine in a non-linear manner, thereby enhancing biofilm growth [72]. The physicochemical properties of pipework materials also influence microbial growth: as the temperature rises, bacteria adhere more strongly to various materials, making it more difficult to control biofilm growth [33].

The debate on pipework materials must go beyond their biofilm-forming propensity. Cast iron pipes, for example, are not only difficult to disinfect; they promote recalcitrant biofilms through corrosion-mediated protection, rendering even high residual chlorine levels ineffective [12]. Conversely, the apparent advantage of copper is only conditional; it is only evident in nutrient-poor water with a constant level of free chlorine, which is rarely the case in real-world systems [4]. Thus, the performance of materials depends on the specific properties of the water and its flow regime, which must be taken into account when selecting materials for pipework.

Although the risk of stagnation is often highlighted, its interaction with water age is more complex than it appears. Stagnation does not simply create conditions favourable to biofilm growth; it alters the system's microbiome. Water age in certain zones favours the establishment of Nitrospira and the depletion of monochloramine; a low water age favours the growth of pathogens and the accumulation of disinfectants [18]. This highlights the link between the proper organization of water flow and the maintenance of a stable microbiome.

Finally, the ability of *Bacillus cereus*, *Sphingomonas spp.* and *Acinetobacter spp.* to colonize biofilms is a result of residual disinfection [73]. The occurrence of these bacteria is linked to changes in water composition, EPS content, aggregation and the potential for surface modification [74]. Ignoring the mechanisms of biofilm formation means that residual disinfection cannot prevent disease, acting merely as a method of combating the consequences of contamination.

Significant gaps in our understanding weaken our ability to control biofilms: the reactivation of VBNC bacteria following stress, the destabilizing role of transient hydraulics, and the complex interactions between mixed materials within a single network remain poorly understood. We remain unable to predict health risks reliably based solely on measurements of biomass or diversity. Crucially, the actual effectiveness of next-generation strategies (phages, enzymes, specialized coatings) has not been demonstrated outside the lab – in the dynamic conditions of real-world distribution networks.

Innovative biofilm control strategies: a comparative assessment

The limitations of conventional disinfection approaches have prompted the development of alternative and complementary strategies targeting different stages of biofilm formation, from initial adhesion to mature community disruption. Table 2 shows a structured comparative assessment of the most promising innovative strategies, evaluating their principle, reported efficacy, limitations, and practical applicability to drinking water networks.

Table 2. Innovative biofilm control strategies: comparative assessment

Strategy	Principle	Mechanism of Action	Reported Efficacy	Key Limitations	Applicability to DWDS	Stage of Development
Phagotherapy	Use of specific bacteriophages to lyse biofilm bacteria	Phages infect and replicate within host bacteria, causing cell lysis and biofilm disruption	2–3 log reduction in laboratory settings [46]	High host specificity; selection of resistant mutants; inactivation by residual chlorine; limited penetration into mature biofilm	**Low** – requires prior identification of target strains; best suited for point-of-use applications or emergency responses	Preclinical / Laboratory
Dispersing enzymes (DNase, proteases, glycosidases)	Enzymatic degradation of the EPS matrix, weakening biofilm structure	Hydrolysis of extracellular DNA, proteins, and polysaccharides, releasing cells from the biofilm	Variable efficacy (30–80% reduction) depending on biofilm type and maturity [23]	High cost; limited stability in water; ineffective against mature biofilms; potential interference with water quality	**Low to moderate** – targeted applications in specific hotspots (e.g., reservoirs, storage tanks)	Laboratory / Pilot
Anti-quorum sensing molecules (furans, AHL analogues, brominated furanones)	Inhibition of bacterial cell-to-cell communication, preventing maturation and virulence	Interference with acyl-homoserine lactone (AHL) signalling pathways, reducing EPS production and biofilm formation	50–80% biomass reduction in laboratory settings; effective against Gram-negative bacteria [23]	Uncertain stability under real-world conditions; non-specific effects on beneficial bacteria; potential toxicity; limited field validation	**Low** – continuing research; no large-scale validation in DWDS	Laboratory / Early research
Innovative antibacterial surfaces (polymer grafting, nanoparticles, superhydrophobic coatings)	Prevention of primary adhesion or controlled release of biocides	Modification of surface physicochemical properties (hydrophobicity, charge) or slow release of antimicrobial agents (Cu, Ag, Zn)	60–90% reduction in adhesion under controlled conditions [11,22]; 2–3 log reduction with Cu/Ag coatings [11,22]	Ageing and loss of efficacy over time (decline after 1–2 years); fouling; high cost; limited validation in real networks	**Moderate** – applicable to new installations or during pipe renovation; requires long-term durability studies	Pilot / Early deployment
Advanced physical disinfection (UV-LED, cold plasma, electroporation)	Inactivation via physical (non-chemical) mechanisms	DNA damage (UV), generation of reactive species (plasma), or	Highly effective against planktonic bacteria (>4 log reduction); limited	Limited penetration depth (mm range); high energy costs; integration challenges in existing	**Low to moderate** – best suited for point-of-use applications (hospitals, buildings)	Pilot / Commercial (point-of-use)

		membrane disruption (electroporation)	penetration into biofilm matrix [11,22]	networks; point-of-use only	or treatment plant outlets	
Probiotic / competitive bacteria	Competitive exclusion of pathogens by beneficial bacteria	Colonization of surfaces by non-pathogenic strains, occupying ecological niches and limiting pathogen establishment	Promising in laboratory settings; limited field data	Risk of introducing non-native species; strain stability; regulatory hurdles; unknown long-term effects	**Very low** – remains speculative for DWDS; requires extensive safety validation	Early research
Combined disinfection approaches (alternating chlorine/monochloramine, chlorine + UV)	Synergistic effects of multiple disinfectants to reduce resistance selection	Sequential or simultaneous application of disinfectants with different mechanisms of action	Reduced selection of resistant strains; improved biofilm control compared to single disinfectants [47]	Complex management; requires precise dosing; potential for increased disinfection by-products	**Moderate to high** – applicable to existing networks with operational adjustments	Operational (some utilities)
Targeted thermal treatment (45°C maintenance)	Heat-induced reduction of active microbial populations	Elevated temperatures (45°C) reduce culturability and metabolic activity of biofilm bacteria	Effective reduction of active populations and pathogens in shower hoses [31]	Limited to hot water systems; temperature fluctuations in networks; energy costs	**Low** – applicable only to domestic hot water systems (hospitals, hotels, large buildings)	Operational (specific systems)
Hydraulic management (programmed flushing using controlled transients)	Detachment of biofilms via controlled hydraulic transients	Generation of brief, controlled increases in flow velocity to dislodge sessile communities without massive water quality degradation	Effective in laboratory and pilot studies; site-specific efficacy [54]	Requires precise hydraulic modelling; efficacy depends on biofilm and material-specific critical velocities; risk of excessive contaminant mobilization	**Moderate** – applicable to networks with identified stagnation zones; requires validation	Pilot / Early deployment

The comparison shows that there is no ideal solution since all options have considerable inconvenience regarding efficiency, cost, complexity, and application. The best performers are those disinfectants that use several mechanisms of action, creating a multi-barrier. Although laboratory tests have demonstrated the strategies' effectiveness, they are not always successful in real settings because of complications (e.g., chlorine, penetration, heterogeneity, and water quality). Hence, only combined disinfection and specific thermal treatments are now applied in practice. The third group of strategies includes materials that could make surfaces antibacterial or self-sterilizing. Some are already used in novel construction or reconstruction to replace old ones; but, these are expensive, frequently inefficient, and rapidly degrade after one or two years. In contrast, hydraulic management through programmed flushing using controlled transients [54] is the most immediately useful strategy, requiring no major infrastructure changes yet relying on precise hydraulic modelling, particularly in networks with identified stagnation zones. Ultimately, combined approaches integrating complementary interventions (e.g., antibacterial surfaces, residual disinfection, hydraulic optimization) within a network-wide management plan offer the best prospect for sustainable biofilm control.

Table 3. Practical recommendations for researchers and managers

Strategy	Principle	Reported Efficacy	Limitations	Applicability to Networks
Phagotherapy	Use of specific bacteriophages to lyse biofilm bacteria	2–3 log reduction in laboratory settings	Host specificity, selection of resistant mutants, degradation by chlorine	Low (requires prior identification of target strains)
Dispersing enzymes (DNase, proteases, glycosidases)	Degradation of the EPS matrix, weakening of the biofilm structure	Variable efficacy depending on biofilm type	High cost, limited stability, ineffective against mature biofilms	Low to moderate (targeted applications)
Anti-quorum sensing molecules (furans, AHL analogues)	Inhibition of bacterial communication, preventing maturation	Effective in laboratory settings; 50–80% biomass reduction	Uncertain stability under real-world conditions, non-specific effects	Low (continuing research)
Innovative antibacterial surfaces (polymer grafting, nanoparticles)	Prevention of primary adhesion or controlled release of biocides	60–90% reduction in adhesion under controlled conditions	Ageing, fouling, high cost	Moderate (new installations or renovation)
Advanced disinfection (UV-LED, cold plasma, electroporation)	Inactivation via physical (non-chemical) mechanisms	Effective against planktonic bacteria; limited biofilm penetration	Limited penetration depth, high cost, integration challenges	Low to moderate (point-of-use applications)

This comparison (Table 3) shows that moving from traditional to modern methods of biofilm control requires a shift from single-factorial to multi-barrier approaches. In addition, it is necessary to consider each of the network's qualities: water qualities, materials, flow conditions, and target microorganisms. The methodology described in the next section can help in this task. It was created for evaluating the options for drinking water networks.

Methodological framework for the analysis of a drinking water network

A review of the factors identified enables us to propose a structured approach for assessing an existing network. This methodology comprises five stages:

Step 1: Mapping and preliminary diagnosis

- Identify areas of stagnation (extremities, loops, reservoirs).
- Raise the age of water in each section.
- Document the materials present and their age.
- Identify any history of coloration, tastes, or bacteriological problems.

Step 2: Physico-chemical characterisation of water

- Measure on several points of the network (and continuously): temperature, pH, turbidity, residual chlorine, dissolved organic carbon, nitrogen, and phosphorus.
- Analyze seasonal variations.

Step 3: Hydraulic evaluation

- Model flow regimes (flows, pressures, shear).
- Identify potential hydraulic transients.

Step 4: Biological characterisation

- Collection of biofilms by coring or cutting samples (where possible)
- Molecular analyses (qPCR, metabarcoding) to identify major populations and pathogens
- Assessment of the presence of VBNC bacteria

Step 5: Summary and action plan

Table 4. Summary of key parameters to be evaluated in a given network

Parameter	Level of impact on biofilm	measurement method	critical threshold	possible courses of action	Priority
Temperature	Very high	In situ probes	>18°C (*Legionella* risk)	Thermal management, insulation	High
residual chlorine	Very high	Colorimetric DPD	<0.2 mg/L (free) / <0.5 mg/L (monochl.)	Dose adjustment, chloration points	Very high
Age of water / Time of stay	Very high	Hydraulic modelling	>24-48h	Scheduled purges, shutdown	Very high
Turbidity	High	Nephelometry	>1 NTU	Upstream filtration, removal of deposits	High
Material	Moderate to high	Inventory	Iron / cast iron > plastic	Replacement / coating	Medium (long term)
Dissolved organic carbon	High	Persulphate - UV method	>2 mg/L	Pretreatment, low release materials	High
pH	Moderate	pH meter	Outside 6.5-8.5	Adjust Processing	Average
Nutriments (N,P)	Moderate	Colorimetry	N > 1 mg/L, P > 0.05 mg/L	Upstream pretreatment	High amount
Flow / Shear	Very high	Modelization	Stagnant areas / very low flow rates	Closed network, purges	Very high

Conclusion

Sustainable control of biofilms in drinking water networks cannot be achieved through isolated interventions; it requires a systemic and precisely targeted strategy. The complexity of the interacting factors can be simplified into a clear operational hierarchy: hydrodynamics (stagnation and water age), effective residual chlorine and temperature are the main levers for action. All other factors act as modulators. Success therefore depends on the simultaneous and deliberate manipulation of these three levers, synchronized with an integrated management plan at the network level.

Beyond the standard recommendations, a number of innovative strategies are emerging that offer real potential for drinking water networks:

1. Scheduled hydraulic flushing, using controlled transients to dislodge biofilms, which is particularly effective in identified areas of stagnation.
2. Superhydrophobic or copper/silver-based antibacterial coatings, which are effective in the laboratory but whose ageing under real-world conditions has yet to be assessed.
3. Dispersing enzymes (DNase, proteases), which show promise in the laboratory but are still costly and have not been validated in a network setting.
4. Combined approaches (alternating chlorine and monochloramine), which limit the selection of resistant bacteria but require rigorous management.
5. Targeted heat treatment at 45°C, applicable to domestic hot water systems.

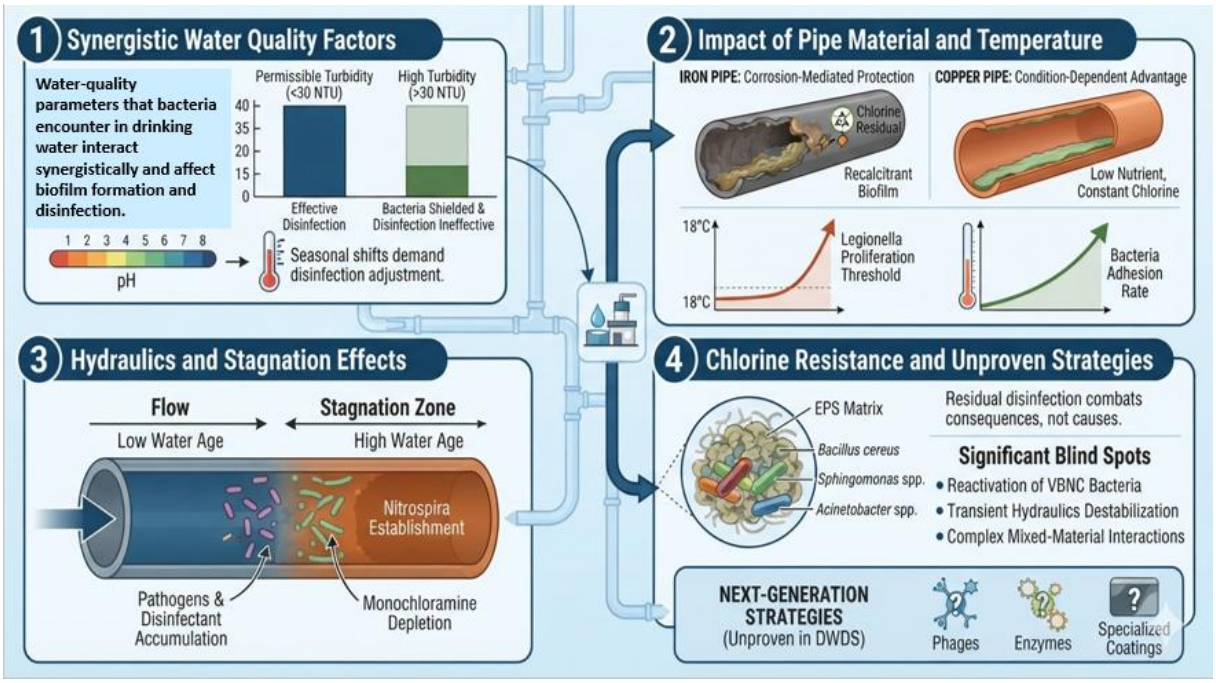


Figure 12: Mechanisms of biofilm formation and persistence in DWDS

Figure 12 shows the need to combine these different approaches to form a multi-barrier strategy, in which each plays its part and works together with the others. The key issue is to shift from managing individual factors to managing their interaction. A systems-based approach, targeting the most cost-effective and influential levers, is the only way of ensuring the microbiological safety of water supplies for consumers.

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- The authors have no financial or proprietary interests in any material discussed in this article.
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References

[1] Zhang, Y., Yang, Z., Wang, Y., Bian, Y., Xu, R., & He, X., 2025, Community structure and influencing factors of biofilms in stagnant water of premise plumbing system. *Journal of Water Process Engineering* **75**, 107958. https://doi.org/10.1016/j.jwpe.2025.107958

[2] Moreno, Y., Moreno-Mesonero, L., Soler, P., Zornoza, A., & Soriano, A., 2024, Influence of drinking water biofilm microbiome on water quality: Insights from a real-scale distribution system. *Science of The Total Environment* **921**, 171086. https://doi.org/10.1016/j.scitotenv.2024.171086

[3] Hemdan, BA., El-Taweel, GE., Goswami, P., Pant, D., & Sevda, S., 2021, The role of biofilm in the development and dissemination of ubiquitous pathogens in drinking water distribution systems: an overview of surveillance, outbreaks, and prevention. *World Journal of Microbiology Biotechnology* **37**, 36. https://doi.org/10.1007/s11274-021-03008-3

[4] Oliveira, I. M., Gomes, I. B., Simões, L. C., & Simões, M., 2024, A review of research advances on disinfection strategies for biofilm control in drinking water distribution systems. *Water Research* **253**, 121273. https://doi.org/10.1016/j.watres.2024.121273

[5] Lin, W., Zhao, K., Wu, Q., Xu, F., Cui, L., Lin, H., Ye, C., & Yu, X., 2025, Biofilms on pipelines shape the microbiome and antibiotic resistome in drinking water. *Water Research* **274**, 123136. https://doi.org/10.1016/j.watres.2025.123136

[6] Meradji, S., Basher, N.S., Sassi, A., Ibrahim, N.A., Idres, T., & Touati, A., 2025, The role of water as a reservoir for antibiotic-resistant bacteria. *Antibiotics* **14**, 763. https://doi.org/10.3390/antibiotics14080763

[7] Gleason, J.A., & Cohn, P.D., 2022, A review of legionnaires' disease and public water systems–Scientific considerations, uncertainties and recommendations. *International*

Journal of Hygiene Environmental Health **240**, 113906. https://doi.org/10.1016/j.ijheh.2021.113906

[8] Erdei-Tombor, P., Kiskó, G., & Taczman-Brückner A, 2024, Biofilm formation in water distribution systems. *Processes* **12**, 280. https://doi.org/10.3390/pr12020280

[9] Neu, L., Proctor, C.R., Walser, J.-C., & Hammes, F., 2019, Small-scale heterogeneity in drinking water biofilms. *Frontiers in microbiology* **10**, 2446. https://doi.org/10.3389/fmicb.2019.02446

[10] Guo, L., Xiao, X., Chabi, K., Zhang, Y., Li, J., Yao, S., & Yu, X., 2024, Occurrence of viable but non-culturable (VBNC) pathogenic bacteria in tap water of public places. *Frontiers of Environmental Science Engineering* **18**, 35. https://doi.org/10.1007/s11783-024-1795-4

[11] Timoncini, A., Lorenzetti, L., Turner, R.J., McGibbon, A., Martini, C., Cofini, E., Bernardi, E., & Chiavari, C., 2024, Inhibition of *Pseudomonas aeruginosa* biofilm formation on copper-based thin foils. *PLoS One* **19**, e0314684. https://doi.org/10.1371/journal.pone.0314684

[12] Alhoshy, M.A., Samhan, F.A., El-Gendy AS., & Razek, T.M., 2025, Impact of Biofilm in Distribution Water Systems on Water Characteristics and Attempts for Treatment. *Water, Air, Soil Pollution* **236**, 463. https://doi.org/10.1007/s11270-025-08077-w

[13] Leena Catherine, A. F., Priyanka, V., Nandhini, B., Jagannathan, S., & Suresh, B., 2026, Microbiologically influenced corrosion dynamics and technological innovations in monitoring and control. *Journal of Microbiological Methods* **243**, 107432. https://doi.org/10.1016/j.mimet.2026.107432

[14] Planko, T., Fitzek, H., Eichinger, S., Rattenberger, J., Koraimann, G., Schröttner, H., 2026, Microbiologically influenced corrosion (MIC) of steel–a study using correlative SEM, EDXS and Raman microscopy. *Materials Chemistry Physics* **355**, 132175. https://doi.org/10.1016/j.matchemphys.2026.132175

[15] Guo, H., Wang, R., Jiang, M., Tian, Y., Jin, Y., Zhao, W., Wang, C., & Yin, J., 2025, Cement-mortar lining failure and metal release caused by electrochemical corrosion of ductile iron pipes in drinking water distribution systems. *Journal of Environmental Sciences* **152**, 488-502. https://doi.org/10.1016/j.jes.2024.06.003

[16] Zhou, X., Zhang, K., Zhang, T., Li, C.,& Mao, X., 2017, An ignored and potential source of taste and odor (T&O) issues—biofilms in drinking water distribution system (DWDS). *Applied Microbiology Biotechnology* **101**, 3537-3550. https://doi.org/10.1007/s00253-017-8223-7

[17] Zlatanović, L., van der Hoek, J.P., & Vreeburg, J., 2017, An experimental study on the influence of water stagnation and temperature change on water quality in a full-scale domestic drinking water system. *Water Research* **123**, 761-772. https://doi.org/10.1016/j.watres.2017.07.019

[18] Healy, H.G., Ehde, A., Bartholow, A., Kantor, R.S., & Nelson, K.L., 2024, Responses of drinking water bulk and biofilm microbiota to elevated water age in bench-scale simulated distribution systems. *npj Biofilms Microbiomes* **10**, 7. https://doi.org/10.1038/s41522-023-00473-6

[19] Li, B., Feng, L., Chouari, R., Samoili, S., & Giannakis, S., 2025, Trace metals induce microbial risk and antimicrobial resistance in biofilm in drinking water. *NPJ Clean Water* **8**, 8. https://doi.org/10.1038/s41545-025-00436-8

[20] Siponen, S., Ikonen, J., Gomez-Alvarez, V., Hokajärvi, A.-M., Ruokolainen, M., Jayaprakash, B., Kolehmainen, M., Miettinen, I.T., Pitkänen, T., & Torvinen, E., 2025, Effect of pipe material and disinfectant on active bacterial communities in drinking water and biofilms. *Journal of applied microbiology* **136**, lxaf004. https://doi.org/10.1093/jambio/lxaf004

[21] Rahmatika, I., Kasuga, I., Kurisu, F., & Furumai, H., 2020, Impacts of organic matter migrating from pipe materials on microbial regrowth in drinking water. *Journal of Water Environment Technology* **18**, 45-53. https://doi.org/10.2965/jwet.19-078

[22] Liu, T., Xiu, J., Huang, X., Geng, B., Hu, L., & Bai, X., 2025, Material-driven microbiologically influenced corrosion mechanisms in drinking water distribution systems. *Water Research* **288**, 124729. https://doi.org/10.1016/j.watres.2025.124729

[23] Flemming, H.-C., van Hullebusch, E.D., Little, B.J., Neu, T.R., Nielsen, P.H., Seviour, T., Stoodley, P., Wingender, J., & Wuertz, S., 2025, Microbial extracellular polymeric substances in the environment, technology and medicine. *Nature Reviews Microbiology* **23**, 87-105. https://doi.org/10.1038/s41579-024-01098-y

[24] Desmond, P., Best, J.P., Morgenroth, E., & Derlon, N., 2018, Linking composition of extracellular polymeric substances (EPS) to the physical structure and hydraulic resistance of membrane biofilms. *Water research* **132**, 211-221. https://doi.org/10.1016/j.watres.2017.12.058

[25] Nisar, M.A., Hayward, C., Ross, K.E., Brown, M.H., Bentham, R., & Whiley, H., 2025, Efficacy of physical and chemical disinfection against clinically relevant free-living amoebae isolated from drinking water and plumbing biofilms. *Frontiers in Microbiology* **16**, 1654984. https://doi.org/10.3389/fmicb.2025.1654984

[26] Potgieter, S., Dai, Z., Havenga, M., Vosloo, S., Sigudu, M., Pinto, A., & Venter, S., 2021, Reproducible microbial community dynamics of two drinking water systems treating similar source waters. *ACS ES&T Water* **1**, 1617-1627. https://doi.org/10.1101/678920

[27] Abkar, L., Moghaddam, H.S., & Fowler, S.J., 2024, Microbial ecology of drinking water from source to tap. *Science of The Total Environment* **908**, 168077. https://doi.org/10.1016/j.scitotenv.2023.168077

[28] Guo, X., Qi, B., Fu, H., Zhang, P., Zhao, J., Ouyang, J., Mao, J., & Yuan, Y., 2026, The impact of chlorine-based disinfection on the corrosion behavior of cast iron pipes in water distribution systems. *Engineering Failure Analysis* **184,** 110301. http://dx.doi.org/10.2139/ssrn.5476113

[29] Oschmann, A.M., Konrat, K., Schaudinn, C., Sohl, G., Wagner, D., Lewin, A., & Arvand, M., 2025, Biofilm formation by the global outbreak strain of *Mycobacterium chimaera* results in significantly reduced efficacy of standard disinfectants. *BMC microbiology* **25**, 738. https://doi.org/10.1186/s12866-025-04439-w

[30] Li, Z., & Zhang, L., 2025, Temperature phase shift determines microbial community succession and assembly pattern in climate-stressed wastewater treatment plants. *Bioresource Technology* **442**, 133723. https://doi.org/10.1016/j.biortech.2025.133723

[31] Yao, M., Ren, A., Yang, X., Chen, L., Wang, X., van der Meer, W., van Loosdrecht, M.C., Liu, G., & Pabst, M., 2025, Unveiling the influence of heating temperature on biofilm formation in shower hoses through multi-omics. *Water Research* **268**, 122704. https://doi.org/10.1016/j.watres.2024.122704

[32] Cazals, M., Bédard, E., Maldonado, J.F.G., & Prévost, M., 2025, What happens in your water system? Impact of materials, temperature, stagnation and chlorination on water quality and biofilm formation. *Chemosphere* **376**, 144248. https://doi.org/10.1016/j.chemosphere.2025.144248

[33] Elgoulli, M., Tankiouine, S., Aitlahbib, O., Zahir, H., ElLouali, M., & Latrache, H., 2020, Effect of water temperature on surfaces' physicochemical properties and adhesion of *Pseudomonas aeruginosa* in turbulence conditions. *EurAsian Journal of BioSciences* **14**, 7245-7251.

[34] Lamas, A., Fernandez-No, I., Miranda, J., Vázquez, B., Cepeda, A., & Franco, C., 2016, Biofilm formation and morphotypes of *Salmonella enterica subsp.* arizonae differs from those of other *Salmonella enterica* subspecies in isolates from poultry houses. *Journal of Food Protection* **79**, 1127-1134. https://doi.org/10.4315/0362-028X.JFP-15-568

[35] Chen, G., Fanouraki, G., Anandhi R.A., Winkelman, B.T., Winkelman, J.T., Waters, C.M., & Mukherjee, S., 2024, Combinatorial control of *Pseudomonas aeruginosa* biofilm development by quorum-sensing and nutrient-sensing regulators. *Msystems* **9**, e00372-00324. https://doi.org/10.1128/msystems.00372-24

[36] World Health Organization, 2024, *Guidelines for drinking-water quality: Small water supplies*. Geneva: World Health Organization. https://iris.who.int/server/api/core/bitstreams/4a3dc8a4-9f08-4d62-b7ec-96d70be6b177/content

[37] Kilic, T., 2025, Factors affecting biofilm formation and the effects of these factors on bacteria. In *Exploring Bacterial Biofilms*. Edited by, IntechOpen. https://10.5772/intechopen.1008877

[38] Qin, S., Chen, W., Lin, Y., Tan, S., Liang, S., Liu, H.,& Zhang, Q., 2025, Effect of hydraulic retention time on the nitrogen removal performance of pure biofilm rotating biological contactor system inoculated with heterotrophic nitrification-aerobic denitrification bacteria and its corresponding mechanism. *Bioresource Technology* **427**, 132428. https://doi.org/10.1016/j.biortech.2025.132428

[39] Tran, P., Lander, S.M., & Prindle, A., 2024, Active pH regulation facilitates *Bacillus subtilis* biofilm development in a minimally buffered environment. *Mbio* **15**, e03387-03323. https://doi.org/10.1128/mbio.03387-23

[40] Yanik, H.D., Mustak, H.K., & Sariçam İnce, S., 2025, Effects of environmental and genetic factors on biofilm formation of various *Salmonella* serotypes. *Turkish Journal of Veterinary Animal Sciences* **49**, 70-75. https://doi.org/10.55730/1300-0128.4372

[41] Zhang, W., Seminara, A., Suaris, M., Brenner, M.P., Weitz, D.A., & Angelini, T.E., 2014, Nutrient depletion in *Bacillus subtilis* biofilms triggers matrix production. *New Journal of Physics* **16**, 015028. https://doi.org/10.1088/1367-2630/16/1/015028

[42] Elgoulli, M., Aitlahbib, O., Tankiouine, S., Assaidi, A., Louali, M.E., Zahir, H., & Latrache, H., 2021a, The theoretical adhesion of *Pseudomonas aeruginosa* and *Escherichia coli* on some plumbing materials in presence of distilled water or tap water. *Folia Microbiologica* **66**, 607-613. https://doi.org/10.1007/s12223-021-00868-y

[43] Elgoulli, M., Zahir, H., Aitlahbib, O., Ellouali, M., Latrache, H., 2021b, Effect of chemical compounds in water on surface properties and adhesion capacity of *Pseudomonas aeruginosa* and *Escherichia coli* in turbulent conditions. *Water SA* **47**, 430-436. https://doi.org/10.17159/wsa/2021.v47.i4.3859

[44] Montoya-Pachongo, C., Douterelo, I., Noakes, C., Camargo-Valero, M.A., Sleigh, A., Escobar-Rivera, J.-C., & Torres-Lozada, P., 2018, Field assessment of bacterial communities and total trihalomethanes: Implications for drinking water networks. *Science of the Total Environment* **616**, 345-354. https://doi.org/10.1016/j.scitotenv.2017.10.254

[45] Chen, H., Zhang, S., Wang, H., Ma, X., Wang, M., Yu, P., & Shi, B., 2025, Co-selective effect of dissolved organic matter and chlorine on the bacterial community and their antibiotic resistance in biofilm of drinking water distribution pipes. *Water Research* **268**, 122664. https://doi.org/10.1016/j.watres.2024.122664

[46] Pang, X., Yang, Y., & Yuk, H., 2017, Biofilm formation and disinfectant resistance of *Salmonella sp.* in mono-and dual-species with *Pseudomonas aeruginosa*. *Journal of Applied Microbiology* **123**, 651-660. https://doi.org/10.1111/jam.13521

[47] Chen, L., Shi, H., Medema, G., van der Meer, W., & Liu, G., 2025, Long-term impacts of free chlorine and monochloramine on the development of drinking water biofilm. *Water Research* **281**, 123566. https://doi.org/10.1016/j.watres.2025.123566

[48] Elgoulli, M., Zahir, H., Ellouali, M., Latrache, H., 2024, Chlorination of *Pseudomonas aeruginosa* in potable water. *International Journal of Environmental Health Research* **6**, 1-8. https://doi.org/10.1080/09603123.2024.2338891

[49] Elgoulli, M., Zahir, H., Ellouali, M., & Latrache, H., 2023, Disruption of *Pseudomonas aeruginosa* Adherent Cells by NaCl and NaOCl in Drinking Water. *Current Microbiology* **80**, 138. https://doi.org/10.1007/s00284-023-03241-z

[50] Chen, J., Guo, Y., Lin, Y., Zhang, Y., Qian, Q., Zhang, X., Lin, P., Chen, C., & Xie, S., 2025, Fate, mobility and pathogenicity of antibiotic resistome in a full-scale drinking water treatment plant: Highlighting the chlorination risks. *Journal of Environmental Management* 390, 126425. https://doi.org/10.1016/j.jenvman.2025.126425

[51] Rogers, J., 2024, Investigating and managing biofilm and material accumulation in chlorine and chloramine drinking water distribution systems. Edited by: University of Sheffield. https://etheses.whiterose.ac.uk/id/eprint/36209/

[52] Zhao, W., Hou, Y., Wei, L., Wei, W., Zhang, K., Duan, H., & Ni, B.-J., 2025, Chlorination-induced spread of antibiotic resistance genes in drinking water systems. *Water Research* **274**, 123092. https://doi.org/10.1016/j.watres.2025.123092

[53] Tierra, G., Pavissich, J.P., Nerenberg, R., Xu, Z., & Alber, M.S., 2015, Multicomponent model of deformation and detachment of a biofilm under fluid flow. *Journal of The Royal Society Interface* **12**, 20150045. https://doi.org/10.1098/rsif.2015.0045

[54] Zeidan, M., & Ostfeld, A., 2022, Using hydraulic transients for biofilm detachment in water distribution systems: Approximated model. *Journal of Water Resources Planning Management* **148**, 04022008. https://doi.org/10.1061/(ASCE)WR.1943-5452.0001539

[55] Hope, J.A., Kleinteich, J., Gerbersdorf, S.U., 2025, Benthic biofilm structure and function under abrupt flow changes. *PLoS One* **20**, e0327216. https://doi.org/10.1371/journal.pone.0327216

[56] Bridges, E., Bircher, S., Cunningham, K., Vasam, V., Hando, J., & Garner, E., 2025, Divergent bacterial communities in water and sediment of chlorinated drinking water storage tanks. *ACS Est Water* **6**, 217-227. https://doi.org/10.1021/acsestwater.5c00928

[57] Learbuch, K., Smidt, H., Van Der Wielen, P., 2021, Influence of pipe materials on the microbial community in unchlorinated drinking water and biofilm. *Water Research* **194**, 116922. https://doi.org/10.1016/j.watres.2021.116922

[58] Xiu, J., Geng, B., Liu, M., Han, X., Zhang, D., & Bai, X., 2025, Biofilm induced microplastics and microbial metabolites release from Polypropylene Random pipes in drinking water distribution systems. *Water Research* **288**, 124626. https://doi.org/10.1016/j.watres.2025.124626

[59] Emelyanenko, A.M., Omran, F.S., Chernukha, M.Y., Avetisyan, L.R., Tselikina, E.G., Putsman, G.A., Zyryanov, S.K., Emelyanenko, K.A., Buglak, A.V., & Boinovich, L.B., 2025, Engineering wettability-controlled copper surfaces to mitigate airborne bacterial contamination in hospitals. *Colloids Surfaces A: Physicochemical Engineering Aspects* **719**, 137085. https://doi.org/10.1016/j.colsurfa.2025.137085

[60] Wang, J., Peipoch, M., Guo, X., & Kan, J., 2022, Convergence of biofilm successional trajectories initiated during contrasting seasons. *Frontiers in Microbiology* **13**, 991816. https://doi.org/10.3389/fmicb.2022.991816

[61] Huang, S., Jiang, F., Dong, Q., Yu, J., Fan, K., Wang, Z., Hao, S., & Qiao, Y., 2025, The impact of climate change induced extreme weather events on microbial dynamics and public health: an in-depth review on water quality and ecosystem resilience. *Frontiers in Environmental Science* **13**, 1674490. https://doi.org/10.3389/fenvs.2025.1674490

[62] Amador, C.I., Røder, H.L., Herschend, J., Neu, T.R., & Burmølle, M., 2025, Decoding the impact of interspecies interactions on biofilm matrix components. *Biofilm* **9**, 100271. https://doi.org/10.1016/j.bioflm.2025.100271

[63] Nithyanand, P., Boya, B.R., Lee, J.H., & Lee, J., 2025, Polymicrobial biofilms: Interkingdom interactions, resistance and therapeutic strategies. *Microbial Biotechnology* **18**, 70218. https://doi.org/10.1111/1751-7915.70218

[64] Wang, Y., Jiang, L., Zhou, F., Zhang, Y., Fine, R.D., Li, M., 2025, The hidden dancers in water: the symbiotic mystery of *Legionella pneumophila* and free-living amoebae. *Frontiers in Microbiology* **16**, 1634806. https://doi.org/10.3389/fmicb.2025.1634806

[65] Schroeter, S.A., Orme, A.M., Lehmann, K., Lehmann, R., Chaudhari, N.M., Küsel, K., Wang, H., Hildebrandt, A., Totsche, K.U., & Trumbore, S., 2025, Hydroclimatic

extremes threaten groundwater quality and stability. *Nature Communications* **16**, 720. https://doi.org/10.1038/s41467-025-55890-2

[66] Fira-Mladinescu, C., Margan, M.-M., Margan, R., Ardelean, F., Sînmârghițan, A.I., Marincov, D., Tuță-Sas, I., Marin, I., Cîndrea, A.-C., & Bodea, D.-A., 2026, Meteorological influence on drinking water quality: microbial variability in groundwater wells and piped distribution networks from western romania. *Microorganisms* **14**, 148. https://doi.org/10.3390/microorganisms14010148

[67] Swinamer, R., Anderson, L.E., Redden, D., Bjorndahl, P., Campbell, J., Krkošek, W.H., & Gagnon, G.A., 2024, Climate-driven increases in source water natural organic matter: Implications for the sustainability of drinking water treatment. *Environmental Science Technology* **58**, 11958-11969. https://doi.org/10.1021/acs.est.4c01894

[68] Chen, L., Ma, M., Li, X., Yu, K., Zhi, C., Cheng, L., Ma, H., Wang, Z., & Qian, X., 2024, Effects of fresh groundwater and seawater mixing proportions and salt-freshwater displacement on coastal aquifer microbial communities. *Water* **16**, 2078. https://doi.org/10.3390/w16152078

[69] Manirakiza, B., Zhang, S., Addo, F.G., Yu, M., & Alklaf, S.A., 2024, Interactions between water quality and microbes in epiphytic biofilm and superficial sediment of lake in trophic agriculture area. *Science of the Total Environment* **912**, 169321. https://doi.org/10.1016/j.scitotenv.2023.169321

[70] Sumanasekera, S.,& Rajapakse, J., 2025, Turbidity as a barrier to water treatment: a review of current and emerging removal technologies, advantages and limitations. https://doi.org/110.20944/preprints202509.2551.v1

[71] LeChevallier, M.W., 2019, Occurrence of culturable *Legionella pneumophila* in drinking water distribution systems. *AWWA Water Science* **1**, e1139. https://doi.org/10.1002/aws2.1139

[72] García-Ávila, F., Sánchez-Alvarracín, C., Cadme-Galabay, M., Conchado-Martínez, J., García-Mera, G., & Zhindón-Arévalo, C., 2020, Relationship between chlorine decay and temperature in the drinking water. *MethodsX* **7**, 101002. https://doi.org/10.1016/j.mex.2020.101002

[73] Wang, Y., Zhang, Z., Xia, M., Zhang, X., Lan, R., Wei, B., Liu, Y., Lu, Y., & Fan, G., 2025, Mechanism and risk control of chlorine-resistant bacteria in drinking water supply systems: A comprehensive bibliometric analysis. *Water* **17**, 956. https://doi.org/10.3390/w17070956

[74] Zhu, Z., Shan, L., Hu, F., Li, Z., Zhong, D., Yuan, Y., & Zhang, J., 2020, Biofilm formation potential and chlorine resistance of typical bacteria isolated from drinking water distribution systems. *RSC advances* **10**, 31295-31304. https://doi.org/10.1039/d0ra04985a

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Assessment of Microplastic Contamination in Surface Waters and Sediments of Pool Malebo, Congo River, Democratic Republic of the Congo

:

Nathan Manimesia Kayemba [1,a], Cédric Manianga K. [1,b], Christian Matamba Mpingija [2,c], Junior Omba Ombetshu [3,d], Clovis Ndege Simisi [1,e], Jean-Paul Koto-te-Nyiwa Ngbolua [4,f*], Crispin Mulaji Kyela [1,g]

[1] *Department of Chemistry and Industry, Faculty of Science and Technology, University of Kinshasa, Kinshasa, Democratic Republic of the Congo*

[2] *Department of Chemistry, General Commission for Atomic Energy/Regional Centre for Nuclear Studies of Kinshasa (CGEA/CREN-K), Mont Amba, Kinshasa, Democratic Republic of the Congo*

[3] *Department of Renewable Energy and Environmental Engineering, Faculty of Oil, Gas and Renewable Energies, University of Kinshasa, Kinshasa, Democratic Republic of the Congo*

[4] *Department of Life Sciences, Faculty of Science and Technology, University of Kinshasa, Kinshasa, Democratic Republic of the Congo*

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[a] **ORCID:** *0009-0000-9960-9366*; ***Email***: *nathankayemba7@gmail.com*

[b] **ORCID:** *0009-0004-4419-2371*; ***Email***: *seraphinmanianga@gmail.com*

[c] **ORCID:** *0009-0000-3732-3346*; ***Email***: *christianmatambs419@gmail.com*

[d] **ORCID:** *0009-0006-8045-1486*; ***Email***: *ombalareserve@gmail.com*

[e] **ORCID:** *0000-0001-9161-3109*; ***Email***: *clovis.ndege@unikin.ac.cd*

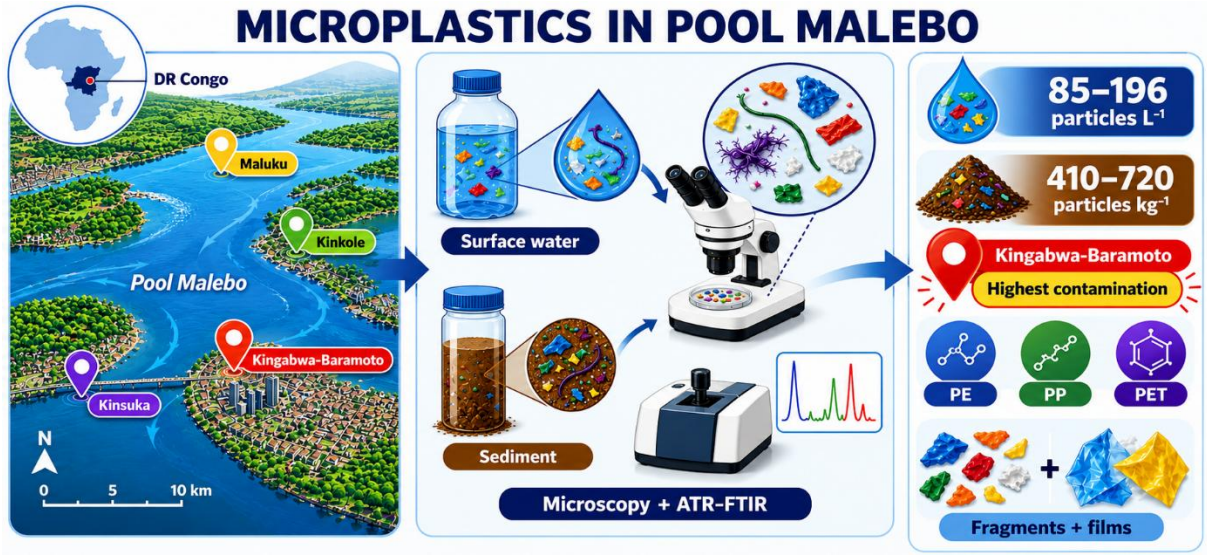
[f] **ORCID:** *0000-0002-0066-8153*; ***Email***: *jpngbolua@unikin.ac.cd*

[g] **ORCID:** *0000-0002-9406-3277*; ***Email***: *crispin.mulaji@unikin.ac.cd*

****Corresponding author:*** Jean-Paul Koto-te-Nyiwa Ngbolua; ***Email***: *jpngbolua@unikin.ac.cd*

Graphical Abstract

Data on microplastics in Central African inland waters remain limited; this study assessed surface-water and surficial-sediment contamination at four Pool Malebo sites, identifying significant spatial differences, with fragments and films dominating and PE, PP and PET as the main polymers. The findings provide baseline data for Pool Malebo and highlight the need for harmonized, repeated monitoring of microplastic pollution in the Congo River system.



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Abstract: Data on microplastics in Central African inland waters remain limited. This study assesses contamination in the surface waters and surficial sediments of four Pool Malebo sites: Maluku, Kinkole, Kingabwa-Baramoto, and Kinsuka, Democratic Republic of the Congo. Sampling was conducted in June 2024, with three independent replicates per site. Water samples were vacuum-filtered, and sediments underwent KOH digestion followed by vacuum filtration. Suspected particles were characterized by stereomicroscopy, and selected particles were identified by attenuated total reflectance Fourier-transform infrared spectroscopy (ATR-FTIR). Mean abundance ranged from 85 to 196 particles L^{-1} in water and from 410 to 720 particles kg^{-1} of dry sediment. Kingabwa-Baramoto showed the highest mean abundances, with significant differences among sites in both compartments ($p < 0.001$). Fragments and films were dominant. The main polymers identified were polyethylene (PE), polypropylene (PP), and polyethylene terephthalate (PET). These findings provide baseline data for Pool Malebo and highlight the need for harmonized, repeated monitoring of microplastic pollution in the Congo River system.

Keywords: *Microplastics, Pool Malebo, Congo River, ATR-FTIR*

Introduction

The production and use of plastics have increased considerably over recent decades. Inadequate waste management promotes their dispersal into aquatic environments. Microplastics, generally defined as plastic particles smaller than 5 mm, can be transported by watercourses, accumulate in sediments, and interact with aquatic organisms [1,2]. Recent studies show that African freshwater systems are insufficiently documented in this respect. A review focusing on African freshwaters highlights, in particular, the frequent occurrence of fragments and fibres, as well as the predominance of polymers such as PET and PP [3]. A meta-analysis of 75 African studies confirms the widespread distribution of microplastics in water, sediments, and biota and highlights the influence of sampling and identification methods on the reported abundances [4].

The Congo Basin is little studied compared to other major river basins. In Pool Malebo, the intensity of urban, domestic, commercial, port, and fishing activities help to distribute plastic waste. A study published in 2024 on the Pool Malebo hydrosystem reported the presence of plastic waste/microplastics in water, sediments, and fish between Maluku and Kinsuka, and emphasized the need for more advanced characterization methods [5]. Quantitative data obtained through water filtration and morphological characterization followed by polymer identification using FT-IR remain limited for this area.

The main scientific gap addressed here is therefore the lack of comparable data on the abundance of microplastics in the surface waters and surficial sediments of Pool Malebo, as well as on their polymer composition. The present study aims to document this contamination at four stations subjected to different levels of socio-economic pressure. The working hypothesis is that stations exposed to greater anthropogenic pressure exhibit higher abundances of microplastics in water and sediments, with a notable presence of polymers commonly used in packaging and consumer products.

The study has four main objectives: (i) to characterize selected physicochemical parameters of the waters studied; (ii) to quantify the abundance of microplastics in surface waters and surficial sediments; (iii) to describe their morphologies, colours, and size classes; and (iv) to identify the main polymers present using FT-IR. The study also seeks to discuss potential sources of contamination based on the observed spatial distribution.

Materials and Methods

Study Area and Sampling Period

Sampling was carried out in June 2024 at four sites in Pool Malebo: Maluku, Kinkole, Kingabwa-Baramoto and Kinsuka. The four stations were selected to cover different contexts of exposure to human activities, particularly domestic discharges, port activities, artisanal fishing and urbanization. Table 1 presents the geographical locations of the study sites; Figure 1 shows their locations on the map.

Table 1. Geographical coordinates of the sampling site

Code	Sampling site	Latitude	Longitude
EW1M	Maluku	4°20′56.56596″ S	15°21′42.40404″ E
EW2K	Kinkole	4°03′06.23664″ S	15°33′11.37276″ E
EW3K-B	Kingabwa-Baramoto	4°19′07.71492″ S	15°20′49.21800″ E
EW4K	Kinsuka	4°19′08.81976″ S	15°20′52.32804″ E

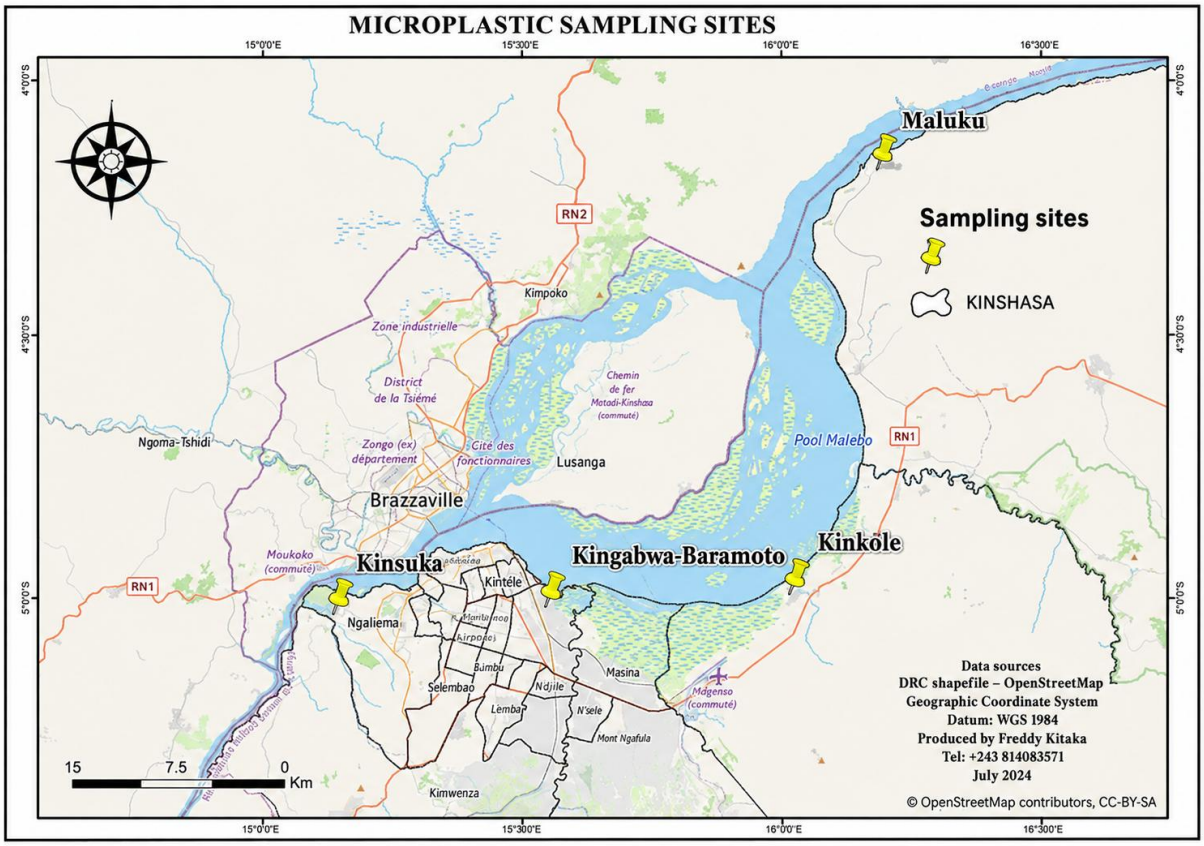


Figure 1. Location of the sampling sites in Pool Malebo.

The campaign was conducted during a single sampling period; therefore, the study does not allow seasonal variations to be compared. Three independent replicates were carried out per site for the microplastic analyses.

Water and Sediment Sampling

Three independent replicates were collected at each station. For water, 1 L was collected and analysed for each replicate, giving a total of 3 L per station and 12 L for the entire sampling campaign. To document particles recently deposited in the surficial sediment compartment, samples were collected from the layer located between 0 and 5 cm depth using a previously cleaned stainless-steel spatula. The results were expressed as particles L^{-1} for water and particles kg^{-1} of dry matter for sediments. The samples were handled using glassware whenever possible, and the operators wore cotton clothing to prevent contamination.

Determination of Physicochemical Parameters

The physicochemical parameters were measured in situ to characterize the environmental conditions at the time of sampling and to examine their exploratory association with microplastic abundance. The parameters determined were temperature, pH, electrical conductivity (EC), total dissolved solids (TDS), salinity and dissolved oxygen. Measurements were performed using a Hanna Instruments multiparameter meter (model HI98194; the field notebook records the model as H198194), manufactured in the United States, after calibration according to the manufacturer's recommendations and laboratory control procedures. The HI98194 is designed for field measurement of pH, conductivity, TDS, salinity, dissolved oxygen and temperature.

Extraction and Counting of Microplastics

Water Samples

For each microplastic counting test, 1 L of collected water was vacuum-filtered. Each filter was then transferred to a previously cleaned and closed glass Petri dish. Vacuum filtration followed a commonly used approach for isolating suspended microplastics from water samples [2,6].

The filters were dried for one to two days under conditions limiting their exposure to dust. After drying, particles visually compatible with microplastics were observed under a microscope at a magnification of at least ×25 and then counted for each sample.

The morphology of each selected particle was described before its classification according to shape, colour and size class. Abundances were normalized to the volume of water filtered and expressed as particles L^{-1}. The same counting protocol was applied to the three replicates from each station.

Counting of Microplastics in Sediment Samples

Microplastics in sediment samples were counted using the alkaline digestion–filtration procedure described below. The sediments were subjected to alkaline digestion with KOH to reduce the organic matter before filtration and observation. The use of alkaline digestion with KOH is established in microplastic extraction protocols, although the concentration, temperature and exposure time must be reported because alkaline treatment can affect some polymers [2,7]. For this purpose, 50 g of sediment was weighed for each analysis. A 10% KOH solution was prepared by dissolving 10 g of KOH in 100 mL of distilled water. Each 50 g portion of sediment was then treated with 100 mL of this solution. The suspension was placed on a magnetic stirrer for 30 min. After resting for 30 min, it was vacuum-filtered. The filters were then placed in glass Petri dishes and dried. The dried filters were subsequently examined under a microscope, and the suspected particles were counted. The final results were reported as particles kg^{-1} of dry matter.

Observation and Classification of Microplastics

The isolated particles were examined using a Leica Microsystems stereomicroscope (Leica EZ4, Germany) at ×40 magnification to characterize their morphology. Visual classification into common morphotypes such as fragments, fibres, films, foams and beads is consistent with established microplastic reporting frameworks [6]. The isolated particles were visually classified according to the criteria presented in Table 2:

Table 2. Criteria used for the visual classification of microplastics

Classification criterion	Categories
Shape	Fibres, fragments, films, foams, granules and beads
Colour	Transparent, white, blue, black, red, green, yellow and grey
Size	20–500 µm; 500 µm–1 mm; 1–5 mm

Identification of Polymers by FT-IR Spectroscopy

Polymer identification was carried out at the Kinshasa Pharmaceutical Laboratory (LAPHAKI) using a Shimadzu Fourier-transform infrared spectrophotometer (IRSpirit-T, Japan) equipped for ATR measurements. Spectral processing was performed using OMNIC v9 software. The spectra obtained were compared to the reference libraries available in the software. A spectrum was considered compatible with a polymer when its match with the reference library was greater than 70%. This threshold was used as an operational criterion in the present study; but, reliable FTIR identification should also consider diagnostic bands, spectral quality and uncertainty rather than relying on the library score alone [6,8]. The detection limit reported in the protocol was 20 µm.

Quality Assurance and Quality Control

Field blanks (n = 3) and laboratory blanks (n = 3) were included. Glass equipment was used whenever possible, and the operators wore 100% cotton clothing. No significant contamination was observed in the blanks. These measures are consistent with recommended QA/QC practices for microplastic analysis, particularly the use of blanks, non-plastic equipment and contamination-resistant handling procedures [6].

Analytical Performance and Method Validation

Table 3 shows that the control measures implemented helped to limit external contamination and assess the performance of the method. No significant contamination was observed in the blanks. A recovery test was also performed on samples artificially spiked with reference microplastics. The mean recovery rate obtained was 92.00 ± 5.00%, indicating an overall satisfactory analytical recovery.

Table 3. Quality-control and method-validation parameters

Parameter	**Procedure or value obtained**
Field blanks	n = 3
Laboratory blanks	n = 3
Analytical replicates	n = 3
FT-IR detection limit	20 µm
Spectral match threshold	> 70%
Contamination observed in the blanks	Not significant
Mean recovery rate	92.00 ± 5.00%

Field and laboratory blanks were used to monitor contamination that could occur during sampling and handling. No significant contamination was observed in the blanks. The spectral match threshold used for polymer identification was greater than 70%. The test performed on samples spiked with reference microplastics gave a mean recovery rate of 92 ± 5%, indicating an overall satisfactory analytical recovery.

Data Processing and Analysis

The data were processed using Microsoft Excel 2021 and IBM SPSS Statistics 26. Descriptive results were presented as means ± standard deviations (n = 3).

For physicochemical parameters, the three independent replicate observations per station were analysed by one-way ANOVA followed by Tukey's HSD post hoc test at $\alpha = 0.05$. Mean ± standard deviation (SD) were calculated from the three replicates. For salinity, all replicate values within each station were identical; consequently, the within-group variance was zero and a conventional F statistic and Tukey HSD test were not estimable for this parameter.

Microplastic abundance in surface water and sediments was analysed separately using one-way ANOVA to assess differences among the four sampling sites. When the overall ANOVA was significant, Tukey's HSD post hoc test was used for pairwise comparisons among sites. Statistical significance was considered at $p < 0.05$.

Relationships between microplastic abundance and selected physicochemical parameters were explored using Pearson correlation coefficients based on station-level values. Given the small number of sampling sites (n = 4), these correlations were considered exploratory and were not used for causal inference.

Results and Discussion

Physicochemical Parameters of the Water

The physicochemical parameters showed marked spatial variability. Kingabwa-Baramoto recorded the highest electrical conductivity (253.33 ± 1.53 µS cm^{-1}), TDS (216.00 ± 1.00 mg L^{-1}) and salinity (0.15 ± 0.00%), whereas Kinsuka showed the lowest conductivity (44.37 ± 0.15 µS cm^{-1}) and TDS (37.63 ± 0.21 mg L^{-1}). Dissolved oxygen was highest at Kinkole (7.46 ± 0.21 mg L^{-1}) and lowest at Maluku (0.52 ± 0.14 mg L^{-1}). One-way ANOVA showed significant differences among stations for pH ($F = 27.30$, $p < 0.001$), electrical conductivity ($F = 17020.20$, $p < 0.001$), TDS ($F = 61446.41$, $p < 0.001$) and dissolved oxygen ($F = 1386.14$, p

< 0.001). Salinity could not be subjected to a conventional F-test because within-station variance was zero. Tukey's HSD showed the group differences indicated by superscript letters in Table 4.

The coincidence of high conductivity and TDS values with the high abundance of microplastics at Kingabwa-Baramoto is consistent with a local anthropogenic influence, but it does not, on its own, establish a causal relationship. Repeated sampling campaigns and a larger number of stations would be required to confirm this association.

Table 4. Physicochemical parameters measured in the waters of Pool Malebo

Station	pH	T (°C)	Electrical conductivity (µS cm^{-1})	TDS (mg L^{-1})	Salinity (%)	Dissolved O_2 (mg L^{-1})
Maluku (EW1M)	6.63 ± 0.11^{b}	27.4 ± 0.00	56.23 ± 2.02^{c}	48.23 ± 0.50^{c}	0.03 ± 0.00	0.52 ± 0.14^{c}
Kinkole (EW2K)	7.33 ± 0.02^{a}	27.8 ± 0.00	108.80 ± 0.20^{b}	92.60 ± 0.10^{b}	0.07 ± 0.00	7.46 ± 0.21^{a}
Kingabwa-Baramoto (EW3K-B)	6.72 ± 0.05^{b}	28.1 ± 0.00	253.33 ± 1.53^{a}	216.00 ± 1.00^{a}	0.15 ± 0.00	0.90 ± 0.13^{c}
Kinsuka (EW4K)	7.29 ± 0.21^{a}	27.6 ± 0.00	44.37 ± 0.15^{d}	37.63 ± 0.21^{d}	0.03 ± 0.00	1.82 ± 0.09^{b}

Values are presented as mean ± standard deviation (n = 3), except for temperature, for which the available field record contains one station-level reading. Different superscript letters within the same column indicate significant differences according to Tukey's HSD test ($p < 0.05$). One-way ANOVA showed significant differences among stations for pH ($F = 27.30$, $p < 0.001$), electrical conductivity ($F = 17020.20$, $p < 0.001$), TDS ($F = 61446.41$, $p < 0.001$) and dissolved oxygen ($F = 1386.14$, $p < 0.001$). For salinity, the within-station variance was zero; therefore, the ANOVA F statistic and Tukey's HSD test could not be estimated.

Abundance of Microplastics in Water and Sediments

Mean microplastic abundance ranged from 85 ± 5 to 196 ± 12 particles L^{-1} in surface water and from 410 ± 18 to 720 ± 34 particles kg^{-1} of dry matter in sediments. Significant differences were observed among sampling sites for both surface water (one-way ANOVA, $F = 100.85$, $p < 0.001$) and sediment ($F = 88.72$, $p < 0.001$). Tukey's HSD post hoc comparisons showed the significant differences among sampling sites indicated by the superscript letters in Table 5. Kingabwa-Baramoto exhibited the highest mean microplastic abundance in both matrices, whereas Maluku showed the lowest mean values.

Table 5. Mean abundance of microplastics in water and sediments

Sampling site	Water (particles L^{-1})	Sediment (particles kg^{-1} dry matter)
Maluku (EW1M)	85.00 ± 5.00^{c}	410.00 ± 18.00^{c}
Kinkole (EW2K)	124.00 ± 8.00^{b}	580.00 ± 25.00^{b}
Kingabwa-Baramoto (EW3K-B)	196.00 ± 12.00^{a}	720.00 ± 34.00^{a}
Kinsuka (EW4K)	103.00 ± 7.00^{bc}	465.00 ± 21.00^{c}

Values are expressed as mean ± standard deviation (n = 3). Different superscript letters within the same column indicate significant differences among sampling sites according to Tukey's HSD post hoc test ($p < 0.05$)

The high microplastic abundance observed at Kingabwa-Baramoto may be consistent with stronger local socio-economic pressure. Particle accumulation and deposition may also contribute to the relatively high concentrations observed in sediments. Precise source attribution requires additional information on plastic use, waste inputs, discharges and local hydrodynamic conditions.

Distribution of Microplastics According to Shape and Colour

Morphotypes

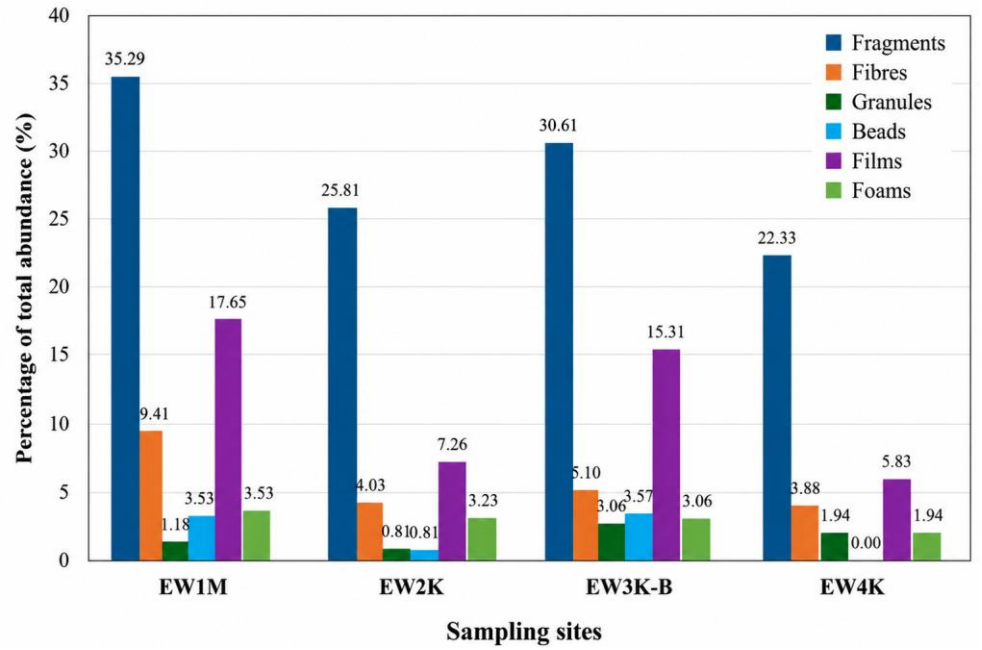


Figure 2. Relative distribution of morphologically classified microplastics by shape in the surface waters of Pool Malebo. Values are expressed as the percentage of the total mean abundance reported in Table 5; they therefore preserve the distinction between the total counted abundance and the subset classified morphologically.

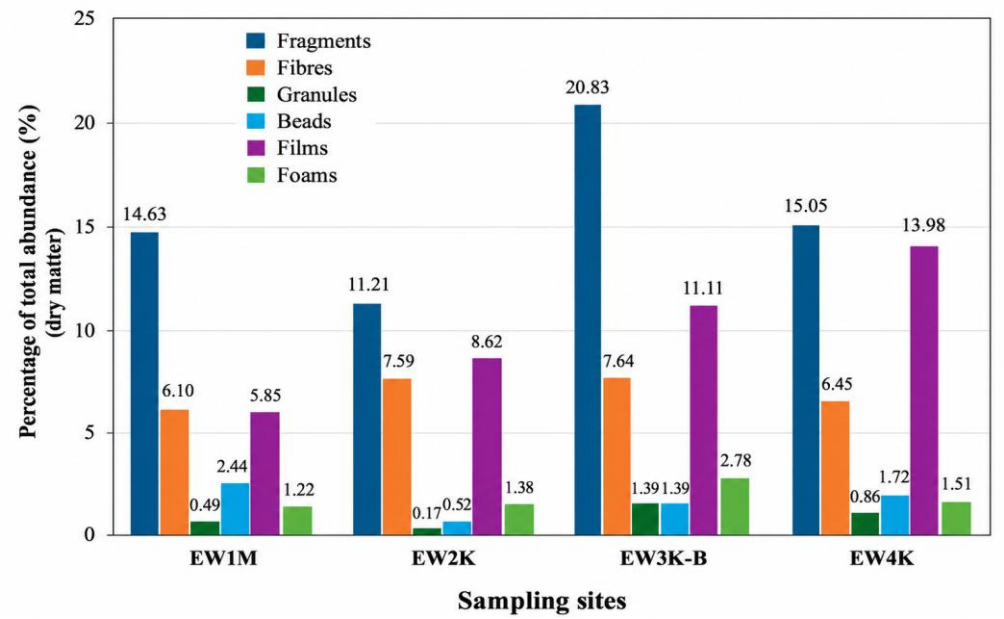


Figure 3. Relative distribution of morphologically classified microplastics by shape in the sediments of Pool Malebo. Values are expressed as the percentage of the total mean abundance reported in Table 5. They therefore preserve the distinction between the total counted abundance and the subset classified morphologically.

Note: Three independent replicates were analysed per site, with 50 g of sediment processed per analysis

Fragments made up the dominant morphotype, followed by films and fibres. Fragments may result from the breaking down of larger plastic waste; films are consistent with the degradation of bags and flexible packaging. The presence of fibres can be linked to synthetic textiles and household wastewater, but this cannot be proved with morphological observations only [3,9].

Colours

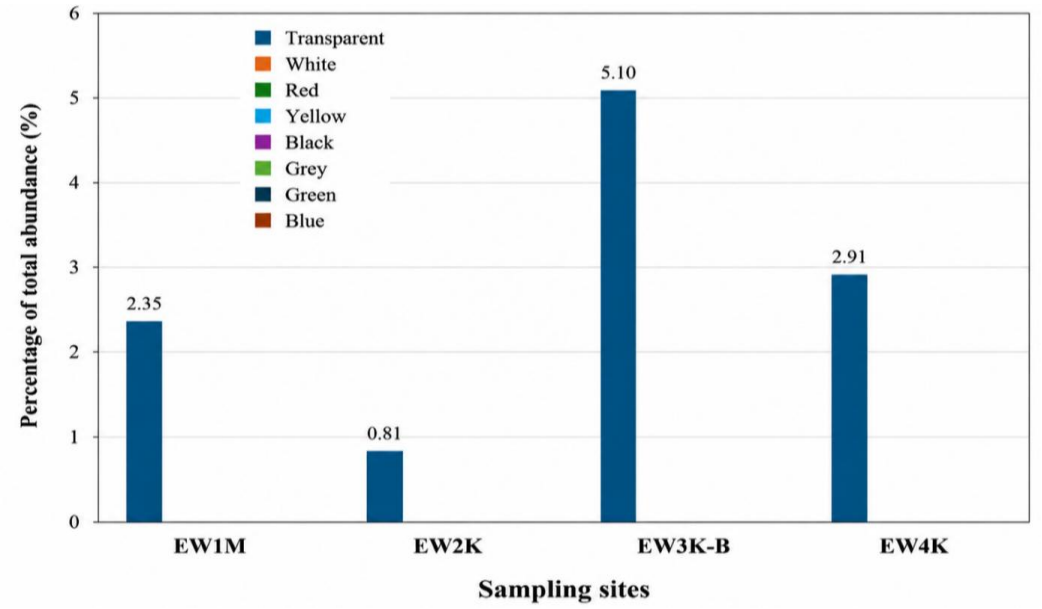


Figure 4. Colour distribution of the classified microplastic subset in the surface waters of Pool Malebo, expressed as a percentage of the total mean abundance reported in Table 5. Only particles actually recorded in the colour-classification dataset are represented; no unobserved colour classes were imputed.

Note: n = 3 independent replicates per site; 1 L of water was filtered per replicate.

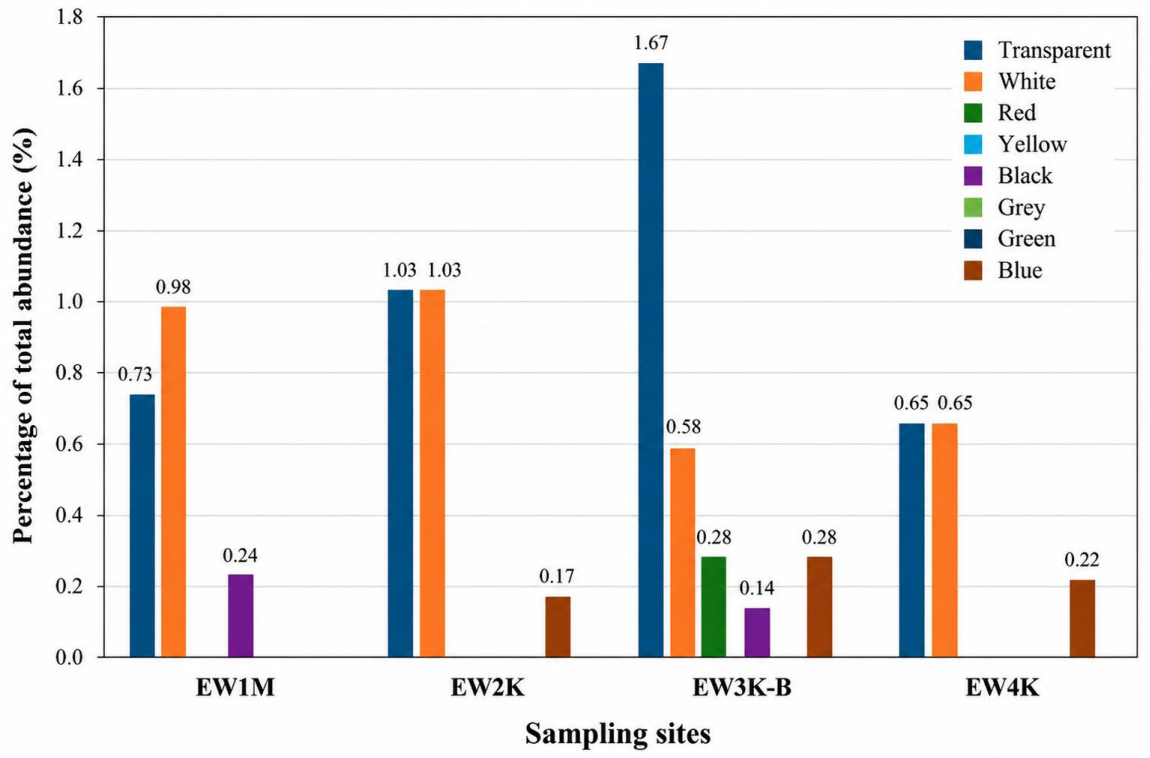


Figure 5. Colour distribution of the classified microplastic subset in the sediments of Pool Malebo, expressed as a percentage of the total mean abundance reported in Table 5. Only particles actually recorded in the colour-classification dataset are represented; no unobserved colour classes were imputed.

Note: Three independent replicates were analysed per site, with 50 g of sediment processed per analysis.

Transparent, white, blue, black and other recorded colour classes were represented among the classified particles. In Figures 2–5, classification values are presented relative to the total mean abundance in Table 5, and the distinction is maintained between total abundance and the subset that was classified. Consequently, the plotted percentages may sum to less than 100% when only a subset of particles was classified. Colour is a descriptive indicator and cannot, on its own, identify the origin or polymer of a particle.

Identification of Polymers by FT-IR Spectroscopy

Sample : EW1M

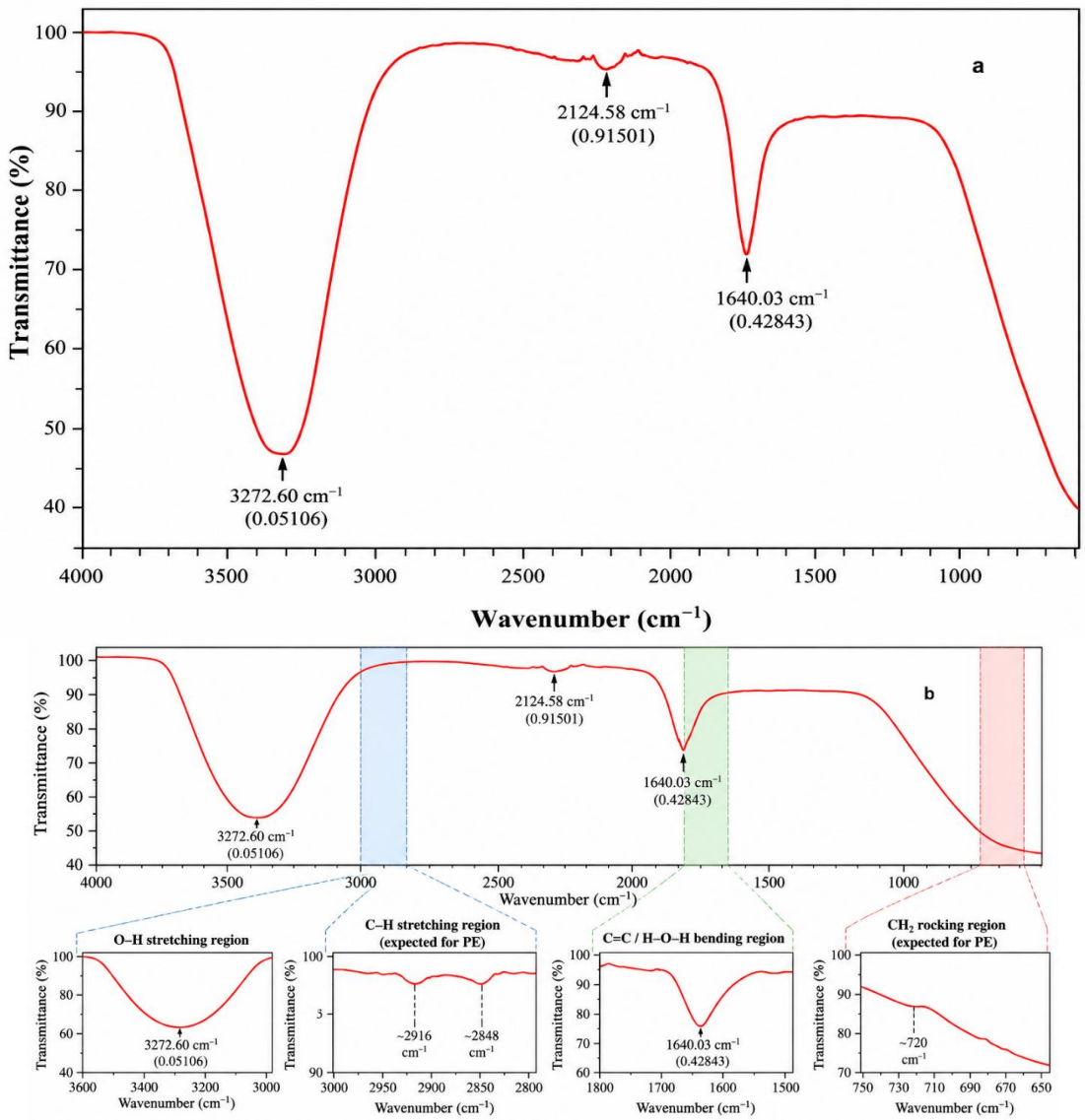


Figure 6. ATR-FTIR spectrum of a particle tentatively identified as polyethylene (PE) in surface water from the EW1M sampling site: (a) original spectrum with the detected peaks; (b) enlarged spectral regions showing the comparison with the characteristic absorption bands of PE.

The OMNIC library result reported for EW1M indicates PE with a 93% match; but, the displayed experimental spectrum does not show the principal PE bands expected near 2915–2848, 1465 and 720 cm^{-1}. The reported experimental peaks at 3272, 1640 and 2124 cm^{-1} are not sufficient to confirm PE and may reflect O–H/N–H stretching, water bending or weak combination/background features [6,8,10] (Table 6).

Table 6. Comparison of the EW1M spectrum with characteristic absorption bands of polyethylene (PE).

Wavenumber (cm^{-1}) – PE reference	**Vibration mode**	**Observation in the present spectrum**	**Interpretation**
2915–2920	C–H asymmetric stretching (CH_2)	Very weak or not clearly visible	Characteristic PE band not clearly identified
2848–2850	C–H symmetric stretching (CH_2)	Very weak or not clearly visible	Characteristic PE band not clearly identified
1462–1472	CH_2 bending (scissoring)	Not clearly evident	Characteristic PE band not clearly identified
717–730	CH_2 rocking	Not evident around ~720 cm^{-1}	Characteristic PE band not identified
—	O–H stretching	Broad band at 3272.60 cm^{-1}	Consistent with adsorbed water and/or hydroxyl groups
—	H–O–H bending / possible C=C	Band at 1640.03 cm^{-1}	May correspond to adsorbed water or possibly C=C

Sample: ES4NBB

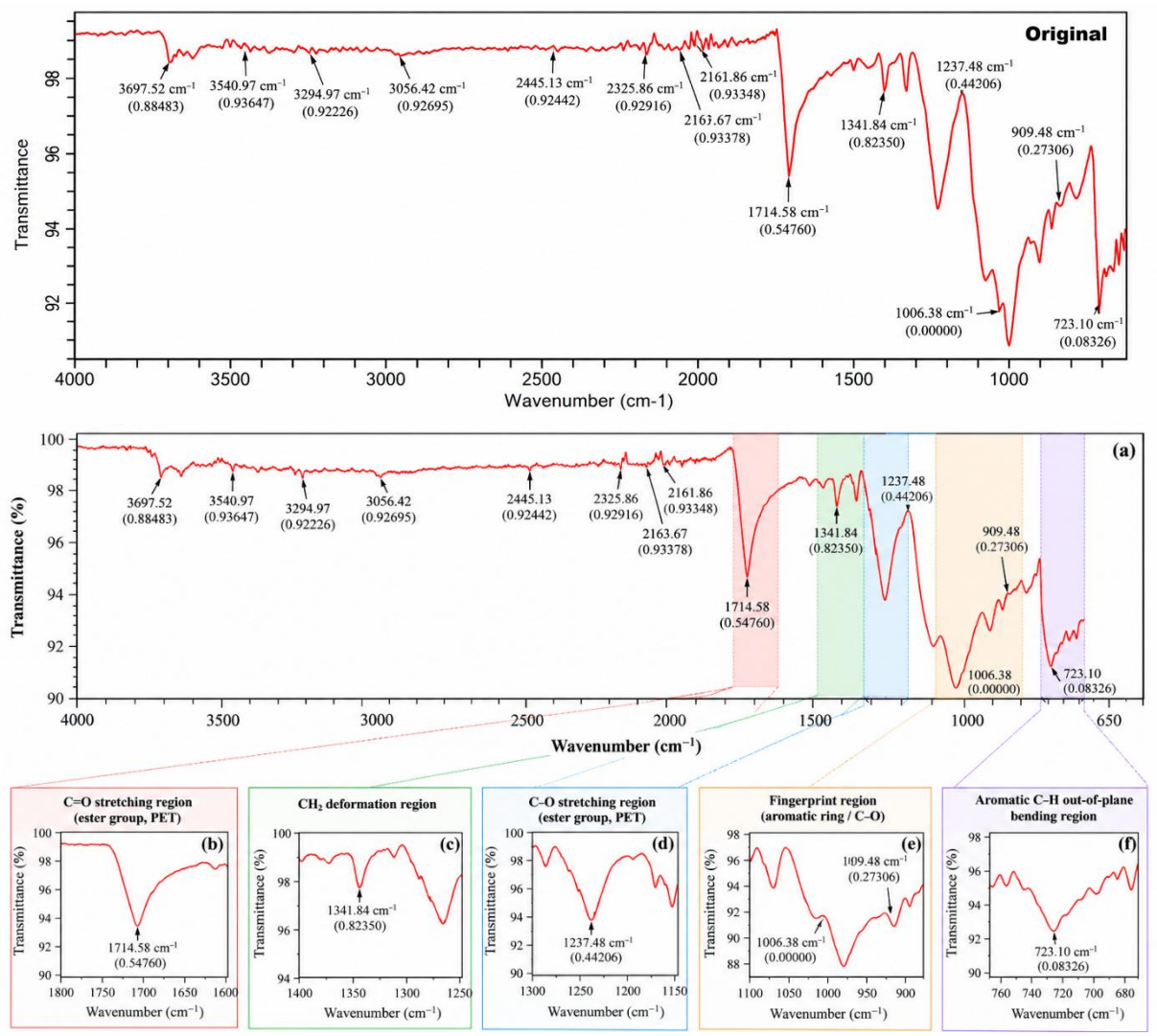


Figure 7. ATR-FTIR spectrum of a plastic particle identified as polyethylene terephthalate (PET) in a sediment sample from the Kinkole sampling site (ES4NBB): (a) original spectrum with the main detected peaks; (b–f) enlarged spectral regions showing the characteristic absorption bands of PET.

The experimental spectrum shown for ES4NBB contains bands near 1714, 1237 and 723 cm^{-1}, together with a band near 3056 cm^{-1}. This pattern is more consistent with a PET-type spectrum than with PE, because the carbonyl stretching band near 1714 cm^{-1} and C–O stretching bands around 1240 cm^{-1} are characteristic of PET, but the band near 723 cm^{-1} is also reported for PET. The OMNIC library match reported for ES4NBB was 92%. Together with the characteristic absorption bands observed near 1714, 1237 and 723 cm^{-1}, this result supports the PET assignment [6,8,11].

Sample: ES2MBM

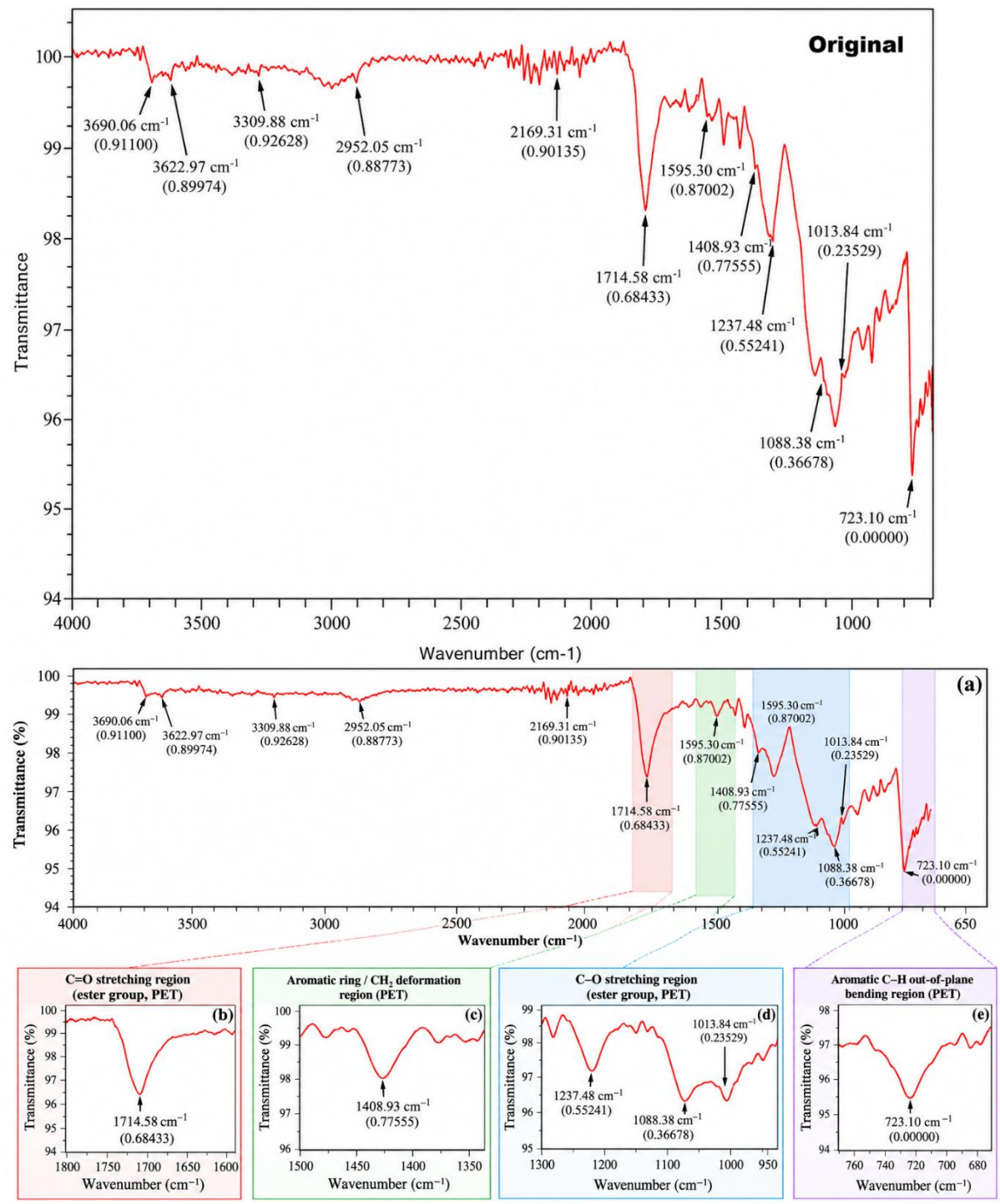


Figure 8. ATR-FTIR spectrum of a particle identified as polyethylene terephthalate (PET) in a sediment sample collected at Kingabwa-Baramoto (**ES2MBM**)

The experimental spectrum for ES2MBM is strongly consistent with polyethylene terephthalate (PET). The principal observed bands are approximately 1714 cm⁻¹ (ester C=O stretching), 1237 and 1088 cm⁻¹ (C–O/C–O–C stretching), 1409 cm⁻¹ (CH deformation) and 723 cm⁻¹ (aromatic C–H out-of-plane vibration). These bands form a coherent PET fingerprint. The additional

features near 2952, 3309, 3622 and 3690 cm^{-1} should not be used as primary PET markers and may reflect surface/atmospheric contributions (Table 7). The OMNIC library match reported for ES2MBM was 94%, supporting the PET assignment when considered together with the characteristic experimental absorption bands [10].

Table 7. Diagnostic ATR-FTIR bands and proposed polymer assignments for the analysed particles.

Sample	Proposed polymer	Observed diagnostic peaks (cm^{-1})	Assignment	OMNIC match (%)	Reference
EW1M	PE (OMNIC assignment; not confirmed manually)	3272; 1640; 2124	3272: O–H/N–H stretching region; 1640: H–O–H bending/amide-I region; 2124: weak combination/background feature. The characteristic PE band expected near 720–730 cm^{-1} was not clearly identified in the displayed spectrum	93	[6,8,10,11]
ES4NBB	PET (provisional)	1714; 1237; 723; 3056; 1342	1714: ester C=O stretching; 1237: C–O stretching; 723: aromatic C–H out-of-plane vibration; 3056: aromatic C–H stretching; 1342: deformation region	92	[6,8,10,11]
ES2MBM	PET	1714; 1237; 1088; 1409; 723	1714: ester C=O stretching; 1237/1088: C–O/C–O–C stretching; 1409: CH deformation; 723: aromatic C–H out-of-plane vibration	94	[6,8,10,11]

Table 8. Main polymers identified by ATR-FTIR spectroscopy and corresponding library match scores.

Sample	Polymer identified	Library match score (%)
EW1M	PE*	93
ES4NBB	PET*	92
ES2MBM	PET	94
EW2K	PP	91
EW3K-B	PET	95

**For EW1M, the PE assignment remains tentative and requires confirmation from the original raw spectrum and OMNIC report.*

All the reported match scores in Table 8 were above 90% (91–95%) and therefore exceeded the 70% threshold adopted in the method. These values increase confidence in the identifications

listed in Table 8, without allowing the polymer composition to be extrapolated to all particles not analysed by FT-IR.

FT-IR library matching mainly assigned PE, PP and PET in the current dataset, but the manual interpretation of the displayed experimental spectra shows that at least the EW1M spectrum requires re-verification. Accordingly, library match scores should be reported together with diagnostic experimental bands rather than used as the sole basis for polymer identification. PE and PP are commonly used in films, plastic bags, packaging and consumer products. PET is widely used in bottles and containers. The presence of these polymers is consistent with a substantial contribution from urban and commercial waste, but source identification requires further tracing analyses.

The polymer composition observed is also consistent with the trends described in recent reviews of African aquatic systems, in which PP, PET and PE are among the polymers frequently reported [3,4,12]

Statistical Analysis

Table 9. Exploratory correlations between microplastic abundance and selected physicochemical parameters

Parameter	Pearson's correlation coefficient (r)
Electrical conductivity	0.89
TDS	0.87
Salinity	0.84
Dissolved oxygen	−0.71

The Pearson coefficients calculated from the four station values (Table 9) indicate positive associations between microplastic abundance and conductivity (r = 0.89), TDS (r = 0.87) and salinity (r = 0.84), as well as a negative association with dissolved oxygen (r = −0.71). Given that n = 4 stations and that detailed physicochemical replicates were absent from the available dataset, these coefficients should be considered exploratory and should not be presented as robust statistical evidence of a causal relationship.

Discussion

The results show contamination at all four stations studied, with a marked spatial gradient and the highest abundances at Kingabwa-Baramoto. This station also showed the highest conductivity and TDS values and a low dissolved oxygen concentration. The most cautious

interpretation is that local conditions and socio-economic pressures may jointly contribute to the observed distribution.

The predominance of fragments and films is consistent with a substantial contribution from the secondary fragmentation of larger plastic waste. Fibres may also originate from domestic and textile activities. Recent reviews of African freshwaters frequently report fragments and fibres, placing the observations from Pool Malebo within the broader context of contamination in African inland waters [3,13-16].

The presence of PE, PP and PET is consistent with the common uses of these polymers in packaging and consumer products. A recent African meta-analysis also identifies PP, PET and PE among the polymers frequently observed in aquatic ecosystems across the continent [4]. Masua Tchomba *et al.* also documented in Pool Malebo microplastics in water, sediments and fish between Maluku and Kinsuka in their 2024 study [5].

Comparisons with other major rivers must be made with caution because concentrations vary with the volume filtered, the type of matrix, the mesh size or filter, the range of sizes detected and the identification method. Recent reviews emphasize the need to harmonize protocols to make studies comparable [2,4,13-17]. Therefore, the values from Pool Malebo should be compared to those in studies which have used the same type of methods and units.

From an ecological standpoint, the presence of microplastics in water and sediments justifies monitoring aquatic organisms and trophic transfer pathways. Experimental studies and recent reviews indicate that microplastics may be ingested by aquatic organisms and interact with other contaminants; but, the present study measures neither ecotoxicological effects nor human exposure. Health implications should therefore be presented as research perspectives rather than as effects demonstrated in Pool Malebo [3,13-17].

Accordingly, future research should move beyond documenting the occurrence and spatial distribution of microplastics to assess actual exposure pathways and biological effects, including ecotoxicological responses in aquatic organisms and, where appropriate, potential human health effects associated with exposure through water and aquatic food resources.

Limitations of the Study

Several limitations must be taken into account. First, only four stations were studied, and sampling was conducted during a single campaign in June 2024; therefore, no conclusions can be drawn regarding seasonal variability. Second, only a fraction of the particles was characterized by FT-IR, which limits the extrapolation of polymer composition to all the

particles observed. Third, the available physicochemical data are station-level values, which greatly limits the scope of the correlations.

Conclusion

This study highlights the presence of microplastics in the surface waters and sediments of the four Pool Malebo stations studied in June 2024. Mean abundances ranged from 85 to 196 particles L^{-1} in water and from 410 to 720 particles kg^{-1} of dry matter in sediments, with the highest values recorded at Kingabwa-Baramoto. Fragments and films dominated the morphotypes observed, and PE, PP and PET were among the polymers identified by FT-IR. These results provide baseline data for monitoring plastic pollution in Pool Malebo. They do not, on their own, establish the exact sources, seasonal trends or health effects of this contamination.

In operational terms, the priority is to establish a harmonized monitoring programme covering water, sediments and, eventually, biota, with standardized QA/QC protocols and campaigns conducted across several seasons. Strengthening the collection and management of plastic waste in riparian areas is also a relevant preventive measure. Future studies should include broader sampling, systematic FT-IR characterization or another validated spectroscopic technique, and statistical analysis based on individual data.

Recommendations

In view of the results and the limitations identified, the following recommendations may be helpful:

1. Establish a regular microplastic monitoring programme in Pool Malebo and the Congo River, using harmonized protocols and documented QA/QC procedures.
2. Strengthen the collection, sorting, recovery and recycling of plastic waste in the riparian areas of Kinshasa and Brazzaville, particularly targeting packaging and products made from PE, PP and PET.
3. Raise awareness among riparian communities, fishers, traders and other local stakeholders about preventing the discharge of plastics into the river.
4. Develop studies on fish and other aquatic organisms to assess the ingestion and trophic transfer of microplastics in Pool Malebo.

Research Perspectives

Future research should particularly:

1. Extend sampling upstream and downstream of Pool Malebo to better characterize spatial gradients.
2. Repeat the sampling campaigns during the dry and rainy seasons to assess seasonal dynamics.
3. Increase the number of replicates and analyse the individual data using appropriate statistical methods, including tests of normality and homogeneity, post hoc comparisons, confidence intervals and effect sizes.
4. Investigate the transfer of microplastics into aquatic organisms and, where resources permit, size fractions below 20 µm using appropriate analytical techniques.
5. Assess the actual biological and health effects associated with microplastic exposure in Pool Malebo, going beyond occurrence and spatial distribution. Future studies should combine exposure assessment with ecotoxicological investigations in aquatic organisms and, where appropriate, human health studies in populations potentially exposed through water and the consumption of aquatic resources.

These studies will contribute to establishing a robust database on plastic pollution in Central Africa and support policies for the sustainable management of the Congo River.

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Author Contributions

Nathan Manimesia Kayemba: Conceptualization, Methodology, Investigation, Data Curation, Formal analysis, Writing-Original Draft, and Writing – review & editing.

Cédric Manianga K.: Methodology, Investigation, Writing – review & editing.

Christian Matamba Mpingija: Investigation, Formal analysis, Writing – review & editing.

Junior Omba Ombetshu: Investigation, Validation, Writing – review & editing.

Clovis Ndege Simisi: Supervision, Validation, Formal analysis, Writing – review & editing.

Jean-Paul Koto-te-Nyiwa Ngbolua: Supervision, Formal analysis, Validation, Writing – review & editing.

Crispin Mulaji Kyela: Supervision, Project administration, Methodology, Validation, Writing – review & editing, Final approval of the manuscript.

References

[1] Hidalgo-Ruz, V., Gutow, L., Thompson, R. C., & Thiel, M., 2012, Microplastics in the marine environment: A review. *Environmental Science & Technology* **46**(6), 3060–3075. https://doi.org/10.1021/es2031505

[2] Lu, H. C., Ziajahromi, S., Neale, P. A., & Leusch, F. D. L., 2021, A systematic review of freshwater microplastics in water and sediments: Recommendations for harmonisation to enhance future study comparisons. *Science of the Total Environment* **781**, 146693. https://doi.org/10.1016/j.scitotenv.2021.146693

[3] Yakubu, S., Miao, B., Hou, M., & Zhao, Y., 2024, A review of the ecotoxicological status of microplastic pollution in African freshwater systems. *Science of the Total Environment* **946**, 174092. https://doi.org/10.1016/j.scitotenv.2024.174092

[4] Nyaga, M. P., Shabaka, S., Oh, S., Osman, D. M., Yuan, W., Zhang, W., & Yang, Y., 2024, Microplastics in aquatic ecosystems of Africa: A comprehensive review and meta-analysis. *Environmental Research* **248**, 118307. https://doi.org/10.1016/j.envres.2024.118307

[5] Masua Tchomba, B., Kaki Ngisila, B., Musibono Eyul'Anki, D., Pwema Kiamfu, V., & Kayembe Sungula, J., 2024, Plastic pollution of Kinshasa rivers: Highlighting microplastic contamination of the Malebo Pool hydrosystem (Congo River) in Kinshasa (DR Congo) and risk to the health of tourists. *International Journal of Innovation and Scientific Research* **76**(1), 93–126. http://www.issr-journals.org/links/papers.php?journal=ijisr&application=pdf&article=IJISR-24-289-12

[6] Primpke, S., Christiansen, S. H., Cowger, W., De Frond, H., Deshpande, A., Fischer, M., Holland, E. B., Meyns, M., O'Donnell, B. A., Ossmann, B. E., Pittroff, M., Sarau, G., Scholz-Böttcher, B. M., & Wiggin, K. J., 2020, Critical assessment of analytical methods for the harmonized and cost-efficient analysis of microplastics. *Applied Spectroscopy* **74**(9), 1012–1047. https://doi.org/10.1177/0003702820921465

[7] Lusher, A. L., & Hernandez-Milian, G., 2018, Microplastic extraction from marine vertebrate digestive tracts, regurgitates and scats: A protocol for researchers from all experience levels. *Bio-protocol* **8**(22), e3087. https://doi.org/10.21769/BioProtoc.3087

[8] Fan, C., Huang, Y.-Z., Lin, J.-N., & Li, J., 2021, Microplastic constituent identification from admixtures by Fourier-transform infrared (FTIR) spectroscopy: The use of polyethylene terephthalate (PET), polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC) and nylon (NY) as the model constituents. *Environmental Technology & Innovation* **23**, 101798. https://doi.org/10.1016/j.eti.2021.101798

[9] Lambert, S., Sinclair, C.J., Boxall, A.B.A., 2014, Occurrence, degradation, and effects of polymer-based materials in the environment. *Reviews of Environmental Contamination and Toxicology* **227**, 1–53. https://doi.org/10.1007/978-3-319-01327-5_1.

[10] Gulmine, J. V., Janissek, P. R., Heise, H. M., & Akcelrud, L., 2002, Polyethylene characterization by FTIR. *Polymer Testing* **21**(5), 557–563. https://doi.org/10.1016/S0142-9418(01)00124-6

[11] Mecozzi, M., & Nisini, L., 2019, The differentiation of biodegradable and non-biodegradable polyethylene terephthalate (PET) samples by FTIR spectroscopy: A potential support for the structural differentiation of PET in environmental analysis. *Infrared Physics & Technology* **101**, 119-126. https://doi.org/10.1016/j.infrared.2019.06.008

[12] Zhu, X., Yan, D., & Fang, Y., 2001, In situ FTIR spectroscopic study of the conformational change of isotactic polypropylene during the crystallization process. *The Journal of Physical Chemistry B* **105**(50), 12461–12463. https://doi.org/10.1021/jp012165f

[13] Zea, Cobos, A.G., Amón, J., León, E., Caballero, P., 2024, Standardization of FTIR-based methodologies for microplastics dtection in drinking water: A meta-analysis indeed and practical approach. *Water* **16**(22), 3170. https://doi.org/10.3390/w16223170

[14] Peng, J., Wang, J., & Cai, L., 2017, Current understanding of microplastics in the environment: Occurrence, fate, risks, and what we should do. *Integrated Environmental Assessment and Management* **13**(3), 476–482. https://doi.org/10.1002/ieam.1912

[15] Vandermeersch, G., Van Cauwenberghe, L., Janssen, C. R., Marques, A., Granby, K., Fait, G., Kotterman, M. J. J., Diogène, J., Bekaert, K., Robbens, J., & Devriese, L., 2015, A critical view on microplastic quantification in aquatic organisms. *Environmental Research* **143**, 46–55. https://doi.org/10.1016/j.envres.2015.07.016

[16] Campanale, C., Massarelli, C., Savino, I., Locaputo, V., & Uricchio, V. F., 2020, A Detailed Review Study on Potential Effects of Microplastics and Additives of Concern on Human Health. *International Journal of Environmental Research and Public Health* **17**(4), 1212. https://doi.org/10.3390/ijerph17041212

[17] Rochman, C. M., Browne, M. A., Halpern, B. S., Hentschel, B. T., Hoh, E., Karapanagioti, H. K., Rios-Mendoza, L. M., Takada, H., Teh, S., & Thompson, R. C., 2013, Policy: Classify plastic waste as hazardous. *Nature* **494**(7436), 169–171. https://doi.org/10.1038/494169a

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Legal Responsibility for the Use of Artificial Intelligence in the Healthcare Sector in Morocco: A Sociological Analysis of the Literature and Legal Texts

Jalila Outalha [1,a], Zineb Khadali [1,b]

[1] *Higher Institute of Nursing Professions and Health Techniques (ISPITS), Care and Biology–Health Team, Laboratory of Care, Health and Sustainable Development (2S2D), Casablanca 22500, Morocco*

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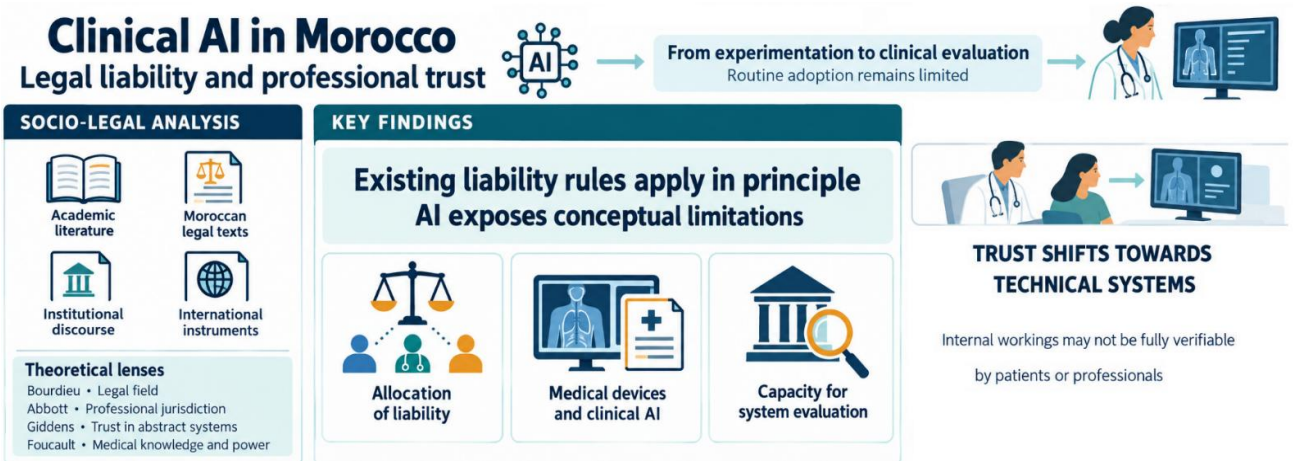
[a] ***ORCID:*** *0000-0002-6919-964X* ; ***Email***: *j.outalha@ispitscasa.ac.ma*

[b] ***ORCID:*** *0009-0002-2123-0211* ; ***Email***: *z.khadali@ispitscasa.ac.ma*

[*] Corresponding author: Jalila Outalha; ***Email***: *j.outalha@ispitscasa.ac.ma*

Graphical Abstract

This article examines the construction and distribution of liability in the Moroccan health sector through a socio-legal analysis informed by Bourdieu, Abbott, Giddens and Foucault. The findings suggest that existing liability rules remain applicable in principle but reveal conceptual limitations when applied to intelligent systems, particularly regarding the allocation of responsibility, clinical AI regulation, institutional evaluation and trust in technical systems.



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Abstract: Recent scientific work on AI in Morocco is moving from algorithmic experimentation towards clinical evaluation, although routine adoption remains limited. This raises questions about legal liability and professional trust when algorithmic systems inform clinical decisions. This article examines the construction and distribution of legal liability in the Moroccan health sector through a socio-legal analysis of academic literature, Moroccan legal texts, institutional discourse and international normative instruments. The analysis draws on Bourdieu, Abbott, Giddens and Foucault. The findings suggest that Morocco does not face a legislative vacuum in the strict sense, as existing liability rules remain applicable in principle, but their application to intelligent systems reveals conceptual limitations. Particular attention is required regarding the allocation of liability, the relationship between medical device legislation and clinical AI, and institutional capacity for system evaluation. The analysis also points to a shift in trust towards technical systems whose internal workings may not be fully verifiable by patients or professionals.

Keywords: *Artificial intelligence, Legal liability, Health law, Trust, Sociological analysis, Morocco.*

Introduction

Artificial intelligence (AI) is increasingly used to analyse health data and support clinical decisions. Its use raises questions about who must validate a system, monitor its performance and answer for harm. These questions concern the organization of care as well as the conduct of individual practitioners [1].

In Morocco, the White Paper on e-Health links digital transformation to improvements in access, coordination and clinical decision support [2]. Bourquia examines the changing role of doctors and the ethical implications of AI in medicine [3]. These sources place AI within wider debates about the development of the health system, professional expertise and patient protection.

Moroccan research includes deep learning for the histopathological classification of breast cancer [4] and machine learning analyses of treatment protocols and cycle counts using hospital data [5]. Studies published in 2026 examine pneumonia detection on chest CT scans and the classification of lung nodules [6,7]. These studies document research and clinical evaluation in particular settings. They do not show that AI use is common across Moroccan healthcare.

International debate addresses failures that have already been observed in evaluations of clinical systems. These findings need to be distinguished from forecasts of future harm and from evidence about use in Morocco. In NBSEH, Brett-Crowther discusses the social and ethical stakes of AI, including control, inequality and the limits of medical applications [8]. Warnings by leading AI researchers, including Hinton and Bengio among the signatories of the Center for AI Safety statement, show that their own work has caused personal alarm [9]. Such warnings are evidence of public concern; they do not establish the frequency of clinical injuries.

AI can connect clinical judgement to decisions made by developers, vendors, healthcare managers and data providers. Errors may arise at several stages, including model development, local deployment and clinical interpretation. This makes the allocation of responsibilities a legal and organizational problem [10,11].

We use ‘liability’ to refer to legally enforceable consequences, and ‘responsibility’ more broadly to include professional, ethical and organizational duties. ‘Accountability’ concerns the obligation to explain decisions and submit them to scrutiny. Participation in an AI system does not automatically entail legal liability.

The sociological question is how these arrangements affect professional jurisdiction, authority and trust. A doctor may remain responsible for a decision while depending on a system that other actors design and control. Our analysis examines how this relationship is represented in legal and

institutional texts and in the selected literature. It does not presume that professional authority has already been redistributed in Moroccan clinical practice.

This study examines how responsibility for AI in healthcare is constructed in the Moroccan legal framework and in relevant scholarly and institutional discourse. We focus on the relationship between legal obligations, control over technical systems and the authority to make clinical decisions. The legal sources examined range from general rules of liability to sector-specific health legislation and data protection legislation, and they are interpreted in the light of international normative standards. Draft Law No. 52.26 on the Integrated National Health Information System, approved by the Council of Government on 22 July 2026, is also currently under way.

Four questions guide the analysis. How do the selected sources allocate responsibility among clinicians, healthcare institutions and technology providers? How do they define authority and trust? What do Moroccan legal provisions and international comparisons reveal about patient protection and the governance of clinical AI? To what extent does Morocco's current legislative framework provide a basis for reconciling technological innovation with the protection of patients' and practitioners' rights?

Moroccan academic literature has begun to explore these matters within managerial, technical and clinical perspectives [12,13], but the legal and sociological dimensions of responsibility and liability remain less apparent. The present study can provide a basis for analysing the allocation and limits of healthcare professionals' liability in use of AI.

The Moroccan publications examined here address managerial, technical and clinical questions [12,13], alongside medical and ethical reflection [3]. We contribute a sociological reading of the allocation of responsibility. This observation should not be read as a comprehensive assessment of Moroccan research.

We draw on four interconnected theoretical perspectives. Bourdieu's analysis of the legal field directs attention to how legal categories acquire authority and how competing interests may shape them [14]. Abbott's concept of professional jurisdiction helps examine claims to expertise and responsibility among medical, institutional and technical actors [15]. Giddens' account of trust in abstract systems illuminates reliance on expertise that users cannot independently verify [16]. Foucault's analysis of medical knowledge and power helps examine how the authority to observe, classify and interpret patients' conditions is organized [17]. These perspectives merely guide interpretation.

Accordingly, we read legal provisions as both normative rules and socially situated classifications of actors and duties. We also examine scholarly and institutional writing as discourse that helps

define AI as a public problem. The four perspectives connect the analysis of legal categories to questions of professional boundaries, knowledge and trust.

The article combines a reading of Moroccan legal and institutional sources with selected international instruments and scientific literature. The comparison concerns the functions of safeguards, including oversight, information, consent and accountability. It does not assume that foreign rules apply directly in Morocco.

Our aim is to identify where established legal duties provide a basis for governing clinical AI and where their application needs clarification. We then examine what these uncertainties mean for professional authority and patient trust. The study develops interpretations grounded in documents and identifies where the current framework remains deficient in the light of international normative instruments, notably the UNESCO Recommendation on AI Ethics and the WHO Guidelines on AI Governance in Health.

Materials and Methods

The Nature of the Research and Rationale for the Approach

A qualitative, sociological and documentary approach is used, since the research aims not to measure quantifiable phenomena but to examine how the legal and social meaning of responsibility is constructed in relation to AI in healthcare. The objective is not to establish statistical frequencies, but to analyse the representations, legal categories and discourses through which responsibility is defined, attributed and justified, including the question of who may bear responsibility, to what extent, and on what grounds.

The choice of a documentary approach is also grounded in the available literature and normative material in Morocco. As indicated in the introduction, AI is being integrated with Moroccan healthcare; the available material includes a substantial body of institutional, scientific and legal discourse. Documentary analysis of legal texts, scientific publications and institutional documents can show how issues are being framed. It does not replace field research. Viewed through the theoretical lens – which treats legal texts as social products embodying relations of power and configurations of responsibility and trust – the analysis examines their conditions of production, their underlying categories, and their potential social functions. Legal rules are considered both as normative prescriptions and as particular ways of defining actors, responsibilities, and relationships between professional, institutional, and technological spheres.

Methodological Dimensions

The research adopts a comparative approach, with three interrelated dimensions. The first, *analytical*, consists in examining how legal, professional, and ethical responsibility are conceptualized in the literature on AI in healthcare. The second, *comparative*, identifies convergences and divergences between the Moroccan framework and selected international and European regulatory approaches, with attention to liability allocation, human oversight, data protection, and medical device regulation. The third, *critical*, entails a reflexive reading of legal and institutional discourse, examining how AI may reconfigure professional roles, authority, and trust in the Moroccan context, while distinguishing between what is established by the texts and what constitutes an analytical hypothesis.

Corpus construction

Two criteria guided the construction of the corpus: first, the direct relevance of each source to the issue of legal, professional and ethical responsibility in AI healthcare use; and second, its institutional or scientific standing. Accordingly, the corpus includes relevant legal texts, institutional documents, and scientific publications. Texts addressing AI outside the healthcare context, or lacking sufficient bibliographic traceability, were excluded.

A further distinction was made between the documentary and interpretative levels. On the one hand, we sought to analyse the normative, institutional and scientific content of the sources as shown in the original documents; on the other hand, we identified the sociological interpretation developed by the researcher. Whenever the analysis moved from the description or interpretation of a source to a theoretical or sociological proposition, this transition distinguished what is established by the corpus from what constitutes the researcher's analytical interpretation or hypothesis.

Organization of the Code

The codification comprises 27 identifiable normative and institutional documents, inventoried in Table 1. They are organized into four analytical tiers according to the degree to which the rule is incorporated into the Moroccan legal system. This criterion allows each text to be positioned according to its normative status and binding force within the Moroccan context. The tiers are analytical groupings; they do not constitute a hierarchy of legal force, which is recorded separately for each document in the table.

The first tier comprises general legal foundations: the Constitution (Articles 24 and 31) and the Law on Obligations and Contracts. The second tier brings together sector-specific health legislation and professional regulation, including Law No. 131.13 on medical practice and its implementing decrees, Framework Law No. 06.22, Law No. 07.22 establishing the High Authority for Health and

its implementing decrees, Law No. 84.12 on medical devices, Law No. 08.12 on the National Council of Medical Practitioners, Law No. 28.13 on biomedical research, and the Code of Medical Ethics. The third tier covers data protection and cybersecurity, notably Law No. 09.08 on personal data, Law No. 05.20 on cybersecurity, and the CNDP opinion on cloud outsourcing. The fourth tier includes international comparison and institutional guidance: the EU AI Act, the EU Medical Devices Regulation, the GDPR, Council of Europe Convention 108+ and the Framework Convention on AI, the UNESCO Recommendation on AI Ethics, the WHO guidance on AI for health (2021 and 2024), the IMDRF SaMD risk framework, and the White Paper on e-Health in Morocco.

Each law or decree is counted once, even when several provisions are discussed. The decree amending the telemedicine rules is classified with health regulation. The Code of Medical Ethics is listed separately from the general decree implementing the law on medical practice. The White Paper and WHO's 2024 guidance are included as institutional sources. Broad references to a national roadmap or to unspecified professional statements are excluded from the enumerated corpus because they do not identify a distinct document. European regulations serve as comparative instruments, subject to their own scope and application provisions. International recommendations and technical guidance are not treated as Moroccan legislation. Convention 108 and its modernizing protocol also require separate attention to treaty status: Morocco's accession to the original Convention does not establish that the modernized text applies automatically. The CNDP cloud opinion listed in Tier III concerns credit institutions and is used only as a sector-specific comparison.

Table 1. Inventory of the 27 core normative and institutional documents

Document	Year	Type	Jurisdiction	Normative status	Tier	Analytical relevance
D01 Constitution, Articles 24 and 31 [22]	2011	Constitution	Morocco	Constitutional norm	I	Privacy and access to healthcare
D02 Code of Obligations and Contracts [23]	1913	Code	Morocco	General civil liability rules	I	Fault, causation and custody; cited consolidated version
D03 Law No. 131.13 on medical practice [24]	2015	Law	Morocco	Binding national legislation	II	Medical duties, information and telemedicine
D04 Decree No. 2.15.447 [25]	2016	Decree	Morocco	Implementing regulation	II	Organization of medical practice
D05 Decree No. 2.18.378 on telemedicine [26]	2018	Decree	Morocco	Regulation, subsequently amended	II	Conditions for remote medical care
D06 Decree No. 2.20.675 [27]	2021	Decree	Morocco	Amends telemedicine regulation	II	Changes to the digital care framework

D07 Framework Law No. 06.22 [28]	2022	Frame work law	Morocco	National legislative framework	II	Health system organization
D08 Law No. 07.22 on the High Authority for Health [29]	2023	Law	Morocco	Institutional legislation; implementatio n provisions relevant	II	Health evaluation and institutional jurisdiction
D09 Decree No. 2.24.642 [30]	2025	Decre e	Morocco	Implements Article 32 of Law 07.22	II	Institutional implementation
D10 Decree No. 2.24.643 [31]	2025	Decre e	Morocco	Implementing regulation	II	Appointment of Authority council members
D11 Law No. 84.12 on medical devices [32]	2013	Law	Morocco	Binding national legislation	II	Device definition and clinical software
D12 Law No. 08.12 on the Medical Order [33]	2013	Law	Morocco	Binding national legislation	II	Professional regulation and jurisdiction
D13 Law No. 28.13 on biomedical research [34]	2015	Law	Morocco	Legislative framework; implementing conditions relevant	II	Protection of research participants
D14 Code of Medical Ethics, Decree No. 2.21.225 [35]	2021	Decre e and code	Morocco	Professional regulation	II	Information, consent and professional duties
D15 Law No. 09.08 on personal data [36]	2009	Law	Morocco	Binding national legislation	III	Health data and automated decisions
D16 Law No. 05.20 on cybersecurity [37]	2020	Law	Morocco	Binding legislation within its scope	III	Security and institutional obligations
D17 CNDP opinion D-110-2021 on cloud outsourcing [38]	2021	Regul atory opinio n	Morocco	Banking-sector opinion; not a general health rule	III	Limited comparison of outsourced data governance
D18 EU AI Act, Regulation 2024/1689 [39]	2024	EU regula tion	EU	Binding EU instrument; phased application	IV	Risk classification and oversight comparator
D19 Medical Devices Regulation 2017/745 [40]	2017	EU regula tion	EU	Binding EU instrument within its scope	IV	Medical software regulation comparator
D20 GDPR, Regulation 2016/679 [41]	2016	EU regula tion	EU	Binding within territorial and material scope	IV	Automated decisions and safeguards
D21 Convention 108+ consolidated text [18]	2018	Treaty text	Council of Europe	Modernised comparator; treaty status distinguished	IV	Data protection and transnational norms
D22 Framework Convention on AI, CETS 225 [42]	2024	Conve ntion	Council of Europe	Treaty obligations subject to applicable status	IV	Rights and accountability comparator

D23 UNESCO Recommendation on AI Ethics [43]	2021	Recommendation	International	Non-binding recommendation	IV	Ethical principles and national translation
D24 WHO guidance on AI for health [44]	2021	Guidance	International	Non-binding guidance	IV	Health-specific ethical governance
D25 IMDRF SaMD risk framework N12 [45]	2014	Technical guidance	International	Non-binding technical framework	IV	Software risk categorization
D26 White Paper on e-Health in Morocco [2]	2022	White paper	Morocco	Institutional proposal; not legislation	IV	National discourse on trust and participation
D27 WHO guidance on large multi-modal models [46]	2024	Guidance	International	Non-binding guidance	IV	Generative AI limitations and oversight

Treaty status note: Convention 108 entered into force for Morocco in 2019. This is distinct from the modernizing protocol underlying Convention 108+. The modernized text is used here as a comparator; its application is not presumed [18,19]

Scientific literature as a subject for analysis

The scholarly literature on legal and ethical responsibility in AI healthcare use is included here for two distinct purposes. First, it serves as a reference for the study's theoretical and analytical framework. Second, it is treated as a subject of analysis in its own right. The latter approach aims to map the disciplinary distribution of discourse on this topic, by identifying the actors and disciplines producing knowledge on the issue, the conceptual and disciplinary languages they employ, and the ways in which responsibility is defined, attributed and problematized across these different fields. This choice is supported by studies that have adopted systematic and mapping reviews of the literature on ethics, responsibility and AI in healthcare [10]. Scientific publications are not included in the document count of Table 1; they are listed separately in the bibliography.

Research process

The research was carried out in four stages. The first identified and collected relevant legal and scientific sources according to the criteria outlined above. The second classified these documents – by disciplinary field (medical, legal, ethical, sociological) and, for the normative corpus, by the four tiers defined earlier. The third stage was a qualitative content analysis of these materials, focusing on how responsibility and trust are conceptualized and how roles are distributed among doctors, patients, institutions, and programmers. The final stage related the findings to the specific features of the Moroccan legal and institutional context.

Analytical tools

Three analytical tools were used. Thematic content analysis [41] was used to identify how responsibility is attributed, distributed, and justified across the corpus – addressing the first research

question. Sociological discourse analysis [42] served to uncover the discursive patterns through which authority is constructed, responsibility is assigned or displaced, and power relations are represented – speaking to the second question. Comparative legal analysis examined divergences between the Moroccan framework and selected international instruments, with attention to the scope of existing rules, liability allocation, and safeguards – thereby addressing the third question.

Results and Discussion

The cross-analysis of the sources shows three connected issues that structure our argument. First, the scientific and medical literature reveals a debate on legal liability, oscillating between general law and technological exceptions. Second, the Moroccan legislative corpus shows that AI-related issues have not become connected to a legal arsenal conceived for an analogue world. Third, a more sensitive question appears: AI does not merely modify technical processes; it reshapes relationships of authority and mechanisms of trust between healthcare stakeholders, a cultural shift that texts, medical and legal, do not yet articulate. The discussion places international evidence of system limitations alongside the documentary analysis without treating findings from other countries as observations of Moroccan practice.

The documentary corpus comprises 27 normative and institutional documents, organized into four analytical tiers according to their degree of incorporation into the Moroccan legal system. The first tier consists of general legal foundations: the Constitution (Articles 24 and 31) and the Code of Obligations and Contracts. The second tier brings together sector-specific health legislation and professional regulation, including Law No. 131.13 on medical practice and its implementing decrees, Framework Law No. 06.22, Law No. 07.22 establishing the High Authority for Health and its implementing decrees, Law No. 84.12 on medical devices, Law No. 08.12 on the National Council of Medical Practitioners, Law No. 28.13 on biomedical research, and the Code of Medical Ethics. The third tier covers data protection and cybersecurity, notably Law No. 09.08 on personal data, Law No. 05.20 on cybersecurity, and the CNDP opinion on cloud outsourcing. The fourth tier includes international comparison and institutional guidance: the EU AI Act, the EU Medical Devices Regulation, the GDPR, Council of Europe Convention 108+ and the Framework Convention on AI, the UNESCO Recommendation on AI Ethics, the WHO guidance on AI for health (2021 and 2024), the IMDRF SaMD risk framework, and the White Paper on e-Health in Morocco. Scientific literature is not counted among these 27 documents.

The Scientific and Medical Literature's View of Legal Liability

Observed limitations of clinical AI

Wong *et al.* evaluated a widely implemented proprietary sepsis prediction model using hospital records. At the studied threshold, the model failed to identify 67% of sepsis cases, but 18% of hospitalizations would have triggered an alert [47]. The analysis documented a performance problem and a potential alert burden. It was a retrospective evaluation with hypothetical alerts, not a demonstration that model use caused those patients' injuries.

Hager *et al.* evaluated large language models in a simulated decision-making environment built from 2,400 real patient cases. The tested models showed problems in diagnosis, adherence to clinical guidance and interpretation of results [48]. These are observed limitations under the study conditions. They cannot be generalized to every AI system or interpreted as a trial of current routine care in Morocco.

WHO's guidance on large multi-modal models addresses inaccurate outputs, automation bias and the need for evaluation and oversight [46]. Together, these sources show why general promises of accuracy are insufficient. Decisions about validation, monitoring and responding to failures should be assigned to identifiable actors across the system's lifecycle.

Clinical duties and organizational control

Civil liability addresses compensation for harm. Criminal and disciplinary responsibility concern different grounds and procedures. Healthcare has long involved several potentially responsible actors, including practitioners, institutions and manufacturers. AI adds questions about data quality, model design, procurement, local validation and monitoring; it does not create distributed responsibility from nothing [1,11].

Errors may arise from defective data, poor model performance, unsuitable deployment or a clinician's interpretation of an output. A sociological analysis needs to consider who controls each stage and who has access to evidence when harm is alleged. Responsibility cannot be inferred solely from the fact that a doctor used an AI tool [1,11].

Price *et al.* show how AI recommendations can complicate the assessment of professional conduct under the US standard of care [49]. Their 2019 discussion can identify a legal problem, but it cannot establish current clinical safety or Moroccan judicial practice. It should be read alongside subsequent empirical evaluations and governance guidance. Their analysis highlights a daunting

paradox for the physician: clinicians risk liability in two symmetrical scenarios – if they ignore a relevant AI recommendation that was nevertheless consistent with good practice, or if they follow an erroneous recommendation that deviated from that same practice. In both cases, the professional standard of care remains applicable.

This situation carries a weighty sociological implication. By evaluating the physician's liability solely according to his or her individual conduct, the current legal framework may encourage a defensive use of AI: it is employed to confirm a diagnosis already well established, but clinicians are wary of relying on it when it suggests an unusual path or departs from standards. The broader question is this: under what conditions can AI become a tool for clinical decision-making, particularly when it challenges established standards?

These studies direct attention to the conditions under which reliance on an output is reasonable. Institutions make choices about purchasing, workflow integration and training, and suppliers control aspects of development and documentation. Our interpretation is that evaluating only the clinician's final decision can leave these organizational contributions insufficiently examined. The legal consequences remain dependent on the applicable rules and the facts of each case.

Brett-Crowther extends concern beyond technical error to human control and unequal access to benefits [8]. In the Moroccan analysis, these concerns can be related to three questions: whether institutions can independently assess the systems they procure; whether patients and practitioners can obtain evidence needed to question an output; and whether oversight reaches the organizations that control the technology. This connection gives the international debate a specific socio-legal focus without treating every forecast of severe risk as an established clinical outcome.

The responsibility gap and the selected Moroccan literature

Matthias' concept of a responsibility gap describes difficulties in attributing responsibility when learning systems behave in ways their designers or users cannot fully anticipate [50]. It provides a conceptual starting point. Whether a particular case creates an unresolved legal gap requires examination of the relevant duties, evidence and remedies.

Morley's mapping review documents the range of ethical questions raised by AI in healthcare [10]. The vocabulary varies with the discipline. Legal scholars frame the issue in terms of attribution and compensation; ethicists prefer transparency and autonomy; technologists reach for interpretability and verifiability. Each field defines the problem in its own way. Abbott's framework helps us interpret disputes over which expertise should define and address such questions [15]. Medical, legal and technical perspectives may emphasize different duties.

The selected Moroccan publications include work on hospital management, healthcare delivery and clinical applications [4-7,12,13]. Bourquia adds a medical and ethical discussion of the doctor's role [3]. Within this selection, the allocation of legal responsibility features less than technical or managerial questions. This suggests that, within the body of Moroccan literature, the question of AI liability has not yet become very apparent. This is not evidence of an absence of legal or sociological concern across the country. Rather, it is a characteristic of the specific academic corpus surveyed – a blind spot in the literature.

This finding concerns the materials examined. Because the literature selection is purposive, we cannot infer the relative size of disciplinary fields or conclude that AI liability is absent from Moroccan public debate. The corpus identifies a need to connect technical evaluation with socio-legal investigation.

A Sociological Reading of Moroccan Legal Texts

General rules and sector-specific provisions: the limits of a concept developed in a different context

At the heart of Moroccan civil liability lies Article 88 of the Code of Obligations and Contracts. It establishes the custodian's liability for damage caused by objects in their custody, provided that a direct causal link can be proven. The custodian may, however, escape liability by demonstrating that he, she or it took all necessary precautions, and that the damage resulted from a sudden accident, force majeure, or the fault of the injured party [23].

So far, so straightforward. But the provision says nothing about the nature of the object in custody, let alone its degree of autonomy. Apply it to an intelligent system, and two immediate difficulties arise. First, the notion of custody itself. Legal doctrine has traditionally defined custody through three elements: use, direction, and supervision. Yet in the case of an AI system, the physician uses the system without directing its inferential reasoning, and the designer has directed the design but is not in control of its use. Custody thus becomes distributed across multiple actors, with no statutory criterion to determine who holds it. Second, the grounds for exemption produce a perverse effect in this context. A user who faithfully complies with the terms of use can reasonably argue that he or she has exhausted all reasonable efforts. The result? A lack of transparency—which ought to be a basis for accountability—paradoxically becomes a ground for exemption, leaving the aggrieved party potentially without effective redress. Article 88 does not establish an AI-specific allocation of responsibility. Its application to a particular system requires legal analysis of custody, causation and the circumstances of the harm.

AI can make those questions difficult because use and control may be divided. A clinician may operate a tool whose training, updates and technical documentation remain controlled by a supplier. A healthcare institution may determine procurement and deployment without developing the model. These configurations invite analysis of the duties of each actor. Opacity may make it harder for an injured patient to identify the source of an error or obtain evidence. But, compliance with instructions or inability to explain a model does not itself establish exemption from liability. Our hypothesis concerns an imbalance in access to information and control. Its legal effects would need to be assessed through case law and the facts of individual disputes.

The same logic extends to sector-specific legislation. Law No. 131.13 grounds medical practice in professional judgement and patient rights. Article 2 requires practice free from improper influence, and Article 3 addresses scientifically established techniques [24]. The telemedicine provisions retain a central role for medical professionals while regulating remote care [24-27]. These rules should not be read as applying identically to every AI application. Abbott's account of jurisdiction helps identify the formal place of professional expertise; Foucault's approach draws attention to the relationship between diagnostic knowledge and authority [15,17]. Neither framework establishes how these provisions operate in practice. Viewed through Foucault's lens, the law still speaks as if the doctor were the sole master of the clinical encounter, reproducing a vertical, hierarchical relationship now transposed into digital space. It seems that technological modernization does not transform the underlying patterns of power.

Consider now Law No. 09.08. Article 11 is devoted to the neutrality of effects. It stipulates that no judicial decision concerning an assessment of a person's behaviour may be based on automated processing of personal data intended to evaluate certain aspects of their personality. Nor may any other decision producing legal effects be taken solely on the basis of such automated profiling [36]. The provision therefore establishes a safeguard—it does not leave the matter entirely unregulated. Yet its scope in relation to clinical artificial intelligence is open to question. An intelligent diagnostic system is typically designed to assess a patient's physiopathological condition, not the personality. And a treatment recommendation does not constitute a decision producing legal effects in the strict sense. So the safeguard’s material reach is ambiguous. Its application to clinical AI depends on the type of processing and decision. A tool that supports a clinician differs from a process that makes a decision solely through automation. These are issues of scope and interpretation rather than evidence that all medical AI falls outside the law.

This is why comparisons with the European framework should be framed with care. The issue is not the presence versus absence of a rule, but rather the level of safeguards provided. Article 22(3) of the General Data Protection Regulation lays out explicit procedural guarantees: the right to

obtain human intervention, the right to express one's point of view, and the right to contest the decision [41]. Article 11 of Law No. 09.08 contains no equivalent explicit set of procedural guarantees. At the same time, the Moroccan provision expressly excludes from the category of automated decisions certain decisions taken in the context of concluding or performing a contract—provided the data subject has had the opportunity to present his or her observations—as well as decisions that satisfy the data subject's request. The real issue, then, is not the absence of a safeguard, but rather the material and procedural limits of the safeguard that does exist when it comes to clinical AI. These guarantees cannot be treated as applying to every clinical algorithm. The comparison highlights questions for Moroccan patient protection without assuming equivalent legal coverage.

A normative paradox emerges here. In 2009, Moroccan law explicitly shielded judges from having their discretion delegated to machines. Yet the law did not then establish an equally explicit safeguard addressing the use of automated processing in medical decision-making. Our hypothesis is that this disparity reflects a difference in the capacity for symbolic mobilization between the two fields at the time the text was drafted [14,15]. The differences between these provisions also invite sociological inquiry. Bourdieu and Abbott help formulate questions about which actors participate in defining legal categories and whose concerns receive institutional recognition [14,15]. The wording of a statute alone cannot demonstrate that one professional group had greater influence during its preparation. Legislative records and interviews would be needed to examine that hypothesis. They may not be available to a researcher.

Finally, Law No. 84.12 includes, within its definition of a medical device, the software for its operation [32]. But this matter turns on the specific location of the software within the device and its intended purpose and configuration. This opens up a research hypothesis regarding adaptability, rather than yielding a definitive legal conclusion. By contrast, the European Article 6(1) of Regulation 2024/1689 links the classification of specified AI systems to product legislation and third-party conformity assessment requirements [39,40]. It does not make all medical AI high-risk. The comparison identifies a question about the coordination of regulatory regimes.

We must distinguish the limitations from the substance of the texts. What these provisions reveal when applied to intelligent systems is not a flaw in legislative craftsmanship. It is, rather, a historical imprint: they were constructed at a time when the question of the distribution of agency between human beings and machines had not yet become a social problem requiring regulation. We are not facing a legislative vacuum, nor an absence of applicable rules. The selected Moroccan provisions provide a legal starting point for AI-assisted care [23,24,32,36]. They do not resolve all questions about the allocation of duties across developers, suppliers, institutions and users. We lack

provisions specifically adapted to the distributed agency and responsibility created by intelligent systems. This aligns with Bourdieu's view of the legal text as a provisional crystallization of the balance of power that existed when it was produced [14]—a snapshot of a world that no longer quite exists.

Institutional jurisdiction and regulatory change

Law No. 07.22 establishes the High Authority for Health and assigns it functions relating to evaluation and quality in the health system [29]. Its implementing decrees provide further elements of institutional organization [30,31]. The law confers upon the Authority a broad and weighty portfolio: assessing the quality of services provided by healthcare institutions, periodically evaluating medicines and health products, scrutinizing professional practice, and delivering expert opinions on health policies. It is an ambitious mandate. Yet it contains no provision to evaluate or approve clinical AI tools, none. The law does not set out a detailed approval pathway specifically for clinical AI. This leaves questions about how broader health evaluation functions intersect with medical device regulation, data protection and institutional duties.

This omission should not, however, be mistaken for institutional paralysis. The Authority's Chair was appointed in 2024, and the implementing decrees followed in 2025. Moreover, the Law's entry into force is conditional upon the publication of all its implementing provisions. A lack of AI-specific wording does not show that no authority can act. The relevant question is which institution is competent for a particular activity, upon which legal basis and with what procedures. The gap we have identified is the absence of an explicit institutional mandate relating specifically to the governance of clinical AI. Assessing operational capacity or the present implementation of all provisions would require additional institutional evidence.

This is sociologically significant—and for a very particular reason. The High Authority for Health is itself an institution whose organizational and regulatory boundaries are still being drawn. Yet the question of clinical AI governance is now urgent. The current moment is thus a rare opportunity to observe how institutional jurisdictions are defined and negotiated between actors, rather than simply deduced from the wording of a finished legal text [15]. Abbott's concept of jurisdiction directs attention to how these functions are allocated and coordinated [15]. For clinical AI, the boundaries between professional oversight, technical assessment and institutional management may become consequential. The documentary analysis identifies these boundaries as subjects for investigation; it does not establish an observed conflict between the institutions concerned.

The same question arises in relation to Bill No. 52.26, on the integrated national health information system, which was approved by the Council of Government on 22 July 2026. According to the government communiqué, the Bill aims to establish a national digital health information system—a centralized platform for collecting, managing and exchanging health data, alongside a shared medical record, a national health identifier, and a unified public hospital information system. Because the Bill remains at the drafting and adoption stage, it offers an exceptional opportunity: the chance to observe a regulatory framework while its positions and institutional boundaries are still being actively negotiated. We can thus see the law being born—rather than retrospectively reconstructing the distribution of power and jurisdiction from a completed, polished legal text [14]. Changes in digital health legislation offer a further opportunity to examine the allocation of responsibilities for health information systems.

Legislative provisions can be studied through successive drafts, explanatory documents and documented interventions by professional organizations [14]. Such material may permit analysis of how competing definitions of responsibility enter or disappear from a final text. It cannot be replaced by an inference from the enacted wording alone. We therefore propose that the final form of the Bill—particularly with regard to the obligations it imposes on professionals and the nature of the sanctions attached to their breach—may indicate the respective positions of the actors involved in this field. The allocation of responsibilities in the final version may reveal which interests have successfully made their way into the emerging regulatory framework. A future investigation could compare draft and adopted provisions, identify participating actors and examine how their proposals affect duties, sanctions and access to remedies. The present corpus does not provide a documented legislative history of those negotiations. But one must recognize that the main question is how the law governs the use of AI.

The main issues identified in the selected provisions concern the allocation of duties across the AI lifecycle, the classification of clinical software and the coordination of evaluation and oversight. General liability rules, medical obligations and data protection safeguards remain relevant [23,24,32,36]. Their application requires attention to the system's function and the relationships among the actors involved. Developing a clearer framework would require consideration of procurement, local validation, documentation, incident reporting and patients' access to explanations and remedies. These are implications of our comparison; not findings that particular Moroccan institutions have failed to fulfil a legally established duty.

We interpret this situation as a possible mismatch between the pace of technological change and the rhythm of legal adaptation. The existing framework tends to address new technological situations, by applying pre-existing legal categories. Yet clinical AI raises questions that these

categories never contemplated—particularly concerning the identification of the relevant actor, the distribution of agency, and the attribution of responsibility. The issue, then, is not strictly a legislative vacuum in the technical sense. Now, existing categories confront forms of technological agency that push them to their very limits.

Patient information and consent

The practical question is what a patient should be told when a technical system contributes materially to a clinical recommendation, and who must provide that information. The duty to inform and secure consent rests on a quiet, often unspoken premise: that the doctor is able to explain the basis of the proposed intervention, and that the information provided reflects a professionally grounded clinical assessment. This assumption has long been woven into the fabric of Moroccan medical law.

Law No. 131.13 affirms the patient's right to receive such information as a fundamental principle. Article 2 grants the patient—or, where applicable, the guardian or legal representative—the right to be informed of the diagnosis, possible treatment options, the prescribed treatment and its potential effects, as well as the consequences of refusing treatment. This information must also be recorded in the patient's medical file [24]. Article 101 goes a step further: it stipulates that any telemedicine act requiring the patient's participation may only be carried out with the patient's explicit, free and informed consent, expressed in writing, including by electronic means [24].

The Code of Medical Ethics, annexed to Decree No. 2.21.225, reinforces and refines these obligations. Article 42 requires the patient's consent for any preventive, diagnostic or therapeutic procedure. Article 43, in turn, places a positive duty on the doctor to provide impartial and appropriate information about the patient's condition, using clear language suited to the patient's capacity for understanding. This information must cover, in particular, the diagnosis, examinations, risks, proposed treatment, alternative options, and their expected effectiveness [35]. Decree No. 2.18.378 of 25 July 2018, specifically Article 12, elaborates on the modalities of consent in telemedicine: consent may be given in writing or by any means allowing it to be recorded, including electronic means, after the doctor has provided comprehensive information concerning the patient's medical condition, the nature of the remote intervention, its expected outcomes, the available treatment options, and the anticipated risks and benefits—as well as the consequences of refusing consent [26,27]. These provisions supply an existing framework for examining the use of technology in care.

The integration of intelligent systems poses a question that the existing Moroccan legal framework does not answer: does the duty to inform extend to disclosing to the patient that an automated or AI-based system has been used in the diagnosis or in determining the treatment protocol? We have found no provision that expressly imposes such a duty. These obligations concern the clinical relationship and are not confined to decisions made without technical assistance. Their application to AI requires interpretation of the information material to the patient's decision, including the system's role and relevant limitations. The selected provisions do not set out a general, explicit AI-specific disclosure rule. This does not imply that established information duties cease to apply. It raises the question of how those duties should be fulfilled when a recommendation depends partly on a system whose operation is difficult to explain.

Article 11 of Law No. 09.08 offers a related, but significantly narrower, legal reference. Entitled "Neutrality of effects", it restricts certain decisions producing legal effects on an individual when they are based solely on automated processing of personal data—particularly where such processing is intended to define the individual's profile or assess aspects of the personality [36]. Yet the provision does not establish a general duty to inform an individual that automated processing has been used, nor does it specifically regulate automated decision-making within the therapeutic relationship. Its relevance to the use of AI in healthcare remains indirect. It should be considered alongside the law's other data protection requirements and the duties attached to clinical care. The automated-decision safeguard is not a complete substitute for a framework governing information and consent in AI-assisted treatment.

By way of comparison, Article 22(3) of the General Data Protection Regulation provides, in the circumstances covered by that provision, explicit procedural safeguards: the right to obtain human intervention, the right to express one's point of view, and the right to contest the decision [41]. No equivalent provision on these safeguards in the context of AI-assisted clinical decision-making appears to exist in the Moroccan legal framework. The issue is how patients can obtain an explanation, seek review and question the use of a system. The existence and scope of any specific right must be established from the applicable legal provisions.

Yet this procedural gap raises a deeper question. The duty to inform presupposes an agent who is capable of interpreting and explaining the basis of the proposed intervention. When an element of the reasoning underlying a clinical recommendation becomes difficult—or even impossible—to interpret, the very nature of the duty shifts. The doctor is no longer communicating solely a professional assessment; he or she is also mediating trust in an abstract system whose internal operations may be opaque.

This dynamic can be illuminated by Giddens's analysis of trust in abstract systems [16]. A clinician may be expected to explain a recommendation while relying on evidence and technical processes that he or she cannot fully verify personally. Significant information need not reproduce the model's internal calculations. It should address the clinical relevance of its output, its limitations and the human decisions surrounding its use. Informed consent, in this new context, may increasingly mean consent to a therapeutic decision whose technical basis neither the doctor nor the patient can wholly apprehend. The issue is not simply whether the patient has formally ticked a box, but whether the conditions under which that consent is obtained remain compatible with the informational assumptions that underpin the very concept of informed consent.

This observation also connects directly to our earlier analysis of Article 88 of the Code of Obligations and Contracts [23]. The opacity of an AI-based system may have a twofold effect on the patient's position. On the one hand, it may provide the professional or system operator with an argument concerning the limits of what could reasonably have been anticipated or controlled—a shield against liability. On the other hand, it complicates the practical fulfilment of the duty to inform, by making the technical basis of the decision difficult to explain in clear, accessible terms. The patient may consequently bear the burden of a form of technical ambiguity, with little capacity to exercise control.

This dependence also raises questions about access to evidence. If the supplier holds technical records and the institution controls deployment information, the patient and clinician may lack material needed to understand an error. Our analysis connects this informational imbalance to the attribution of responsibility; it does not establish that opacity itself excuses liability under Article 88 [23]. We present this as an analytical hypothesis—one that will require verification through field research and examination of judicial practice. Further research should examine the information provided in actual consultations, the documentation retained by institutions and suppliers, and how complaints or disputes are handled. These data would allow the documentary interpretation to be tested against practice.

New Manifestations of Authority and Trust in AI-Driven Healthcare Practices

Medical knowledge and reliance on technical expertise

Foucault's account of the medical gaze helps examine the authority attached to observing, classifying and interpreting illness [17]. For clinical AI, this directs attention to the data and categories through which a patient's condition becomes an object of knowledge. It also raises questions about who can inspect or contest those categories. In a context where the intelligent system emerges as a new actor on the clinical stage, this dynamic undergoes a quiet but significant

transformation. Authority is no longer concentrated in a single pair of hands. The doctor is now called upon to balance his or her expertise against the outputs of the machine.

AI can introduce additional technical expertise into the production of a clinical judgement. Bourquia's discussion of the doctor's changing role offers a medical perspective on this development [3]. We interpret it as a question about the relationship between professional authority and technical dependence. Bourquia has captured this shift with the evocative concept of "added technical authority": the doctor is no longer the sole authority; responsibility now extends to other actors involved in the design and operation of the technology, including programmers. In the present research, we understand this proposition as an interpretive framework—a way of seeing the landscape—rather than a claim of empirical verification. The selected texts cannot establish how that relationship is negotiated in Moroccan consultations.

Trust may concern the clinician, the system and the institution responsible for its deployment [51]. In digital medicine, trust operates across several interrelated levels: trust in human intent (i.e., in the doctor); trust in technology (i.e., in the intelligent system); and trust in the institution (i.e., in the legal and regulatory framework). Shevtsova *et al.* identify several factors affecting trust and acceptance, including properties of the technology, healthcare professionals and the context of use [52]. These findings support an analysis that distinguishes the object of trust and the conditions under which it is granted.

Giddens' framework makes this dependence on external expertise sociologically intelligible [16]. Both patients and clinicians may rely on systems that they cannot independently audit. Trust, Giddens argues, shifts from familiar individuals to technical systems whose inner workings the ordinary agent has no means of verifying. Applied to clinical artificial intelligence, this framework applies to both patient and doctor. The physician may be in the unfamiliar position of placing trust in a system whose logic he or she cannot fully interpret—a reversal of the traditional epistemic order, in which the doctor was the one who knew, and the patient was the one who trusted.

The relationship between patient and doctor can thus be mediated by a wider set of technical and organizational relationships. This creates a possible tension between the clinician's formal responsibility and his or her practical control over the system. Responsibility should be examined alongside the institutional arrangements that make such reliance reasonable, including evaluation, training and access to review. Examining that tension is more helpful than assuming that AI replaces medical authority.

Professional concerns and the economic use of data

Concerns about professional autonomy can be interpreted through Abbott's account of jurisdiction [15]. Questions about who may define a diagnosis, recommend treatment or certify a system's reliability concern different forms of expertise. When a new actor enters the field—whether human, technological, or algorithmic—previously stable boundaries must be renegotiated. Whether these claims produce conflict, collaboration or new forms of dependence requires empirical investigation.

The ethical literature discusses ambiguity in responsibility and the relationship between medical judgement and AI [53,54]. Attar *et al.* argue that the ambiguity surrounding the distribution of responsibilities between doctor and intelligent system may generate real tensions in professional practice—particularly when an error occurs in diagnosis or treatment [53]. Farhud and Zokaei reinforce this point, emphasizing the ethical and professional implications of the interaction between human medical judgement and artificial intelligence, including the thorny questions of responsibility and accountability that arise [54]. Mahomed examines related ethical, social and legal questions in an African context [55]. Ezzerouali *et al.* consider privacy protection under Moroccan law more broadly [56].

Economic arrangements also matter because technical expertise and access to data may be controlled by commercial organizations. The terms governing access, reuse and disclosure of data can affect both professional autonomy and patient trust. Zuboff's analysis of surveillance capitalism offers a framework for questioning the commercial use of data [57]. It does not establish that particular extractive practices occur in Moroccan healthcare. Applied here, it prompts questions about who controls health information, who benefits from its reuse and what mechanisms allow patients or public institutions to challenge those arrangements. Zuboff's framework provides a broader analytical lens through which to examine the economic dimension of data in the development of digital and intelligent systems in healthcare. It draws our attention to a structural tension—a fundamental incompatibility, perhaps—between the economic valorization of data and the ethical principles that have long governed the handling of health information.

Institutional discourse and participation

The Moroccan White Paper presents trust and participation as concerns for digital health development [2]. The document's stated aspirations do not demonstrate either effective participation or the exclusion of patients from decisions. We propose a sociological reading of this text, arguing that it quietly reproduces the existing epistemological hierarchy within the medical field. Technical knowledge remains largely monopolized by healthcare professionals and digital experts, and citizens are cast as subjects of assessment rather than partners in decision-making.

Wynne's work challenges accounts that reduce public reservations about expertise to a deficit of information [58]. Institutional discourse of this kind tends to assume that public reservations about technology stem from a simple lack of information. The remedy, accordingly, is informational and educational—not participatory. Wynne has shown, however, that this assumption overlooks a crucial dimension: the capacity of non-specialists to reflect critically on their relationship with experts and on the epistemological value of their own local knowledge. Trust in science, he argues, depends on the social connections that individuals perceive as relevant to scientific knowledge, rather than simply on the quantity of information available to them. Callon *et al.* examine arrangements through which experts and affected publics can participate in decisions under uncertainty [59]. These views suggest questions for digital health governance: who helps define the problem, whose experience is recognized, and what opportunities exist to contest a proposed solution? This latter approach—bringing together experts and non-experts in the formulation and discussion of technical decisions—is what Callon *et al.* have termed "hybrid forums."

The UNESCO Recommendation provides an international statement of ethical principles [43]. Its existence does not establish that those principles have been incorporated into Moroccan law. Merry's analysis of the local translation of international norms helps frame this question [60]. Transnational norms are not automatically transferred to local contexts; rather, they pass through intermediaries who translate and reformulate them for local use. These intermediaries are, at the same time, knowledge brokers and actors susceptible to co-optation by states and interest groups. For clinical AI, examining translation would require tracing connections between international guidance, national rules and institutional procedures. A reference to the UNESCO Recommendation tells us little, in itself, about what will actually be incorporated into the Moroccan system.

We therefore treat the possible legitimizing role of ethical discourse as a hypothesis. International mappings of AI ethics guidelines show the importance of examining the relationship between principles and their implementation [61]. In Morocco, assessing that relationship would require evidence about monitoring, enforcement, procurement and remedies. The gap between an institutional discourse that adopts the vocabulary of ethics, sovereignty and universality, and a legislative reality that lacks a specialized framework for the distribution of responsibility, may point to a legitimizing function. Such discourse may precede binding legal norms, or act as a temporary mechanism for framing a field whose regulation has not yet been fully established.

This hypothesis rests on theoretical foundations that predate the critical literature on AI. Meyer and Rowan demonstrated, decades ago, that organizations incorporate prevailing institutional norms as "myths" that confer legitimacy and resources upon them [62]. Crucially, this incorporation may be

accompanied by a separation of formal structures from actual activities—such that institutional legitimacy may substitute, at least in part, for direct coordination, inspection and evaluation. DiMaggio and Powell similarly showed that organizations within a given field tend to conform to dominant models in response to normative and mimetic pressures, rather than solely out of considerations of efficiency [63]. These two analyses allow us to refine our hypothesis: the point is not that ethical discourse is false or insincere, but rather that its adoption may fulfil a legitimizing function independent of the extent to which it is translated into binding rules and effective accountability mechanisms. This proposition can be examined by comparing normative discourse with the monitoring, enforcement and accountability mechanisms that accompany it.

This hypothesis finds a parallel in the international literature under the concept of "ethics washing"—a term that captures situations in which ethical principles, guidelines or discourse are mobilized in ways that respond to public concerns about technology without necessarily producing equivalent regulatory constraints or effective accountability [64,65]. Wagner analyses ethics as a potential escape from regulation, particularly through the processes of "ethics-washing" and "ethics-shopping" [64]. Van Maanen extends this discussion specifically to AI ethics, arguing that ethical frameworks may be susceptible to appropriation by dominant actors when they remain focused on principles and discourse without sufficiently addressing the political and social conditions of technological development [65-67]. We present this as a research hypothesis requiring further empirical validation—rather than as a conclusive finding about the Moroccan context. The present analysis cannot establish such a separation within particular Moroccan organizations. It identifies a proposition that could be examined through organizational research.

Conclusion

This study examines responsibility for AI-assisted healthcare in Morocco through four sociological perspectives. It draws on legal texts, academic literature and institutional statements, and treats legal provisions as both normative rules and socially situated classifications of actors and duties. The central sociological issue is the relationship between formal responsibility and practical control over the knowledge, data and infrastructure used in care.

The literature review shows that the idea of distributed liability remains largely theoretical rather than an established practice, with physicians continuing to bear the main burden of responsibility under existing standards of professional care. In Morocco, academic work on the subject has focused on managerial, technical and clinical aspects, and legal and sociological dimensions have received less attention. This suggests that the issue has not yet been seen as a distinct legal problem in Morocco. International evaluations show that failures in performance and reliability are already

observable, although the evidence must be interpreted according to study design and setting. Public warnings and ethical debate reinforce the need for scrutiny. For Moroccan healthcare, local validation, traceability, institutional responsibility and access to review are therefore central questions for governance.

It appears that the Moroccan legal system does not face a legislative vacuum in the strict sense. Civil, professional and medical liability rules are applicable in theory, but their enforcement in practice becomes more complex when medical decisions hinge on AI-based systems. These rules were developed for a model in which responsibility could be attributed to identifiable human actors, whereas AI systems introduce a more complex relationship between human decision-making and technological systems. The selected legal and institutional sources provide existing duties and safeguards, while leaving questions about their application to particular AI systems. Three areas require particular legislative clarification: the allocation of liability among the different actors involved in the development, deployment and use of AI systems; the relationship between the legislation governing medical devices and the clinical use of AI; and the institutional responsibility for assessing and overseeing such systems. A further issue concerns the requirements of information and informed consent. Although these requirements are addressed in the context of telemedicine, the existing framework does not address situations in which an AI system contributes to the development of a diagnosis or therapeutic decision. These implications concern the selected provisions and do not suggest that there is a comprehensive absence of safeguards in Moroccan law.

The analysis of legal and institutional discourse does not suggest that AI is displacing the physician's authority. Rather, it points to a transformation in the conditions under which that authority is exercised. Existing regulatory frameworks, including digital healthcare, continue to place the physician at the centre of clinical decision-making. Technological modernization therefore does not necessarily imply a corresponding redistribution of professional authority. Concurrently, the basis of trust between physicians and patients is being reshaped. The literature points to situations in which physicians may have to rely on systems whose internal processes they cannot fully understand or verify. This poses significant challenges to a legal framework that continues to assume that responsibility can ultimately be attributed to a human decision-maker. The concerns expressed by physicians in the literature can also be understood as reflecting tensions over professional jurisdiction, as the introduction of AI may challenge boundaries that have previously been relatively stable. Trust depends on the arrangements that support justified reliance and allow decisions to be challenged.

This analysis focuses on the normative and discursive construction of responsibility, rather than on its empirical negotiation and management within healthcare institutions. This delimitation suggests three priority areas for further research: qualitative studies with healthcare professionals on how they perceive and allocate responsibility; scrutiny of the parliamentary development of Bill No. 52.26; and testing whether ethical discourse serves to legitimize emerging forms of AI governance in healthcare. Future research should also examine clinical and procurement practices, legislative negotiations and patients' experiences. The study's limits follow from its documentary design and purposive selection: it does not measure routine adoption, patient injuries, professional attitudes or judicial outcomes in Morocco.

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References

[1] Gerke, S., Minssen, T. & Cohen, I. G., 2020, Ethical and legal challenges of artificial intelligence-driven healthcare, in A. Bohr and K. Memarzadeh (eds), Artificial Intelligence in Healthcare, (London: Academic Press), pp. 295-336. https://doi.org/10.1016/B978-0-12-818438-7.00012-5

[2] Doukkali, A., El Achgar, H., Yassine, A., Chaacho, S., & Aachati, S., 2022, Livre blanc sur la e-santé au Maroc : réalités, enjeux and leviers de développement (Rabat: Centre d'Innovation en e-Santé, Université Mohammed V). https://www.cies.ma/pdf/Livre-blanc-E-santee.pdf

[3] Bourquia, A., 2025, Le médecin à l'ère de l'intelligence artificielle : vers une nouvelle médecine, humaine, éthique and augmentée (Casablanca: Prestige Diffusion).

[4] El Agouri, H., Azizi, M., El Attar, H., El Khannoussi, M., Ibrahimi, A., Kabbaj, R., Kadiri, H., BekarSabein, S., EchCharif, S., Mounjid, C., & El Khannoussi, B., 2022, Assessment of deep learning algorithms to predict histopathological diagnosis of breast cancer: first

Moroccan prospective study on a private dataset. *BMC Research Notes* **15**, 66. https://doi.org/10.1186/s13104-022-05936-1

[5] Ait Brahim, H., El-Hadaj, S. & Metrane, A., 2024, Machine learning analysis of breast cancer treatment protocols and cycle counts: A case study at Mohammed VI Hospital, Morocco, *Systems and Soft Computing* **6**, 200097. https://doi.org/10.1016/j.sasc.2024.200097

[6] Sekkat, H., Madkouri, Y., Khallouqi, A., Talbi, M., El Mouden, O., Halimi, A., El Rhazouani, O., El Merabet, Y., & Bentayeb, F., 2026, Clinical evaluation of an AI-based pneumonia detection system on chest CT: a qualitative and quantitative analysis. *Emergency Radiology* **33**(4), 653–665. https://doi.org/10.1007/s10140-026-02465-3

[7] Ajertil, A., Farahat, Z., Bouallou, A., Le Tertre, E., Elbher, M.-B. J. B., El quessar, A., Kabbaj, N., Cherkaoui Malki, M., Chat, L., Hammani, L., & Ngote, N., 2026, First steps in clinical implementation of a lung nodule classification method by artificial intelligence. *Frontiers in Radiology* **6**, 1714951. https://doi.org/10.3389/fradi.2026.1714951

[8] Brett-Crowther, M., 2026, The role of artificial intelligence. *Natural Built Social* Environment *Health* **2**(4), 141–150. https://doi.org/10.63095/NBSEH.26.998182

[9] Center for AI Safety, 2023, Statement on AI risk. Available online at: https://safe.ai/work/statement-on-ai-extinction-risk

[10] Morley, J., Machado, C. C. V., Burr, C., Cowls, J., Joshi, I., Taddeo, M. & Floridi, L., 2020, The ethics of AI in health care: A mapping review. *Social Science and Medicine* **260**, art. 113172. https://doi.org/10.1016/j.socscimed.2020.113172

[11] Bottomley, D. & Thaldar, D., 2023, Liability for harm caused by AI in healthcare: An overview of the core legal concepts. *Frontiers in Pharmacology* **14**, 1297353. https://doi.org/10.3389/fphar.2023.1297353

[12] Rabhi, I., Ziani, S. & Budas, I., 2025, Exploiter l'intelligence artificielle pour renforcer la gestion de la qualité hospitalière au Maroc : vers un modèle stratégique intégré. *Revue Dossiers de Recherches en Économie and Management des Organisations* **10**(1), pp. 1-18. https://doi.org/10.34874/PRSM.dremo-vol10iss1.4457

[13] Radah, A. & Elhia, M., 2025, Intelligence artificielle and amélioration de l'offre de soins au Maroc : défis and perspectives, Journal of Integrated Studies in Economics, Law. *Technical Sciences and Communication* **1**(1), pp. 1-18. https://revues.imist.ma/index.php/JISELSC/article/view/54520

[14] Bourdieu, P., 1986, La force du droit : éléments pour une sociologie du champ juridique. *Actes de la Recherche en Sciences Sociales* **64**, pp. 3-19. https://doi.org/10.3406/arss.1986.2332

[15] Abbott, A., 1988, The System of Professions: An Essay on the Division of Expert Labor (Chicago: University of Chicago Press).

[16] Giddens, A., 1990, The Consequences of Modernity (Cambridge: Polity Press).

[17] Foucault, M., 1963, Naissance de la clinique : une archéologie du regard médical (Paris : Presses Universitaires de France).

[18] Council of Europe, 2018, Convention 108+: Convention for the protection of individuals with regard to the processing of personal data, consolidated text incorporating the amendments in Protocol CETS No. 223 (Strasbourg: Council of Europe). https://rm.coe.int/convention-108-convention-for-the-protection-of-individuals-with-regar/16808b36f1

[19] Council of Europe Treaty Office, 2026, Charts of signatures and ratifications of Treaty 108 and Treaty 223. Available online at: https://www.coe.int/en/web/conventions/full-list?module=signatures-by-treaty&treatynum=108

[20] Bardin, L., 2013, L'analyse de contenu, 2e éd. (Paris : Presses Universitaires de Franc)e.

[21] Fairclough, N., 2010, Critical Discourse Analysis: The Critical Study of Language, 2nd ed., (Harlow: Longman).

[22] Royaume du Maroc, 2011, Constitution du Royaume du Maroc, promulguée par le dahir n° 1-11-91 du 27 chaabane 1432 (29 juillet 2011), Bulletin officiel, n° 5964 bis, 30 juillet 2011, pp.3600-3637 https://www.chambredesrepresentants.ma/sites/default/files/documents/constitution_ar_2011_1.pdf

[23] Royaume du Maroc, 1913, Dahir formant Code des obligations & des contrats, promulgué le 9 ramadan 1331 (12 août 1913), tel que modifié & complété jusqu'à la loi n° 31-18 du 6 septembre 2018, Version consolidée au 26 août 2019, WIPO Lex. https://www.wipo.int/wipolex/ar/legislation/details/19845

[24] Royaume du Maroc, 2015, Loi n° 131-13 relative à l'exercice de la médecine, promulguée par le dahir n° 1-15-26 du 19 février 2015, telle que modifiée. Secrétariat général du gouvernement, texte consolidé. https://www.sgg.gov.ma/Portals/0/textesconsolides/131_13.pdf

[25] Royaume du Maroc, 2016, Décret n° 2.15.447 du 6 joumada II 1437 (16 mars 2016) pris pour l'application de la loi n° 131-13 relative à l'exercice de la médecine, Bulletin officiel, n° 6454, pp.467-473. https://www.sante.gov.ma/Reglementation/PRATIQUEDESMETIERSDESANTEDANSLESECTEURPRIVE/2-15-447.pdf?ID=32

[26] Royaume du Maroc, 2018, Décret n° 2.18.378 du 11 dhou al-qiada 1439 (25 juillet 2018) relatif à la télémédecine, Bulletin officiel, n° 6694, pp.4932-4933. https://www.sante.gov.ma/sites/Ar/reglementation/DocLib4/2-18-378.pdf

[27] Royaume du Maroc, 2021, Décret n° 2-20-675 du 22 janvier 2021 modifiant & complétant le décret n° 2-18-378 relatif à la télémédecine. Bulletin officiel 7022, 16 septembre 2021, 1645. https://www.sgg.gov.ma/BO/bo_fr/2021/BO_7022_Fr.pdf

[28] Royaume du Maroc, 2023, Dahir n° 1-22-77 du 14 joumada I 1444 (9 décembre 2022) portant promulgation de la loi-cadre n° 06-22 relative au système national de santé, Bulletin officiel, n° 7178, 23 chaabane 1444 (16 mars 2023), pp.829-833. https://www.sgg.gov.ma/BO/FR/2873/2023/BO_7178_fr.pdf

[29] Royaume du Maroc, 2023, Dahir n° 1-23-84 du 16 joumada I 1445 (30 novembre 2023) portant promulgation de la loi n° 07-22 relative à la création de la Haute Autorité de la Santé, Bulletin officiel, n° 7253, 4 décembre 2023, pp.10229-10234.

[30] Royaume du Maroc, 2025, Décret n° 2.24.642 du 27 janvier 2025 pris pour l'application de l'article 32 de la loi n° 07.22 relative à la création de la Haute Autorité de la Santé. Bulletin officiel 7379, 17 février 2025, 1236. https://www.sgg.gov.ma/BO/AR/3111/2025/BO_7379_Ar.pdf

[31] Royaume du Maroc, 2025, Décret n° 2.24.643 du 11 février 2025 fixant les modalités de nomination des membres du Conseil de la Haute Autorité de la Santé. Bulletin officiel 7379, 17 février 2025, 1236–1237. https://www.sgg.gov.ma/BO/AR/3111/2025/BO_7379_Ar.pdf

[32] Royaume du Maroc, 2013, Dahir n° 1-13-90 du 22 chaoual 1434 (30 août 2013) portant promulgation de la loi n° 84-12 relative aux dispositifs médicaux, Bulletin officiel n° 6188,

12 kaada 1434 (19 septembre 2013), pp. 6129-6147. https://www.ammps.gov.ma/uploads/textes-reglementaires/lois/loi-84-12-relative-aux-dispositifs-medicaux.pdf

[33] Royaume du Maroc, 2013, Loi n° 08-12 relative à l'Ordre national des médecins, promulguée par le dahir n° 1-13-16 du 13 mars 2013. https://www.sante.gov.ma/Reglementation/ORDRESPROFESSIONNELS/08-12.pdf

[34] Royaume du Maroc, 2015, Dahir n° 1-15-110 du 18 chaoual 1436 (4 aout 2015) portant promulgation de la loi n° 28.13 relative à la protection des personnes participant aux recherches biomédicales. Bulletin officiel n° 6396, pp. 3458-3468. https://fr.scribd.com/document/715763910/28-13

[35] Royaume du Maroc, 2021, Décret n° 2-21-225 du 17 juin 2021 relatif au Code de déontologie de la profession médicale. Bulletin officiel, édition française, 7066, 17 février 2022, 166–175. https://cnom.ma/wp-content/uploads/2025/03/Code-de-Deontologie-de-la-profession-medicale-BO-n-7066-17-2-2022.pdf

[36] Royaume du Maroc, 2009, Dahir n° 1-09-15 du 22 safar 1430 (18 février 2009) portant promulgation de la loi n° 09-08 relative à la protection des personnes physiques à l'égard du traitement des données à caractère personnel, Bulletin officiel, n° 5714, 5 mars 2009, pp. 345-356. https://www.sgg.gov.ma/BO/bo_fr/2009/bo_5714_fr.pdf

[37] Royaume du Maroc, 2020, Dahir n° 1-20-69 du 4 hija 1441 (25 juillet 2020) portant promulgation de la loi n° 05-20 relative à la cybersécurité, Bulletin officiel, n° 6906, 6 août 2020, pp. 1294-1300. https://www.sgg.gov.ma/Portals/0/BO/2020/BO_6906_Fr.pdf

[38] Commission nationale de contrôle de la protection des données à caractère personnel (CNDP), 2021, Délibération n° D-110-2021 du 30 avril 2021 portant avis sur le projet de directive fixant les règles minimales d'externalisation vers le Cloud par les établissements de crédit. https://cndp.ma/wp-content/uploads/2023/12/CNDP-Deliberation-D-110-2021-20210430.pdf

[39] European Parliament & Council of the European Union, 2024, Regulation (EU) 2024/1689 laying down harmonised rules on artificial intelligence (Artificial Intelligence Act). Official Journal of the European Union, L 2024/1689, 12 July 2024. https://eur-lex.europa.eu/eli/reg/2024/1689/oj

[40] European Parliament & Council of the European Union, 2017, Regulation (EU) 2017/745 on medical devices. Official Journal of the European Union, L 117, 5 May 2017, 1–175. https://eur-lex.europa.eu/eli/reg/2017/745/oj

[41] European Parliament & Council of the European Union, 2016, Regulation (EU) 2016/679 on the protection of natural persons with regard to the processing of personal data and on the free movement of such data (General Data Protection Regulation). Official Journal of the European Union, L 119, 4 May 2016, 1–88. https://eur-lex.europa.eu/eli/reg/2016/679/oj

[42] Council of Europe, 2024, Framework Convention on Artificial Intelligence and Human Rights, Democracy and the Rule of Law, CETS No. 225, opened for signature on 5 September 2024 (Strasbourg: Council of Europe). https://rm.coe.int/1680afb20c

[43] United Nations Educational, Scientific and Cultural Organization (UNESCO), 2022, Recommendation on the Ethics of Artificial Intelligence, adopted on 23 November 2021 (Paris: UNESCO). https://unesdoc.unesco.org/ark:/48223/pf0000381137

[44] World Health Organization, 2021, Ethics and governance of artificial intelligence for health: WHO guidance (Geneva: World Health Organization). https://www.who.int/publications/i/item/9789240029200

[45] International Medical Device Regulators Forum, 2014, Software as a Medical Device: Possible Framework for Risk Categorization and Corresponding Considerations, IMDRF/SaMD WG/N12FINAL:2014, 18 September 2014. https://www.imdrf.org/sites/default/files/docs/imdrf/final/technical/imdrf-tech-140918-samd-framework-risk-categorization-141013.pdf

[46] World Health Organization, 2024, Ethics and governance of artificial intelligence for health: guidance on large multi-modal models (Geneva: World Health Organization). https://www.who.int/publications/i/item/9789240084759

[47] Wong, A., Otles, E., Donnelly, J. P., Krumm, A., McCullough, J., DeTroyer-Cooley, O., Pestrue, J., Phillips, M., Konye, J., Penoza, C., Ghous, M., & Singh, K., 2021, External validation of a widely implemented proprietary sepsis prediction model in hospitalized patients. *JAMA Internal Medicine* **181**(8), 1065–1070. https://doi.org/10.1001/jamainternmed.2021.2626

[48] Hager, P., Jungmann, F., Holland, R., Bhagat, K., Hubrecht, I., Knauer, M., Vielhauer, J., Makowski, M., Braren, R., Kaissis, G., & Rueckert, D., 2024, Evaluation and mitigation of the limitations of large language models in clinical decision-making. *Nature Medicine* **30**, 2613–2622. https://doi.org/10.1038/s41591-024-03097-1

[49] Price, W. N. II, Gerke, S. & Cohen, I. G., 2019, Potential Liability for Physicians Using Artificial Intelligence. *JAMA* **322**(18), pp. 1765-1766. https://doi.org/10.1001/jama.2019.15064

[50] Matthias, A., 2004, The responsibility gap: Ascribing responsibility for the actions of learning automata. *Ethics and Information Technology* **6**(3), pp. 175-183. https://doi.org/10.1007/s10676-004-3422-1

[51] Laï, M.-C., 2024, Éthique, intelligence artificielle and santé: Pour la construction d'un cadre éthique opérationnel. (Paris: L'Harmattan).

[52] Shevtsova, D., Ahmed, A., Boot, I. W. A., Sanges, C., Hudecek, M., Jacobs, J. J. L., Hort, S., & Vrijhoef, H. J. M., 2024, Trust in and acceptance of artificial intelligence applications in medicine: mixed methods study. *JMIR Human Factors* **11**, e47031. https://doi.org/10.2196/47031

[53] Attar, H., Belhaj, A., Salamate, F. E., & Zahi, J., 2024, Ethics in the Era of Artificial Intelligence: Challenges and Perspectives. *Journal of Business and Economics* **12**(1), pp.1-12. https://revues.imist.ma/index.php/jbe/article/download/48053/25223/132564

[54] Farhud, D. D., & Zokaei, S., 2021, Ethical issues of artificial intelligence in medicine and healthcare. *Iranian Journal of Public Health* **50**(11), i–v. https://doi.org/10.18502/ijph.v50i11.7600

[55] Mahomed, S., 2018, Healthcare, artificial intelligence and the Fourth Industrial Revolution: Ethical, social and legal considerations. *South African Journal of Bioethics and Law* **11**(2), pp. 93-95. https://doi.org/10.7196/sajbl.2018.v11i2.00664

[56] Ezzerouali, S., Arifin, R., & Banane, M. C., 2025, Can Moroccan law ensure substantive justice in protecting private life from AI's impact? *Substantive Justice International Journal of Law* **8**(1), pp.1-15. https://doi.org/10.56087/substantivejustice.v8i1.333

[57] Zuboff, S., 2019, The Age of Surveillance Capitalism: The Fight for a Human Future at the New Frontier of Power (New York, NY: Public Affairs).

[58] Wynne, B., 1992, Misunderstood misunderstanding: social identities and public uptake of science. *Public Understanding of Science* **1**(3), 281-304. https://doi.org/10.1088/0963-6625/1/3/004

[59] Callon, M., Lascoumes, P. & Barthe, Y., 2001, Agir dans un monde incertain: essai sur la démocratie technique, (Paris : Le Seuil, coll. « La couleur des idées »).

[60] Merry, S. E., 2006, Transnational human rights and local activism: mapping the middle. *American Anthropologist* **108**(1), pp. 38-51. https://doi.org/10.1525/aa.2006.108.1.38

[61] Jobin, A., Ienca, M., & Vayena, E., 2019, The global landscape of AI ethics guidelines. *Nature Machine Intelligence* **1**, 389–399. https://doi.org/10.1038/s42256-019-0088-2

[62] Meyer, J. W. & Rowan, B., 1977, Institutionalized organizations: formal structure as myth and ceremony. *American Journal of Sociology* **83**(2), pp. 340-363. https://doi.org/10.1086/226550

[63] DiMaggio, P. J. & Powell, W. W., 1983, The iron cage revisited: institutional isomorphism and collective rationality in organizational fields. *American Sociological Review* **48**(2), pp. 147-160. https://doi.org/10.2307/2095101

[64] Wagner, B., 2018, Ethics as an escape from regulation: from ethics-washing to ethics-shopping? In: E. Bayamlıoğlu, I. Baraliuc, L. A. W. Janssens, and M. Hildebrandt (Eds.), Being Profiled: Cogitas Ergo Sum: 10 Years of Profiling the European Citizen (Amsterdam: Amsterdam University Press), pp. 84–89. https://doi.org/10.1515/9789048550180-016

[65] Van Maanen, G., 2022, AI Ethics, Ethics Washing, and the Need to Politicize Data Ethics. *Digital Society* **1**(9), 1-23. https://doi.org/10.1007/s44206-022-00013-3

[66] Li, P., Yang, J., Islam, M. A., & Ren, S., 2025, Making AI less 'thirsty'. *Communications of the ACM* **68**(7), 54–61. https://doi.org/10.1145/3724499

[67] World Bank, 2022, Morocco Country Climate and Development Report (Washington, DC: World Bank). https://www.worldbank.org/en/country/morocco/publication/morocco-country-climate-and-development-report

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Modern Contraceptive Use, Practices and Barriers among Women of Reproductive Age Living with a Partner in the Baobab Health Area, Kinshasa

Josué Onoya Wedi [1,2,a], *Nana Kenge Mujinga* [1,b], *Theresia Mindada Kadongo* [1,c *]

[1] *Higher Institute of Medical Technical Education, Kinshasa, Democratic Republic of the Congo*

[2] *Doctoral School of Health Sciences, Higher Institute of Medical Techniques of Kinshasa (ISTM-KIN), Kinshasa, Democratic Republic of the Congo*

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[a] **ORCID:** 0000-0002-7115-9452; **Email:** wedijosue@gmail.com

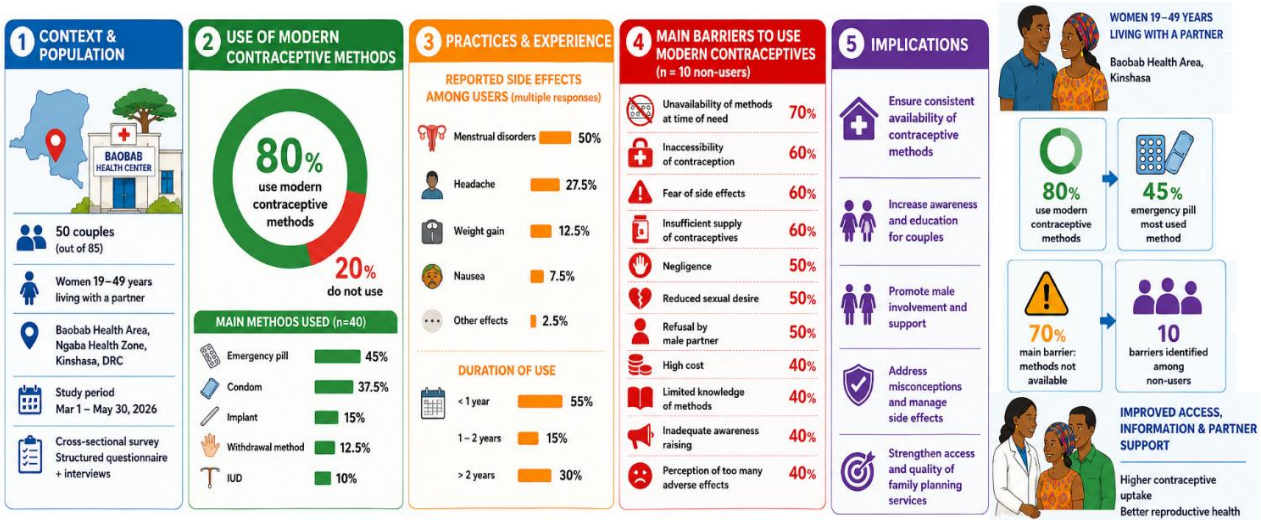
[b] **ORCID:** 0009-0003-0738-3606; **Email:** Kengenana33@gmail.com

[c] **ORCID:** 0009-0006-2645-3042; **Email:** mindadatheresia@gmail.com

***Corresponding author:** Josué Onoya Wedi, **Email:** wedijosue@gmail.com; Phone number: +243 895193650

Graphical Abstract

This study examines the use of modern contraceptive methods and the main reasons for their non-use among women of reproductive age living with a partner in the Baobab Health Area. The results showed that most women used modern contraceptive methods, particularly the emergency pill and condoms. Non-use was mainly related to unavailability, inaccessibility, fear of side effects, insufficient supply, cost, limited knowledge and refusal by the male partner. Improving contraceptive availability and strengthening awareness among couples regarding their correct use are therefore important for promoting modern contraceptive use.



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Abstract: This study aims to identify the main reasons for the non-use of modern contraceptive methods among women of reproductive age living with a partner in this health area. The study was conducted from 1 March to 30 May 2026 among 50 women of reproductive age living with a partner who attended the Baobab Referral Health Centre. They were selected by simple random sampling from a total of 85 eligible women. The study falls within the field of reproductive health. To collect the data, we used the survey method, the interview technique and a survey questionnaire as the data collection instrument. The results showed that 80% of women used modern contraceptive methods, of whom 45% used the emergency pill, 37.5% used condoms, 15% used implants, 12.5% used the calendar method, and 10% used an IUD. Regarding the reasons for the non-use of contraceptive methods within the couple, 70% reported that the method was unavailable at the time of need; 60% reported inaccessibility of contraception when needed, fear of side effects, and insufficient contraceptive supply/stock; 50% cited negligence, reduced sexual desire and refusal by the male partner; and 40% cited the high cost of purchasing contraceptives, limited knowledge of contraceptive methods, insufficient awareness-raising and the perception that contraception causes too many adverse effects. To improve the use of modern contraceptive methods among women of reproductive age living with a partner in this health area, contraceptive methods should be made available and couples should be made aware of their correct use.

Keywords: *Modern contraceptive methods, Non-use, Women of reproductive age*

Introduction

The non-use of modern contraceptive methods among women of reproductive age is a major public health concern. It is mainly explained by fear of side effects, opposition from the partner, lack of information and limited access to health services [1].

The main causes of the non-use of modern contraception include psychosocial and cultural factors, such as opposition from the partner or family, social pressure to have many children, and religious or cultural beliefs against family planning. They also include health-related barriers, such as fear of side effects (weight gain, amenorrhoea and the perceived risk of future infertility), poor understanding of how the different methods work, as well as barriers related to access to and quality of services. These include the geographical distance from health centres, non-availability of contraceptive products, and fear of stigmatization or lack of confidentiality among healthcare staff [2].

Modern contraceptive methods refer to scientific and medical means of preventing pregnancy in an effective and controlled manner. They are based on biological mechanisms that prevent fertilization or implantation of the embryo [3].

Family planning, on the other hand, refers to the range of means used to control births, with the aim of enabling women, and therefore families, to choose when to have a child [4].

Family planning offers women considerable benefits, particularly by helping to prevent complications associated with high-risk pregnancies, such as those occurring in women with heart or kidney disease, as well as pregnancies that occur too early, too late or too frequently. Furthermore, by preventing unwanted pregnancies, family planning methods also help to avoid induced abortions, whose rates remain high in many sub-Saharan African countries, particularly in urban areas of Cameroon. Such abortions constitute an important cause of maternal morbidity and mortality. The consequences of the non-use of modern contraception are numerous and include unwanted pregnancies, an increased risk of unsafe abortion, and increased maternal and infant mortality [5].

In developed countries, the use of modern contraceptive methods is widespread, because of good access to health services, a high level of sexual education and policies that support family planning. Modern contraceptive prevalence among married women or women in a union is generally high in developed countries, although levels vary between countries and according to the year and source of the estimate [6]. In countries such as Canada, France, the United Kingdom, Germany and the United States, modern contraceptive prevalence is approximately 60–75%, and levels are also high

in several Nordic countries [6]. The most commonly used methods include oral contraceptives, intrauterine devices (IUDs), contraceptive implants, condoms and voluntary sterilization [6,7]. These high levels of contraceptive coverage contribute to reducing unintended pregnancies and associated health risks, enabling women to better plan their pregnancies and reproductive lives [7].

In Côte d'Ivoire, a high proportion of participants (75.4%) used contraception as part of family planning. Adverse effects were reported by 85.4%, with amenorrhoea and weight gain being the most frequent. The most commonly used methods were injectables (41.6%) and implants (28.5%); the pill and IUD were less frequently used [5].

In Mali, at the Referral Health Centre of Commune VI in the Bamako District, 2,097 clients attended consultations, of whom 1,376 (65.62%) were previous users of family planning services. New family planning clients accounted for 721 (34.38%) cases, representing an average of 60 women per month. The mean age of the clients was 26.74 years; 27.6% had no formal education, 46.6% were housewives, 90.7% were married and 96.6% were Muslim. Overall, 65.8% of women had approval to use contraceptive methods, and discussions with the partner had taken place in 80.9% of cases. Spotting was reported as a side effect in 40% of cases. The most commonly used contraceptives were long-acting methods, particularly implants (46%) and intrauterine devices (30.7%). Factors associated with contraceptive use included age, occupation, regular discussion with the partner and partner support [1]

In Tunisia, a cross-sectional survey of a sample of 4,374 women aged 15–49 years found an overall contraceptive prevalence of 66.4%, and 82% of women used a modern contraceptive method. Contraceptive use was associated with multiparity, lower educational level and younger age [8].

In the Democratic Republic of the Congo (DRC), among couples including non-pregnant women aged 15–49 years living in a marital union in the Dibindi Health Zone of Mbuji-Mayi, modern contraceptive prevalence was 18.4%. This prevalence remained low despite the availability of family planning services in the health zone. Several women refused to use modern contraceptive methods despite having information about them, because of their desire for motherhood, religious restrictions, opposition from their partner and fear of side effects [9].

The present study was undertaken to improve maternal health among women of reproductive age in this geographical area. Women of reproductive age in this health area could benefit from greater promotion of family planning in order to prevent unwanted pregnancies and reduce complications that may endanger their lives. In terms of social benefit, this study may contribute to reducing unwanted pregnancies and their associated complications, while promoting better access to health

services among the population. Furthermore, this study may provide a basis for future researchers to develop and conduct other relevant research projects related to maternal health.

Accordingly, the general objective of this study is to identify the main reasons for the non-use of modern contraceptive methods among women of reproductive age living with a partner in the Baobab Health Area.

Materials and Methods

Study Setting

The study was conducted in the Baobab Health Area, within the Ngaba Health Zone, located in Ngaba commune, Kinshasa city-province, Democratic Republic of the Congo (Fig. 1).

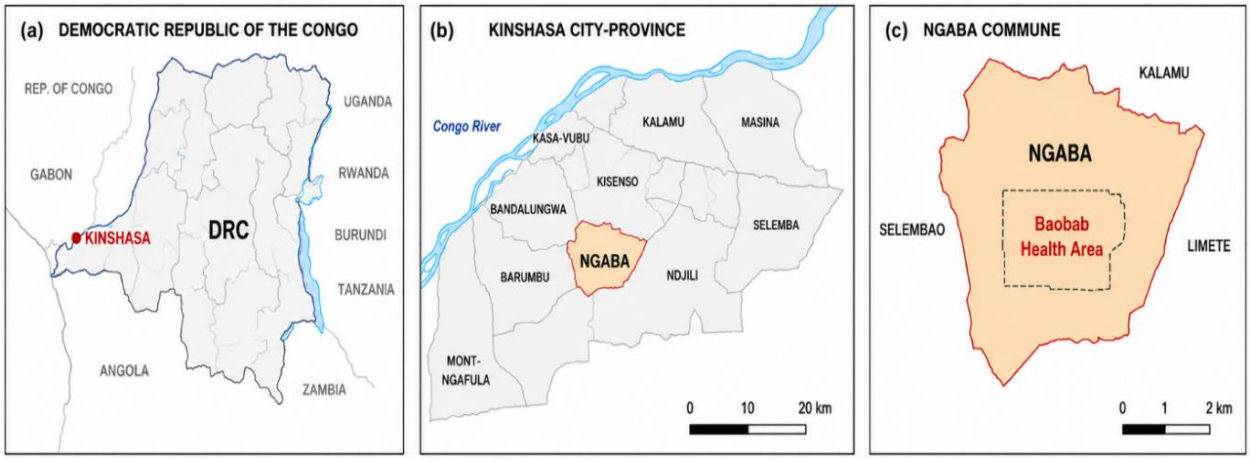


Figure 1. Location of the study area: (a) Kinshasa city-province within the Democratic Republic of the Congo; (b) Ngaba commune within Kinshasa city-province; and (c) Baobab Health Area within Ngaba commune

Study population and sample size

The study population consisted of 85 women of reproductive age living with a partner who attended the Baobab Referral Health Centre between 1 March and 30 May 2026. Among them, 50 women who met the selection criteria were selected by simple random sampling.

The sample size was determined using Fisher's formula through OpenEpi software. As the proportion was unknown, P = 50% and Q = 50% were used, resulting in a sample size of 50 women, who were selected by simple random sampling.

Study design and data collection

This was a descriptive cross-sectional study in the field of reproductive health. Data were collected using a survey questionnaire administered through interviews.

The interviews lasted an average of 30 minutes and were conducted to collect the information required for the study. Data collection took place from 3 to 20 April 2026. The interviews were conducted face-to-face with the participating women and in private.

Ethical considerations

Before data collection, informed consent was obtained from the authorities of the Baobab Health Area and from the women participating in the study. The confidentiality and anonymity of the information collected were ensured.

Data processing and analysis

The collected data were entered into Microsoft Excel 2010 and then imported into SPSS version 25 for statistical analysis. Descriptive analysis consisted of presenting the frequencies and percentages for each parameter, including the socio-demographic characteristics of women of reproductive age living with a partner and data relating to their reasons for not using modern contraceptive methods.

Results and Interpretation

Table 1. Socio-demographic characteristics of women of reproductive age living with a partner (n = 50)

No.	Socio-demographic characteristics	Frequency (n = 50)	%
	Age group	**X=26.6 years**	
1	≤18 years	9	18
2	19–34 years	31	62
3	≥35 years	10	**20**
	Marital status		
1	Married	30	60
2	Cohabiting	20	40
	Educational level		
1	No formal education (illiterate)	6	12
2	Primary education	6	12

3	Secondary education	21	42
4	State diploma	9	18
5	Higher/university education	8	16
	Occupation		
1	Civil servant	12	24
2	Trader	25	50
3	Unemployed	5	10
4	Housewife	8	16
	Parity	**X=2.6 childbirths**	
1	Primiparous	28	56
2	Multiparous	12	24
3	Grand multiparous	10	20
	Gravidity	**X=4.9 pregnancies**	
1	Primigravida	9	**18**
2	Multigravida	16	32
3	Grand multigravida	25	50
	History of abortion	**X=2.2 abortions**	
1	No previous abortion	11	22
2	One abortion	12	24
3	2–4 abortions	21	42
4	≥5 abortions	6	12

Regarding age, 62% of participants were aged 19–34 years, 20% were aged ≥35 years, and 18% were aged ≤18 years.

According to marital status, married participants were the majority, accounting for 60%, compared to 40% who were cohabiting.

Regarding educational level, participants with secondary education were the most represented, accounting for 42%, followed by those with a State diploma (18%), those with university education (16%), and those with primary education and no formal education (12% each).

According to occupation, 50% were traders, 24% were civil servants, 16% were housewives, and 10% were unemployed.

Regarding parity, 56% were primiparous and 24% were multiparous, and the remainder were grand multiparous.

Regarding gravidity, 50% were grand multigravida, 32% were multigravida, and the remaining participants were primigravida.

Regarding the number of abortions, 42% had 2 to 4 abortions, 24% had one abortion, and 22% had no abortions.

Table 2. Use of modern contraceptive methods among women of reproductive age (n = 50)

Use of modern contraceptive methods	**Frequency**	**%**
Yes	40	80
No	10	20
Total	**50**	**100**

These results show that 80% of the women used modern contraceptive methods, compared with 20% (10 out of 50 women of reproductive age) who did not use them.

Table 3. Modern contraceptive methods used and reported adverse effects (n = 40)

Modern contraceptive methods used and reported adverse effects	**Frequency (n = 40)**	**%**
Modern contraceptive methods		
Emergency contraceptive pill	18	45
Condom	15	37.5
Implants	6	15
Calendar method	5	12.5
Intrauterine device (IUD)	4	10
Reported adverse effects		
Pain and cramps	6	15
Allergy	6	15
Menstrual disturbances	10	25
Amenorrhoea	12	30
Arm tenderness	6	15
Heavy and painful periods	16	40

Note: Multiple responses were allowed; therefore, the sum of frequencies may exceed the number of participants (n = 40), and percentages may exceed 100%.

In regard to the modern contraceptive methods used by the women, 45% used emergency contraceptive pills, 37.5% used condoms, 15% used implants, 12.5% used the calendar method, and 10% used an intrauterine device (IUD).

Regarding the disadvantages associated with the use of these methods among the women, the table shows that 40% reported heavy and painful periods, 30% reported amenorrhoea, and 15% reported pain and cramps, allergy, and arm tenderness.

Table 4. Reasons for non-use of contraceptive methods (n = 10)

Reasons for non-use of contraceptive methods	**Frequency (n = 10)**	**%**
Method unavailable at the time of need	7	70
Inaccessibility of contraception when needed	6	60
Fear of side effects	6	60
Insufficient contraceptive supply/stock	6	60
Reduced sexual desire	5	50
Male partner refusal	5	50
Negligence	5	50
High cost of contraceptives	4	40
Limited knowledge of contraceptive methods	4	40
Insufficient awareness	4	40
Perception of excessive adverse effects	4	40

Note: Multiple responses were allowed; therefore, the sum of frequencies and percentages exceeds the number of non-users (n = 10) and 100%, respectively

Regarding the reasons for non-use of contraceptive methods among the women, 70% reported that the method was unavailable at the time of need; 60% reported inaccessibility of contraception when needed, fear of side effects, and insufficient contraceptive supply/stock; 50% reported negligence, reduced sexual desire and male partner refusal; and 40% cited the high cost of contraceptives, limited knowledge of contraceptive methods, insufficient awareness and the perception that contraception causes too many adverse effects.

Discussion

Use of Modern Contraceptive Methods

These results show that 80% of the women used modern contraceptive methods, whereas 20% (10 out of 50 women) did not use them.

The rate of modern contraceptive method use was 69% [10].

It appears that 75.4% of the participants in the context of family planning used contraception. This study calls for diversification of the contraceptive methods offered, strengthened individualized counselling and intensified awareness-raising activities, with a view to ensuring more informed, equitable and sustainable access to modern contraception [5].

Modern Contraceptive Methods Used and Disadvantages of Use

In regard to the modern contraceptive methods used among the women, 45% used emergency contraceptive pills, 37.5% used condoms, 15% used implants, 12.5% used the calendar method, and 10% used an intrauterine device (IUD).

Regarding the disadvantages associated with the use of these methods among the women, the table shows that 40% reported heavy and painful periods, 30% reported amenorrhoea, and 15% reported pain and cramps, allergy and arm tenderness.

The majority of respondents used hormonal contraceptive methods (15.94%), non-hormonal methods (35.34%) and natural methods (48.70%). Among hormonal methods, pill users predominated (72.97%); among non-hormonal methods, 78.04% used condoms; and among natural contraceptive methods, 68.14% used the lactational amenorrhoea method (LAM). The majority of couples (86.4%) chose to space their children by 2 to 4 years, which is a recommended practice for maternal and child health [10,11].

The most commonly used methods were injectables (41.6%) and implants (28.5%); the pill and intrauterine device were less frequently used. The most frequently reported adverse effects were amenorrhoea and weight gain (85.4%) [5].

Reasons for Non-Use of Contraceptive Methods

Regarding the reasons for non-use of contraceptive methods among the women, 70% reported that the method was unavailable at the time of need; 60% reported inaccessibility of contraception when needed, fear of side effects, and insufficient contraceptive supply/stock; 50% reported negligence, reduced sexual desire and male partner refusal; and 40% cited the high cost of contraceptives, limited knowledge of contraceptive methods, insufficient awareness and the perception that contraception causes too many adverse effects.

The use of contraceptive methods remains limited by various social, cultural, and structural factors. Social and cultural pressures—such as the value placed on having large families and the perception of contraception as contrary to community norms—act as significant barriers to its adoption. These are compounded by misconceptions and rumours, particularly fears regarding side effects, infertility, or the long-term adverse consequences of contraceptive methods. A lack of communication between spouses, along with insufficient support or agreement from a partner, can also limit women's ability to access family planning. Furthermore, difficulties in accessing health services—stemming from factors such as the geographical remoteness of facilities, inadequate healthcare provision, and the unavailability of certain methods—hinder the effective use of contraception. Finally, low levels of education and a lack of economic empowerment among women can reduce their ability to access information, make independent decisions, and fully exercise their sexual and reproductive health rights [10].

With the aim of determining the frequency of modern contraceptive method use and reporting adverse effects associated with modern contraceptive methods at the family planning unit of the Referral Health Centre of Commune VI in Bamako District, 65.8% of women had approval to use the methods, and in 80.9% of cases there had been discussions with their partner. The reported side effect was spotting in 40% of cases. The most commonly used contraceptive methods were long-acting methods, namely implants (46%) and intrauterine devices (30.7%). Factors associated with the use of these methods were age, occupation, and clients who regularly discussed contraception with their partners and had their support [1].

Conclusion

In conclusion, our study focused on the main reasons for non-use of modern contraceptive methods among women of reproductive age living with a partner in the Baobab Health Area, Ngaba Health Zone, Kinshasa city-province, Democratic Republic of the Congo.

The study was conducted from 1 March to 30 May 2026 among 50 women of reproductive age living with a partner who attended the Baobab Referral Health Centre. They were selected by simple random sampling from a total of 85 eligible women. To collect the data, we used the survey method, the interview technique and a survey questionnaire as the data collection instrument.

Overall, 80% of the women used modern contraceptive methods, of whom 45% used emergency contraceptive pills, 37.5% used condoms, 15% used implants, 12.5% used the calendar method, and 10% used an intrauterine device (IUD). Regarding the reasons for non-use of contraceptive methods among the women, 70% reported that the method was unavailable at the time of need;

60% reported inaccessibility of contraception when needed, fear of side effects, and insufficient contraceptive supply/stock; 50% reported negligence, reduced sexual desire and male partner refusal; and 40% cited the high cost of contraceptives, limited knowledge of contraceptive methods, insufficient awareness and the perception that contraception causes too many adverse effects.

To improve the use of modern contraceptive methods among women of reproductive age living with a partner in this Health Area, contraceptive methods should be made available, contraception should be promoted, and couples should be made aware of their correct use.

References

[1] Keita, M., Fomba, S., Tall, S., Alou, S., Diallo, M., Djoukou, K. N., Dramane, H., Diassana, M., Diassana, B., Konate, M., Diakite, I. K., Konake, M. S., Maiga, M., Traore, M., Diarra, S. M., Elansari, M. S. A. M. E., Traore, Y., & Hamadoun, H., 2020, L'utilisation des méthodes contraceptives modernes au Centre de Santé de Référence de la Commune VI du District de Bamako. *Health Sciences and Disease* **21**(10). https://www.hsd-fmsb.org/index.php/hsd/article/view/2344

[2] Ndiaye, C. A. T., Delaunay, V., & Adjamagbo, A., 2003, Connaissance et utilisation des méthodes contraceptives en milieu rural sereer au Sénégal. *Santé : Cahiers d'Études et de Recherches Francophones* **13**(1), 31–37. https://www.documentation.ird.fr/hor/fdi:010072965

[3] Leye, M. M. M., Faye, A., Diongue, M., Wone, I., Seck, I., Ndiaye, P., & Dia, A. T., 2015, Déterminants de l'utilisation de la contraception moderne dans le district sanitaire de Mbacké (Sénégal). *Santé Publique* **27**(1), 107–116. https://doi.org/10.3917/spub.151.0107

[4] Kazadi, K.T., Beya, T.B., Masengu, I.A., Ilunga, T.D. and Luboya, K.J., 2022, Determinants of Low Use of Contraceptive Methods by Women of Childbearing Age in Mwene Ditu Town, DRC: A Cross-Sectional Study. *Open Access Library Journal* 9, 1-14. https://doi.org/10.4236/oalib.1109165

[5] Olou, L. N., Adakanou, A., Zoua, G., Kobenan, A., & Horo, A., 2025, Utilisation des méthodes contraceptives modernes chez les femmes en âge de procréer dans 3 centres de planification familiale à Abidjan. *Revue Africaine des Sciences Sociales et de la Santé Publique* **7**(2), 235-246. https://doi.org/10.4314/rasp.v7i2.16

[6] United Nations, Department of Economic and Social Affairs, Population Division, 2024, *World contraceptive use 2024*. (New York, NY: United Nations). https://www.un.org/development/desa/pd/world-contraceptive-use

[7] World Health Organization, 2025, *Family planning/contraception methods*. World Health Organization. (Geneva: World Health Organization). https://www.who.int/news-room/fact-sheets/detail/family-planning-contraception

[8] Dimassi, K., Douik, F., Douzi, M. A., Saidi, O., & Ben Romdhane, H., 2017, Les déterminants sociaux de l'utilisation des méthodes contraceptives en Tunisie. *Revue d'Épidémiologie et de Santé Publique* **65**(1), 53-59. https://doi.org/10.1016/j.respe.2016.06.330

[9] Ntambue, A. M., Tshiala, R. N., Malonga, F. K., Ilunga, T. M., Kamonayi, J. M., Kazadi, S. T., Matungulu, C. M., Musau, A. N., Mulamba, D., Dramaix-Wilmet, M., & Donnen, P., 2017, Utilisation des méthodes contraceptives modernes en République Démocratique du Congo : Prévalence et barrières dans la zone de santé de Dibindi à Mbuji-Mayi. *PAMJ Clinical Medicine* **26**(199). https://doi.org/10.11604/pamj.2017.26.199.10897

[10] Namegabe, J.-C. P., Mokoso, J. D. D. M., Ngeleza, O. N., Wanguwabo, D. B., Ngaboyeka, G. A., & Ntukamazina, D., 2026, Facteurs associés à l'utilisation des méthodes contraceptives modernes chez les couples de la Zone de santé de Bagira, Sud-Kivu, République Démocratique du Congo. *Revue des Sciences de la Santé* ***5***(2), 722-735. https://doi.org/10.71004/rss.026.v5.i2.119

[11] Matungulu, C. M., Kandolo, S. I., Mukengeshayi, A. N., Nkola, A. M., Mpoyi, D. I., Mumba, S. K., Kabamba, J. N., Cowgill, K., & Kaj, F. M., 2015, Déterminants de l'utilisation des méthodes contraceptives dans la zone de santé Mumbunda à Lubumbashi, République Démocratique du Congo. *The Pan African Medical Journal* **22**, 329. https://doi.org/10.11604/pamj.2015.22.329.6262

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Perceived Environmental and Socio-Health Impacts of Artisanal Gold Mining in the Banalia/Bangba Sector, Banalia Territory, Democratic Republic of the Congo

Stanislas Linangelo Bokungu[1,a], Junior Omba[2,b], Aimé-Claude Libakata Enyangola[3,c], Jeannot Lingondo Mokemba[4,d], Sabrine Yasenge Yasongbi[5,e], Adrien Moango Manga[5,f], Zoé-Arthur Kazadi Malumba[5,g], Corneille Ewango Ekokinya[5,h], Koto-Te-Nyiwa Ngbolua[6,i], Stéphane Mbuyamba Ngalula[6,j], Crispin Mulaji Kyela[6,7,k,*]

[1] *Higher Pedagogical Institute of Kisangani, Kisangani, Democratic Republic of the Congo*

[2] *Geographical Institute of the Congo, Kinshasa, Democratic Republic of the Congo*

[3] *Pontifical Gregorian University, Faculty of Social Sciences, Development Economics, Piazza della Pilotta, Rome, Italy*

[4] *Higher Pedagogical Institute of Ubundu, Kisangani, Democratic Republic of the Congo*

[5] *University of Kisangani, Faculty of Sciences, Kisangani, Democratic Republic of the Congo*

[6] *University of Kinshasa, Faculty of Sciences and Technology, Kinshasa, Democratic Republic of the Congo*

[7] *Centre for Research in Human Sciences (CRESH), Kinshasa, Democratic Republic of the Congo*

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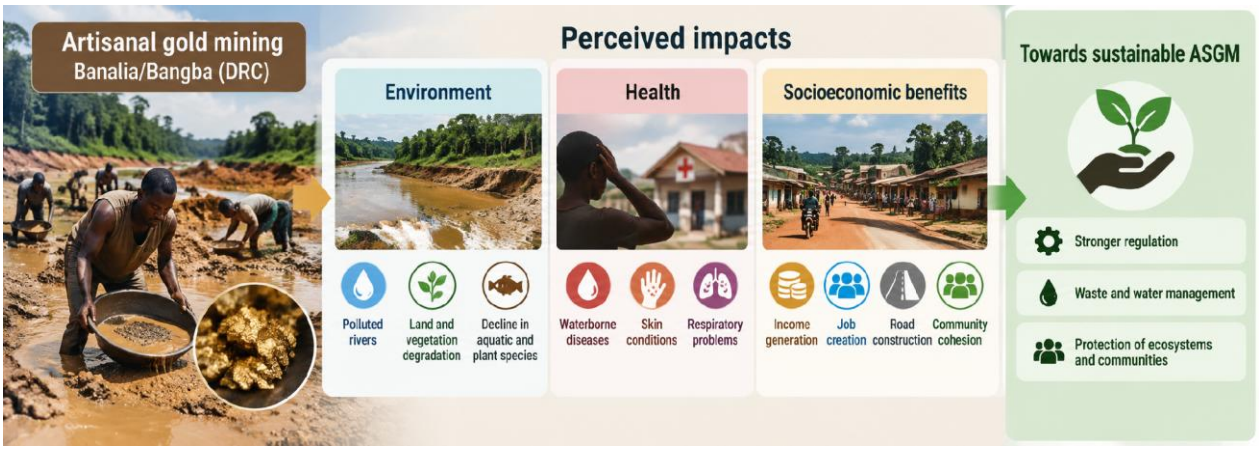
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[a] **ORCID:** *0009-0008-0343-7896*; **Email:** stanislaslinangelo@gmail.com
[b] **ORCID:** *0009-0006-8045-1486*; **Email:** ombalareserve@gmail.com
[c] **ORCID:** *0000-0001-5109-3700*; **Email:** libakatae@gmail.com
[d] **ORCID:** *0000-0002-1849-9554*; **Email:** lingondo2000@gmail.com
[e] **ORCID:** *0009-0001-4589-1287*; **Emails:** yasengesabrine@gmail.com
[f] **ORCID:** *0009-0004-6883-0294*; **Emails:** moangoadrien@gmail.com
[g] **ORCID:** *0009-0002-6178-0760*; **Emails:** kazadizoe364@gmail.com
[h] **ORCID:** *0000-0001-5622-5127*; **Emails:** corneille.ewango@unikis.ac.cd
[i] **ORCID:** *0000-0002-0066-8153*; **Email:** jpngbolua@unikin.ac.cd
[j] **ORCID:** *0009-0005-7381-1546*; **Emails:** stephane.mbuyamba@unikin.ac.cd
[k] **ORCID:** *0000-0002-9406-3277*; **Emails:** crispin.mulaji@unikin.ac.cd

*** Corresponding author:** Crispin Mulaji Kyela; **Email:** *crispin.mulaji@unikin.ac.cd*

Graphical Abstract

Artisanal mining is an important source of income for rural populations in the Democratic Republic of the Congo, but may also affect the environment and health. This study describes the perceived environmental and socio-health impacts of artisanal gold mining in the Banalia/Bangba sector, particularly river pollution, waste accumulation, degradation of soils and vegetation cover, and water-related diseases. As these findings are based on reported perceptions rather than analytical or clinical measurements, further investigations and strengthened environmental and health oversight are needed.



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Abstract: Artisanal mining is a source of income for many rural populations in the Democratic Republic of the Congo, but may affect the environment and health. This study describes the perceived environmental and socio-health impacts of artisanal gold mining in the Banalia/Bangba sector. A descriptive cross-sectional survey was conducted in 2021 among 100 key informants. Respondents mainly reported river pollution, waste accumulation, degradation of soils and vegetation cover, as well as water-related diseases. In the absence of analytical or clinical measurements, these observations do not allow a causal relationship to be established. Strengthened environmental and health oversight, together with further investigations, is therefore needed.

Keywords: *Artisanal gold mining, Environmental impacts, Health*

Introduction

Artisanal and small-scale gold mining (ASGM) constitutes an important economic activity in many developing countries. Worldwide, it provides livelihoods for several million people and supports various related activities, including trade, transport, catering and services [1].

The economic importance of this activity has increased over recent decades, particularly as a result of global demand for gold, changes in its price and the lack of formal employment opportunities in many rural areas. Artisanal gold mining can exert considerable pressure on the environment and population health.

The extraction and processing techniques used by artisanal miners are often poorly mechanized and insufficiently regulated in technical, environmental and health respects. They can lead to deforestation, soil degradation and erosion, siltation of watercourses, habitat destruction and, depending on the processes used, contamination of soils and water resources. Mining activities can also alter the living conditions of local populations.

The economic attractiveness of mining areas can lead to population movements and the arrival of workers, traders and other economic actors. This population growth may increase pressure on natural resources, health infrastructure and available social services.

In mining communities, inadequate sanitation infrastructure, overcrowding, limited access to safe drinking water and exposure to occupational hazards may contribute to public health problems [2].

The environmental consequences of artisanal mining can be pronounced in tropical forest regions, including destruction of forest cover, disturbance of watercourses, degradation of agricultural land, dust emissions and, in some contexts, chemical pollution of soils and water. The use of mercury (Hg) for gold amalgamation is, in particular, a major environmental and health concern [3].

In the Democratic Republic of the Congo, artisanal mining expanded significantly from the 1980s onwards, in the context of economic liberalization policies and changes in the regulation of the mining sector. The north-eastern and central-eastern provinces of the country, which contain substantial gold resources, are particularly affected. In these regions, artisanal gold mining represents an essential economic activity for many families and constitutes an important source of income in rural areas. It therefore contributes to local economic dynamics alongside agriculture, livestock farming and trade [4]. Banalia Territory, located in Tshopo Province, is among the areas characterized by substantial artisanal gold-mining activity. In the Banalia/Bangba Sector, this

activity contributes to the livelihoods of local populations, but is also accompanied by significant changes to the natural environment.

The use of mercury in gold ore processing constitutes, in particular, an environmental and health concern. Prolonged exposure to mercury, combined with deforestation, soil disturbance and the destruction of alluvial terraces, may contribute to the contamination of soils and watercourse sediments and alter aquatic and terrestrial habitats. In the longer term, these changes may affect the ecological functioning of ecosystems and increase the risks of exposure among local populations [5,6].

Although several studies have documented the environmental effects of artisanal mining in different regions of the DRC, data specifically addressing the environmental and socio-health consequences of artisanal gold mining in the Banalia/Bangba Sector remain limited. In particular, the available local data do not allow an integrated characterization of community perceptions concerning water, waste, biodiversity and health problems associated with mining sites.

This is an important gap because ASGM constitutes a priority sector in development and poverty-reduction policies in the DRC. It also has direct links with several Sustainable Development Goals (SDGs), particularly those relating to poverty eradication, health, access to safe drinking water, ecosystem protection and the promotion of sustainable communities [7,8].

In this context, the present study aims to describe the perceived environmental and socio-health impacts of ASGM in the Banalia/Bangba Sector, Banalia Territory. More specifically, it seeks to document the forms of environmental degradation reported by local stakeholders, the health problems reported, and the perceived socio-economic benefits of ASGM activities.

Materials and Methods

Study Area

The study was conducted in 2021 in the Banalia/Bangba Sector, located in Banalia Territory, Tshopo Province, Democratic Republic of the Congo. This area is characterized by ASGM activities that constitute an important source of income for part of the local population. Artisanal mining takes place within a rural environment where populations also depend on natural resources for agriculture, fishing, hunting, forestry and other subsistence activities. This coexistence of mining and rural activities makes the analysis of these interactions particularly important. Figure 1 below shows the different sites within the study area.

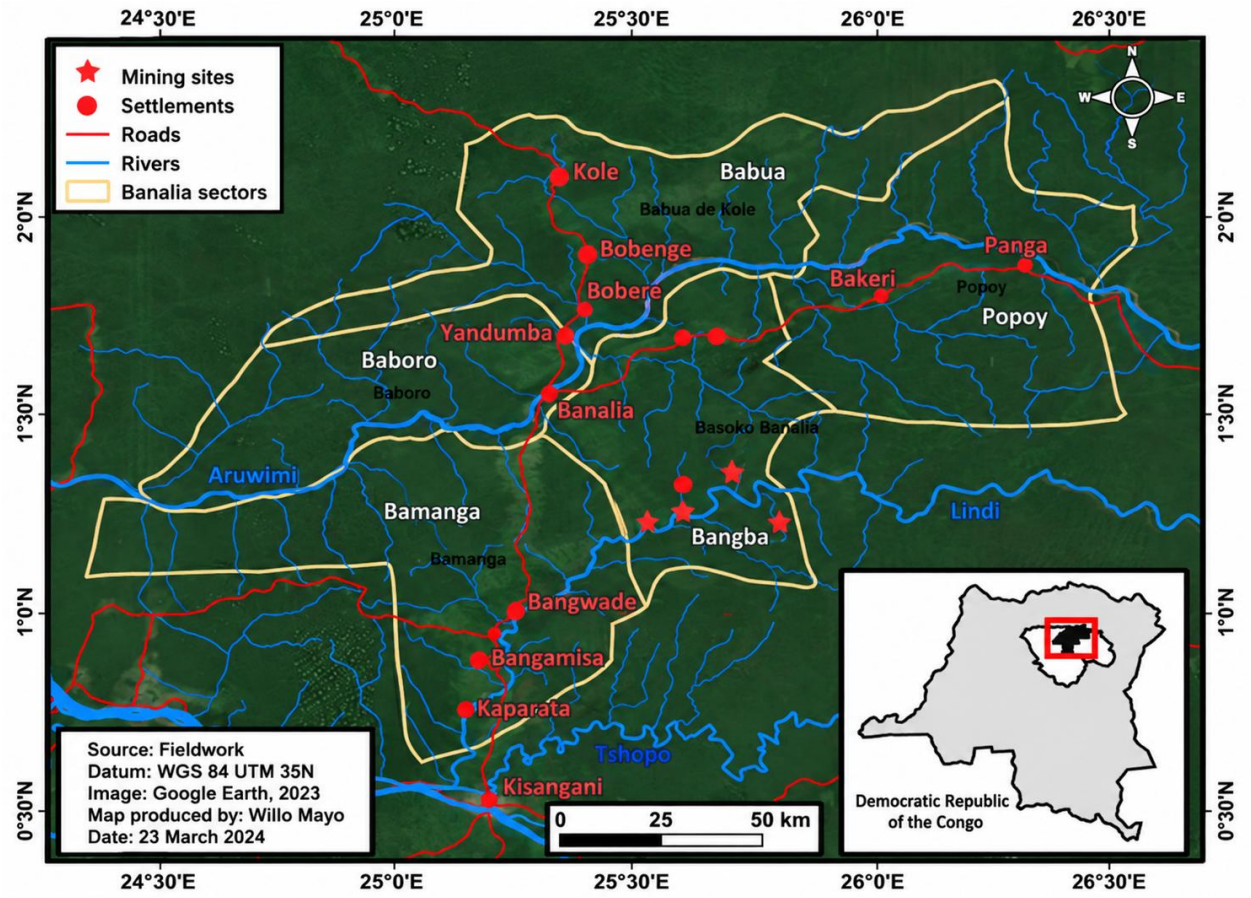


Figure 1. Map of the study area showing mining sites and settlements in the Banalia–Bangba sector

Methodological Approach and Data Analysis

This was a descriptive cross-sectional purposive survey with qualitative and quantitative components, conducted in 2021. Semi-structured interviews were used to collect the perceptions, experiences and observations of stakeholders familiar with the realities of artisanal mining in the Banalia/Bangba sector. These interviews yielded data which the research team examined to study environmental changes, sanitation conditions, reported health problems and the perceived socio-economic impacts of mining activities.

The sample comprised **100 participants**, selected on the basis of their knowledge of the local context, experience of mining activities or involvement in community life. The source version specifies neither the source population nor the formal inclusion and non-inclusion criteria, the detailed recruitment procedure, or a sample size calculation. Consequently, this non-probability

sample does not allow the statistical representativeness of the sector's entire population to be estimated. The interviews addressed gold-mining practices, observed environmental changes, water resources, waste management, reported health problems and the perceived socio-economic impacts of mining activities.

Following data collection, open-ended responses were grouped into thematic categories using content analysis. Categorical variables derived from the coding were entered into Excel and summarized using frequencies and proportions. Chi-square goodness-of-fit tests were used to assess whether the observed frequencies differed significantly from an equal distribution across response categories. The null hypothesis assumed equal expected frequencies among categories. Statistical significance was set at $p < 0.05$.

Results and Discussion

The results concern the composition of the sample, waste and sanitation, river pollution as perceived by respondents, areas of sites reported as degraded, aquatic and plant species reported as having become rarer, reported health problems, and the perceived socio-economic impacts of mining activities.

Environmental Impacts

The 100 participants represented six socio-professional categories, as shown in Table 1.

Table 1. Socioprofessional categories of the study participants

No.	Participant category	n	%
1	Artisanal miners	30	30
2	Local residents	20	20
3	Local authorities	20	20
4	Gold traders	15	15
5	Mine operators	10	10
6	Others	5	5
Total		**100**	**100**

The distribution of respondents differed significantly among the six professional categories ($\chi^2 = 23.00$, df = 5, $p < 0.001$). Artisanal miners were the most represented category (30%), followed by local residents and local authorities (20% each), then mine operators and other participants represented 10% and 5%, respectively.

Waste was frequently cited as a source of deterioration of living conditions at the mining sites (Table 2). The accumulation of solid waste and wastewater, combined with inadequate waste collection and disposal systems, was reported as an environmental and public health concern. These data are based on participants' reports, not direct environmental measurements.

Table 2. Participants' perceptions of waste as a factor contributing to environmental degradation at mining sites

No.	Response	n	%
1	Source of insanitary conditions	28	56
2	Perceived health hazard	14	28
3	Source of unpleasant odours	8	16
Total		**50**	**100**

The distribution of responses concerning the main nuisances differed significantly among the three categories ($\chi^2 = 14.08$, df = 2, $p < 0.001$). Sources of insanitary conditions were the most frequently reported nuisance (56%), followed by perceived health hazards (28%) and unpleasant odours (16%).

Regarding the question on the condition of the rivers presented in Table 3, respondents associated this situation with the washing of gold-bearing sands and the absence of sanitation facilities in some camps. These results reflect a perception of pollution.

Table 3. Participants' perceptions of the pollution status of rivers

No.	Response	n	%
1	River reported as polluted	75	75
2	River reported as not polluted	25	25
Total		**100**	**100**

The perception of river pollution differed significantly between the two response categories (χ^2 = 25.00, df = 1, $p < 0.001$). Overall, 75% of respondents reported the river as polluted, but 25% reported it as not polluted.

For the four sites presented in Table 4, the areas reported as degraded totalled **13 ha in 2021**.

Table 4. Number of artisanal miners and areas reported as degraded at each mining site

No.	Mining site	Number of artisanal miners	Reported degraded area (ha)
1	Lolima	40	7
2	Guma	25	3
3	Bogbolo	20	2
4	Mavi Tshopo	15	1
Total		**100**	**13**

The analysis of the relationship between the number of artisanal miners and the area reported as degraded revealed a **very strong positive linear correlation** (r = 0.997; p = 0.0026). This association was statistically significant at the 5% level. Across the four sites, higher numbers of artisanal miners were associated with larger reported degraded areas. Given the small number of sites and the reported nature of the degraded-area estimates, this association should be interpreted cautiously.

Table 5. Aquatic species reported as having become rare or locally disappeared

No.	Vernacular name	Scientific name	n	%
1	Sulu	*Labeo longipinnis*	15	15
2	Foka	*Chrysichthys nigrodigitatus*	10	10
3	Ndakalla (sardines)	*Stolothrissa tanganicae*	12	12
4	Mbenga	*Hydrocynus goliath*	14	14
5	Sela	*Labeo degeni*	8	8
6	Mboto	*Distichodus sexfasciatus*	13	13
7	Ngolo (catfish)	*Clarias gariepinus*	15	15
8	Apili (oysters)	*Ostrea metazoa*	13	13
Total			**100**	**100**

The distribution of the reported aquatic species did not differ significantly from an equal distribution ($\chi^2 = 3.36$, df = 7, p = 0.850). Frequencies ranged from 8% for *Labeo degeni* to 15% for *Labeo longipinnis* and *Clarias gariepinus*.

Regarding the flora, participants notably cited *Gilbertiodendron dewevrei*, *Pericopsis elata*, *Vernonia amygdalina* and *Entandrophragma cylindricum* as species that had become locally rarer

Table 6. Plant species reported as having become rare or locally disappeared

No.	Vernacular name	Scientific name	n	%
1	Limbalu	*Gilbertiodendron dewevrei*	30	30
2	Mogoya	*Pericopsis elata*	25	25
3	Botuma	*Vernonia amygdalina*	30	30
4	Liboyo	*Entandrophragma cylindricum*	15	15
Total			**100**	**100**

The distribution of the reported plant species did not differ significantly from an equal distribution ($\chi^2 = 6.00$, df = 3, p = 0.112). *Gilbertiodendron dewevrei* and *Vernonia amygdalina* were the most frequently reported species (30% each), followed by *Pericopsis elata* (25%) and *Entandrophragma cylindricum* (15%).

Socio-health Impacts

Table 7. Health problems reported by participants

No.	Reported health problem	n	%
1	Reported skin conditions	30	30
2	Reported waterborne diseases	50	50
3	Reported respiratory problems	20	20
Total		**100**	**100**

The distribution of reported health problems differed significantly among the three categories ($\chi^2 = 14.00$, df = 2, $p < 0.001$). Waterborne diseases were the most frequently reported health problem (50%), followed by skin conditions (30%) and respiratory problems (20%).

The distribution of perceived socio-economic benefits differed significantly among the five categories ($\chi^2 = 77.50$, df = 4, $p < 0.0001$). Wealth creation was the main social value identified by respondents, accounting for 50% of responses, followed by job creation (30%) and road construction (10%). Coexistence among communities and a reduction in banditry each accounted for 5% of responses.

These results show that economic benefits, particularly wealth and job creation, occupy a predominant place in respondents' perceptions of the social benefits of the activities studied.

Table 8. Summary of chi-square goodness-of-fit tests for the variables investigated

Variable	χ^2	df	*p*-value	Statistical significance
Professional category	23.00	5	< 0.001	Significant
Insanitary conditions/nuisances	14.08	2	< 0.001	Significant
River perceived as polluted/not polluted	25.00	1	< 0.001	Significant
Aquatic species	3.36	7	0.850	Not significant
Plant species	6.00	3	0.112	Not significant
Reported health consequences	14.00	2	< 0.001	Significant
Perceived socio-economic benefits	77.50	4	< 0.0001	Significant

Note: χ^2 = chi-square statistic; df = degrees of freedom.

Discussion

The study was based on a descriptive cross-sectional purposive survey conducted using semi-structured interviews and content analysis, supplemented by frequencies and proportions. Given the nature of the sampling and the absence of direct environmental or clinical measurements, the discussion should focus on perceived impacts rather than on causally demonstrated effects.

The sample comprised 100 participants belonging to several stakeholder categories: artisanal miners, local residents, local authorities, traders, mine operators and other resource persons.

The composition of the sample was as follows: artisanal miners, 30%; local residents, 20%; local authorities, 20%; traders, 15%; mine operators, 10%; and other categories, 5%. These proportions correspond to Table 1.

The results highlight the perceived duality of artisanal and small-scale gold mining (ASGM): the activity is associated with local economic benefits, and is also described by participants as a source of environmental and socio-health pressures.

The high representation of artisanal miners (30%) reflects the study's strategy for selecting resource persons. Owing to the non-probability sampling approach, however, this proportion cannot be used to estimate their actual representation within the population of the sector.

Table 4 shows a strong positive correlation between the number of artisanal miners and the reported degraded area across the four mining sites ($r = 0.997$, $p = 0.0026$). This result should be interpreted

cautiously because it is based on only four sites and the method used to estimate the degraded areas was not documented. The observed association therefore does not establish a causal relationship between the number of artisanal miners and land degradation.

The perceived environmental impacts concerned several environmental components: water, soils, sanitation and biodiversity [9]. But, the study did not include instrumental measurements to quantify water quality, chemical contamination, air quality or changes in biodiversity.

Regarding water and waste, 75% of respondents reported that the rivers were polluted, and waste was described as a source of insanitary conditions, health risks and unpleasant odours. These findings are consistent with a local perception of deterioration in living conditions, but they should be distinguished from an analytical demonstration of pollution.

Environmental degradation and deterioration of water quality have also been documented in artisanal gold-mining areas elsewhere in sub-Saharan Africa [10]. Unlike those analytical studies, the present findings represent respondents' perceptions and were not confirmed by physicochemical measurements.

Tables 5 and 6 list aquatic and plant species reported as having become rarer or having disappeared locally. These observations are particularly relevant in the forest context of Tshopo Province, which supports substantial biological diversity and forms part of the wider Congo Basin forest ecosystem [11,12]. In the absence of standardized inventories, comparable historical data and control sites, it is not possible to attribute these changes to mining activities or to conclude that there has been a 'collapse' in biodiversity. Rather, these findings represent ecological signals that should be investigated through dedicated field studies.

Waterborne diseases (50%), skin conditions (30%) and respiratory problems (20%) were the main reported health categories. Their coexistence with sanitation problems and perceived river pollution is a matter of concern, but the study does not allow a causal relationship to be established. In other African artisanal gold-mining contexts, mercury exposure has been investigated through both fish contamination and human exposure assessments [15]. Such evidence cannot be extrapolated directly to Banalia/Bangba, but it supports the need for targeted biomonitoring and environmental analyses in the study area.

The perceived positive impacts were mainly economic: wealth creation (50%) and job creation (30%). These perceived benefits should also be considered within the broader socio-economic and

institutional dynamics of artisanal gold production in the DRC, including the informal production and trading arrangements [11]. Other responses concerned road construction (10%), coexistence among communities (5%) and a reduction in banditry (5%). These data illustrate the socio-economic importance attributed to artisanal gold mining by respondents, but they do not allow the actual distribution of income or public and private investment to be assessed, owing to the absence of dedicated economic data.

Overall, the findings describe a local trade-off between perceived economic benefits and reported environmental and health pressures. They support the relevance of regulating ASGM through measures that integrate waste management, access to water and sanitation, reduction of chemical exposures, and ecosystem protection. Mercury use nevertheless remains a major concern in Congolese artisanal gold mining, where local perceptions of exposure and environmental risk have previously been documented [13-15]. But, any recommendation concerning the cessation or substitution of mercury use at the Banalia/Bangba sites should be based on confirmation of its actual use and on a characterization of local processes.

Conclusion

This descriptive cross-sectional survey, conducted in 2021 among 100 resource persons, highlights several perceived environmental and socio-health impacts of artisanal gold mining in the Banalia/Bangba sector. Respondents mainly reported river pollution, waste-management problems, degradation of land and vegetation cover, the local decline of certain species, and health problems dominated by reported waterborne diseases. At the same time, they highlighted economic benefits, particularly wealth and job creation. Owing to the purposive sampling approach and the absence of direct environmental, biological or clinical measurements, these findings should be interpreted as reported perceptions and observations. They are not a causal demonstration of the effects of artisanal gold mining. Similar interactions between artisanal mining, rural livelihoods, employment and local socio-economic transformations have been documented in other West African mining contexts.

It is recommended that environmental and health oversight of mining sites be strengthened, together with waste and wastewater management, protection of water sources, and prevention of occupational and chemical exposures. The presence of mercury and the ways in which it is used at the sites studied should be documented before quantifying or attributing any specific risk to this metal.

Further studies are needed to assess the reported observations objectively, including physicochemical and microbiological analyses of water, soil and sediment analyses, standardized ecological inventories, and epidemiological studies with explicit definitions of exposures and health outcomes. Such investigations would make it possible to estimate potential contamination levels and assess associations between mining-related exposures and health without drawing conclusions beyond what the data support.

References

[1] Seccatore, J., Veiga, M. M., Origliasso, C., Marin, T., & De Tomi, G., 2014, An estimation of the artisanal small-scale production of gold in the world. *Science of the Total Environment* **496**, 662–667. https://doi.org/10.1016/j.scitotenv.2014.05.003

[2] Mangambu Mokoso, J. D. D., Ntahobavuka Habimana, H., Basinyize Birhashwirwa, P., Lokumu Ilombelombe, L.-G., & Robbrecht, E., 2018, Pteridaie: Indicator of the vegetation succession and dynamics in the forests Chablis and edges in Kahuzi-Biega National Park (Eastern D. R. Congo, Albertine Rift). *International Journal of Biological Research* **6**(1), 5–13. https://doi.org/10.14419/ijbr.v6i1.9241

[3] Koy, J. K., Tabu, A., Bamulezi, G. G., Kebongobongo, M. M., Mombenga, S. A., Kalala, J.-C., Welepele, C., Tréfon, T., & Lamarre, E., 2024, Évaluation préliminaire des impacts environnementaux de l'orpaillage dans le Domaine de chasse de Bili-Uéré en République démocratique du Congo. *VertigO – La revue électronique en sciences de l'environnement,* **24**(3). https://doi.org/10.4000/14ehm Bedidjo

[4] Bedidjo, A., 2018, *Voix du Congo : Étude sur l'orpaillage et l'utilisation du mercure dans l'exploitation minière artisanale en Ituri*. Association des Exploitants Miniers Artisanaux pour la Pacification et Reconstruction de l'Ituri (AEMAPRI), International Peace Information Service (IPIS). https://ipisresearch.be/fr/publication/voix-du-congo-etude-sur-lorpaillage-et-lutilisation-du-mercure-dans-lexploitation-miniere-artisanale-en-ituri/

[5] Yamfwa Besa Kafola, O., Muswaswa, A. M., Gizanga Valu, R., Musibono Eyul'Anki, D., & Biey Makaly, E., 2024, Problem of artisanal gold mining in the mining area of Mangi, Tshopo Province in the Democratic Republic of Congo. *International Journal of Progressive Sciences and Technologies* **43**(1), 92–104. https://doi.org/10.52155/ijpsat.v43.1.5990

[6] Nkuba, B., Bervoets, L., & Geenen, S., 2017, Le mercure dans l'exploitation de l'or : Responsabilité environnementale et perceptions locales. In A. Nyenyezi Bisoka, S. Geenen, A. Ansoms, & J. Omasombo Tshonda (Eds.), *Conjonctures congolaises 2016 : Glissement politique, recul économique* (pp. 191–213). (Paris: L'Harmattan).

[7] Initiative pour la Transparence dans les Industries Extractives en République Démocratique du Congo (ITIE-RDC)., **2023,** *Rapport ITIE sur le secteur de l'exploitation minière artisanale et à petite échelle dans la chaîne de valeur du cuivre-cobalt-zinc***.** Kinshasa, République Démocratique du Congo : ITIE-RDC**.** https://eiti.org/sites/default/files/2023-04/ASM%20-%20ITIE-RDC%20-%20Rapport%20final%20-%2027-03-2023.pdf

[8] De Haan, J., Dales, K., & McQuilken, J., 2020, *Mapping artisanal and small-scale mining to the Sustainable Development Goals*. Newark, DE: University of Delaware, Minerals, Materials and Society Program, in partnership with Pact.

[9] Mangambu Mokoso, J. D. D., Bondoo Norbert, A., & Mbenga Robert, E., 2021, Regards sur les impacts environnementaux de projet d'exploitation minière semi-industrielle dans le Bassin du Congo : Cas de la rivière Aruwimi (Territoire de Basoko, RD Congo). *European Scientific Journal* **17**(29), 328–347. https://doi.org/10.19044/esj.2021.v17n29p328

[10] Taylor, H., Appleton, J. D., Lister, R., Smith, B., Chitamweba, D., Mkumbo, O., Machiwa, J. F., Tesha, A. L., & Beinhoff, C., 2005, Environmental assessment of mercury contamination from the Rwamagasa artisanal gold mining centre, Geita District, Tanzania. *Science of the Total Environment* **343**(1–3), 111–133. https://doi.org/10.1016/j.scitotenv.2004.09.042

[11] Ahoussi, K. E., & Yapo, A. P., 2021, Étude de la minéralisation des eaux de surface en éléments traces métalliques (ETM) des zones d'orpaillage de la sous-préfecture de Kokumbo, Centre-Ouest de la Côte d'Ivoire. *Afrique Science* **19**(4), 36–50. https://www.afriquescience.net/admin/postpdfs/68089a83b5ff33f919c0371abb69f8821721775556.pdf

[12] Alliance du Cobalt Équitable, 2021, *Rapport annuel 2021 : Rapport sur l'impact et les finances de 2021*. The Impact Facility. https://www.faircobaltalliance.org/app/uploads/2022/03/Rapport-sur-limpact-et-les-finances-de-2021.pdf

[13] Doucouré, B., 2014, Développement de l'orpaillage et mutations dans les villages aurifères du sud-est du Sénégal. *Afrique et Développement* **39**(2), 47–67. http://www.jstor.org/stable/afrdevafrdev.39.2.47

[14] Kanninen, M., Murdiyarso D., Seymour F., Angelsen A., Wunder S., German L., 2007, *Do Trees Grow on Money? The Implications of Deforestation Research for Policies to Promote REDD*, Bogor, Indonesia, CIFOR, 61 p. https://redd.unfccc.int/uploads/2_129_redd_20090209_cifor_do_trees_grow_on_money_en.pdf

[15] Ikingura, J. R., & Akagi, H., 1996, Monitoring of fish and human exposure to mercury due to gold mining in the Lake Victoria goldfields, Tanzania. *Science of the Total Environment* **191**(1), 59–68. https://doi.org/10.1016/0048-9697(96)05178-9

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Cross-border Illicit Economies, Environmental Degradation and Health Vulnerabilities in the Lake Chad Basin: A One Health Perspective

Moussa Bobbo [a*]

Department of History, University of Maroua, PO BOX: 46 Maroua,Cameroon, Road of Kongola

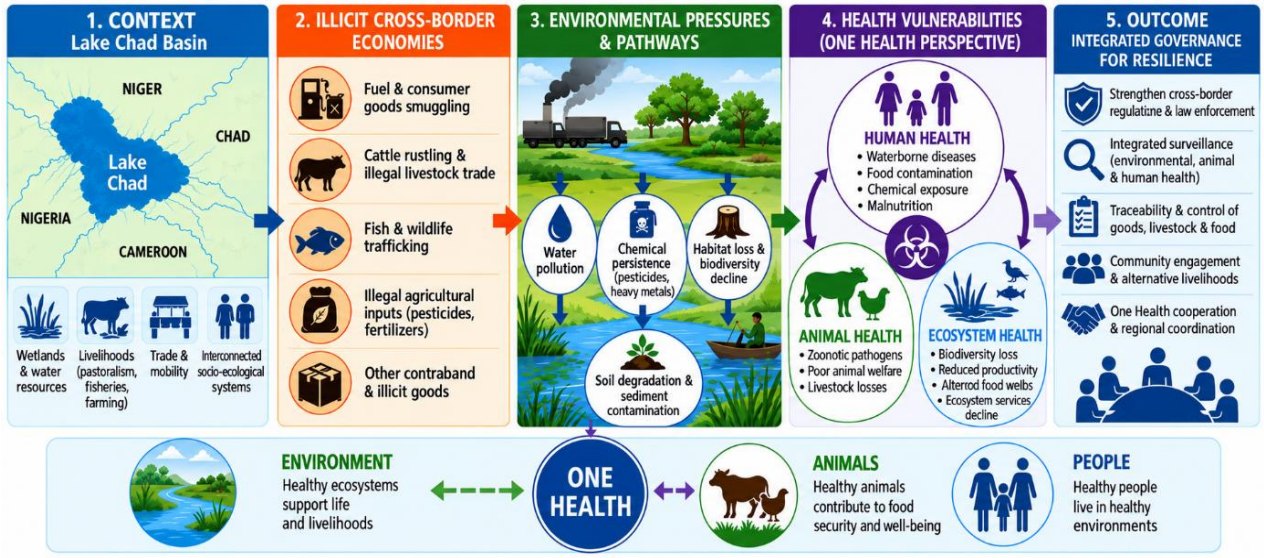
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Corresponding author:** Moussa Bobbo; ***Email address: *bobbo_moussa31@yahoo.com*

Graphical Abstract

The Lake Chad Basin is an interconnected socio-ecological system where cross-border illicit economies may intensify environmental and health vulnerabilities. From a One Health standpoint, weak regulation of livestock, fish, fuel, agricultural inputs and wildlife flows may increase ecological pressures and exposure to environmental contaminants. The article calls for integrated cross-border surveillance, traceability, food safety monitoring and One Health cooperation.



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Abstract: This article examines how cross-border illicit economies may contribute to environmental degradation and health vulnerabilities in the Lake Chad Basin. Drawing on a qualitative review of scientific literature, institutional reports and documented cases from Cameroon, Chad, Niger and Nigeria, the study sees human health, ecosystems, livestock, and natural resource governance as linked by the frame of reference of One Health**.** The article shows how the trafficking and informal circulation of livestock, fish, fuel, agricultural inputs and wildlife may interact with ecological pressures, weak regulation and insufficient health controls. Environmental risks, economic insecurity and health vulnerabilities converge because of pesticide persistence in soils, toxic elements in groundwater, contaminants in fish and cattle rustling. The article calls for integrated cross-border surveillance, traceability, food safety monitoring and One Health cooperation.

Keywords: *Illicit economies, Environmental health, One Health*

Introduction

The Lake Chad Basin is one of the most ecologically sensitive and socially interconnected regions in Africa. The hydrographic basin covers approximately 2.38 million km², extending across parts of Cameroon, Chad, Niger, Nigeria and the Central African Republic [1]. Its wetlands, rivers, floodplains and aquatic ecosystems support agriculture, livestock farming, fishing, trade and domestic water supply. The Lake Chad Basin Commission (LCBC) describes the basin as a strategic ecological and socio-economic system whose sustainability depends on coordinated transboundary management [2].

The same ecological and commercial interconnections both support livelihoods and also facilitate the movement of goods outside formal regulatory systems. Cross-border trade in the region includes legitimate trade, informal exchanges and, in some cases, clearly illicit activities. Documented examples include the smuggling of fuel and consumer goods, livestock theft, contraband, wildlife trafficking and the illegal movement of other goods. In the Lake Chad region, criminal and insurgent actors have exploited trade networks to generate revenue [3,4].

The dominant analytical framework generally focuses on security. But, the environmental and health consequences of these economies deserve greater attention. When goods circulate outside sanitary, environmental and veterinary controls, potential risks can be transmitted through food chains, water systems, soils, livestock and human populations. The problem is acute in a region where households depend on natural resources and where public institutions often face difficulties in monitoring remote border areas.

How do transboundary illicit economies interact with environmental degradation and health vulnerabilities in the Lake Chad Basin, and how can a One Health approach improve regional responses? The central argument advanced in this study is that illicit economies should not be considered exclusively as a security issue. They also constitute socio-environmental processes. Their health implications emerge through several mechanisms: ecological degradation, unsafe production and transport practices, exposure to contaminants, weak food traceability, livestock mobility and inadequate transboundary regulation. The article does not argue that all informal or illicit trade directly generates a health effect. Rather, it identifies documented environmental risks and examines how weaknesses in the regulatory arrangements surrounding transboundary economies can amplify population exposure.

Methodology and Analytical Framework

This study adopts a qualitative and interdisciplinary approach combining documentary analysis with a One Health analytical framework. The corpus comprises peer-reviewed scientific publications, institutional reports and documented case studies of environmental contamination, fisheries, groundwater, livestock mobility, smuggling and illicit economies in the Lake Chad Basin.

The analysis focuses on Cameroon, Chad, Niger and Nigeria, as these countries constitute the core of the conventional Lake Chad Basin and share interconnected ecological, trade and mobility systems [5]. The data were analysed according to four dimensions: (1) cross-border economic flows, (2) environmental pressures, (3) exposure pathways and health vulnerabilities, and (4) governance responses.

The One Health perspective is particularly relevant because environmental change, animal health and human health are not independent variables within the Lake Chad Basin. Fishing, livestock farming, agriculture and water use connect human populations to the same ecological systems [6]. This approach therefore makes it possible to analyse the environmental and health consequences of informal and illicit economies together, rather than treating them within separate sectors.

Cross-Border Illicit Economies in an Interconnected Socio-Ecological Space

The circulation of goods across the Lake Chad Basin relies on cross-border mobility. Roads, waterways, pastoral corridors and local markets connect Baga Kawa, Baga Sola, Bol, Diffa, northern Cameroon and other trading centres. Before the intensification of insecurity, canoes regularly transported fish, agricultural produce and manufactured goods between Chad and Nigeria; return journeys carried foodstuffs and consumer goods. These routes had long constituted a genuine economic lifeline for peripheral communities [7].

The distinction between informal and illicit economies is therefore essential. Informal trade is not necessarily criminal. Many border communities rely on it because formal markets are costly, distant or difficult to access [8]. The problem arises when commercial practices include smuggling, stolen products, prohibited goods or criminal taxation.

Livestock farming provides a particularly important illustration. Livestock theft has become increasingly transnational in the Lake Chad Basin. According to data reported by the Institute for Security Studies, documented incidents of livestock theft linked to Boko Haram in the border areas of Cameroon and Chad increased from two in 2015 to 131 by August 2024, with 390 incidents and

146 deaths recorded over the period. Stolen livestock are frequently transported across borders and then reintroduced into legal markets, making their traceability difficult [4].

This process has implications that extend beyond security and household incomes. Livestock mobility without effective veterinary surveillance can complicate disease detection, vaccination coverage, animal identification and food safety controls. The same cross-border routes that facilitate legitimate pastoral mobility may therefore become pathways through which animals, goods and potentially certain pathogens circulate beyond the effective capacity of national regulatory systems [9].

Wildlife trafficking constitutes another example. The LCBC Strategic Action Programme explicitly identifies the illegal trade in threatened plant and animal species as an environmental threat and calls for stronger implementation of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), alongside enhanced protection of wetlands and biodiversity [10]. Wildlife trafficking is not merely a conservation issue; it also raises concerns relating to ecological integrity, food systems and zoonotic risks [11].

Environmental Degradation and Contamination along Illicit or Weakly Regulated Chains

The environmental consequences of illicit economies are often indirect. Where regulatory oversight is weak, economic activities may intensify without sufficient environmental safeguards. Pressure on fishery resources, unregulated resource exploitation, wildlife trafficking, fuel smuggling, informal waste disposal and the uncontrolled use of agricultural inputs can cumulatively affect ecosystems already under pressure from climate variability and population growth.

Fisheries illustrate this tension particularly well. Fish represent a source of food, income and cross-border trade. The LCBC has identified the need to protect spawning grounds, promote sustainable fishing techniques and control destructive fishing practices. When fishery resources become subject to taxation, predation or illicit trade, the economic survival of communities may increasingly depend on exploitation practices that reduce ecological resilience.

Environmental contamination constitutes another concern. Kidd, Stern and Lemoalle [12] investigated the presence of mercury and other contaminants in fish from Lake Chad, providing an important scientific basis for monitoring pollutants within the lake's food webs. This study does not attribute contamination to illicit trade, but it shows why the circulation and consumption of fishery products require continuous environmental and health surveillance.

Agricultural inputs constitute another pathway of exposure. Crampon *et al.* [13] detected the presence of 1,1′-dimethyl-4,4′-bipyridinium (paraquat) in irrigated soils of the Lake Chad Basin in Niger, with concentrations at depths that raised concerns about possible long-term migration towards groundwater. The authors highlighted the potential implications for groundwater: a major water resource on which densely populated communities depend.

More recent research reinforces the importance of this issue. Shuaibu *et al.* [14] identified groundwater contamination by lead (Pb), iron (Fe), manganese (Mn) and cadmium (Cd) in the transboundary Komadugu-Yobe Basin, in the Lake Chad region. Pollution indices indicated greater contamination in downstream areas. The health risk assessment revealed significant non-carcinogenic and carcinogenic risks for both adults and children and linked the contamination to multiple sources, including agricultural, domestic and industrial activities.

These findings are important for the study of illicit economies because they demonstrate the vulnerability of the ecological systems that underpin transboundary livelihoods. Where environmental contamination coexists with weak regulation of the circulation of goods, the distance between environmental exposure and human consumption may increase. Identifying responsibility becomes more difficult.

From Environmental Pressure to Health Vulnerability

The health consequences of transboundary illicit economies can be understood through several pathways of exposure. The first is the food chain. Fish, meat, agricultural products and other goods circulate through several markets before reaching consumers. When traceability and sanitary inspection are insufficient, exposure to contaminants or poor handling conditions becomes more difficult to detect.

The second pathway concerns water. In many communities of the Lake Chad Basin, surface water and groundwater are closely linked to domestic uses, irrigation, fishing and livestock farming. Groundwater contamination therefore generates several risks simultaneously. The 2025 study on the Komadugu-Yobe Basin [15] identifies health risks affecting both adults and children, showing that environmental contamination can have intergenerational implications.

The third pathway concerns livestock. Cross-border movements of cattle are essential to pastoral livelihoods, but stolen or untraceable animals circulating through informal markets may escape veterinary control. In this region, drought, population displacement and insecurity encourage cross-border movements through areas that are difficult to monitor.

Finally, trafficking and labour exploitation represent a socio-health dimension. The 2025 report on trafficking in persons in Chad documents the exploitation of children in fishing activities around the Lake Chad region and indicates that pastoral routes cross several international borders [16]. These practices illustrate how economic vulnerability, environmental pressure and human exploitation can become mutually reinforcing.

The key analytical issue is therefore that health vulnerability does not result exclusively from pathogens or pollution. It also emerges from governance failures. When populations live and trade in environments where environmental inspection, veterinary control, food safety and public health surveillance are fragmented across several borders, cumulative risks become difficult to identify.

Figures 1, 2, 3 and 4 highlight the close interdependence between spatial dynamics, livelihoods, transboundary economies, and environmental and health vulnerabilities in the Lake Chad Basin.

Figure 1 shows that this area integrates a socio-ecological system, structured by the lake, wetlands, floodplains, agricultural and pastoral areas, as well as major mobility routes. The geographical proximity of Cameroon, Chad, Niger and Nigeria facilitates the intensive movement of people, animals, fishery products and agricultural products. This strong territorial connectivity represents both a resource for local populations and a factor facilitating the circulation of goods that partially escape state control mechanisms.

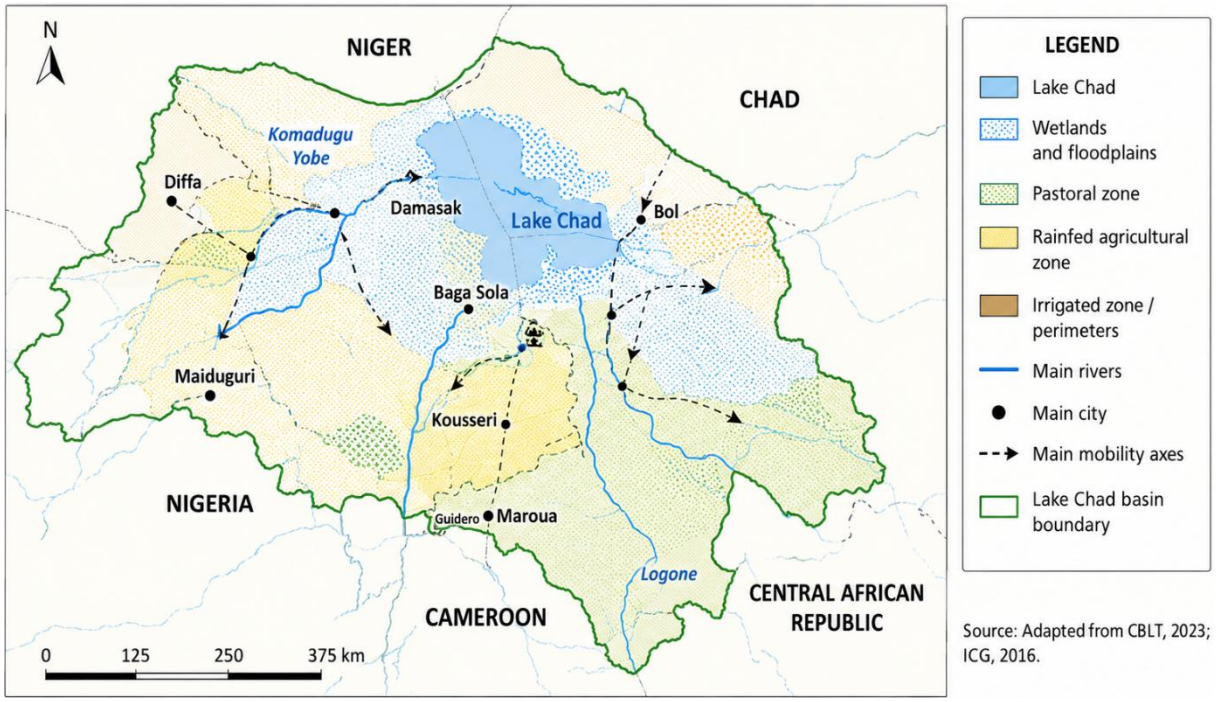


Figure 1. Spatial organization of the Lake Chad Basin, main areas of mobility and livelihood systems. Source [14]

Figure 2 highlights the central role of fishing in local economies. Aquatic resources simultaneously provide a source of income, employment, animal protein and food security for many riparian communities. Fishing, processing, transport and commercialization activities form part of largely transboundary trade chains. This dependence on fishery resources creates a particular vulnerability: overexploitation of stocks, destructive fishing practices, contaminants present in aquatic environments and weak sanitary controls can simultaneously affect the environment and population health. Fishery resources converge with food security, the local economy, ecosystem conservation and public health.



Figure 2. Fishing activities and dependence of riparian communities on the aquatic resources of Lake Chad

Figure 3 constitutes the analytical core of this study. It shows a chain of vulnerability linking transboundary illicit economies to health risks within a One Health framework. Activities such as livestock trafficking, fuel smuggling, wildlife trafficking, the illicit circulation of agricultural inputs and inadequately regulated trade in fishery products place pressure on natural resources. These pressures can then contribute to the degradation of soils, water, wetlands and biodiversity. They create situations of exposure through water, food, animals or contaminated products, which may simultaneously affect human and animal health. Weak security, poor regulation or deficient monitoring allows illicit trafficking to generate environmental and health externalities.

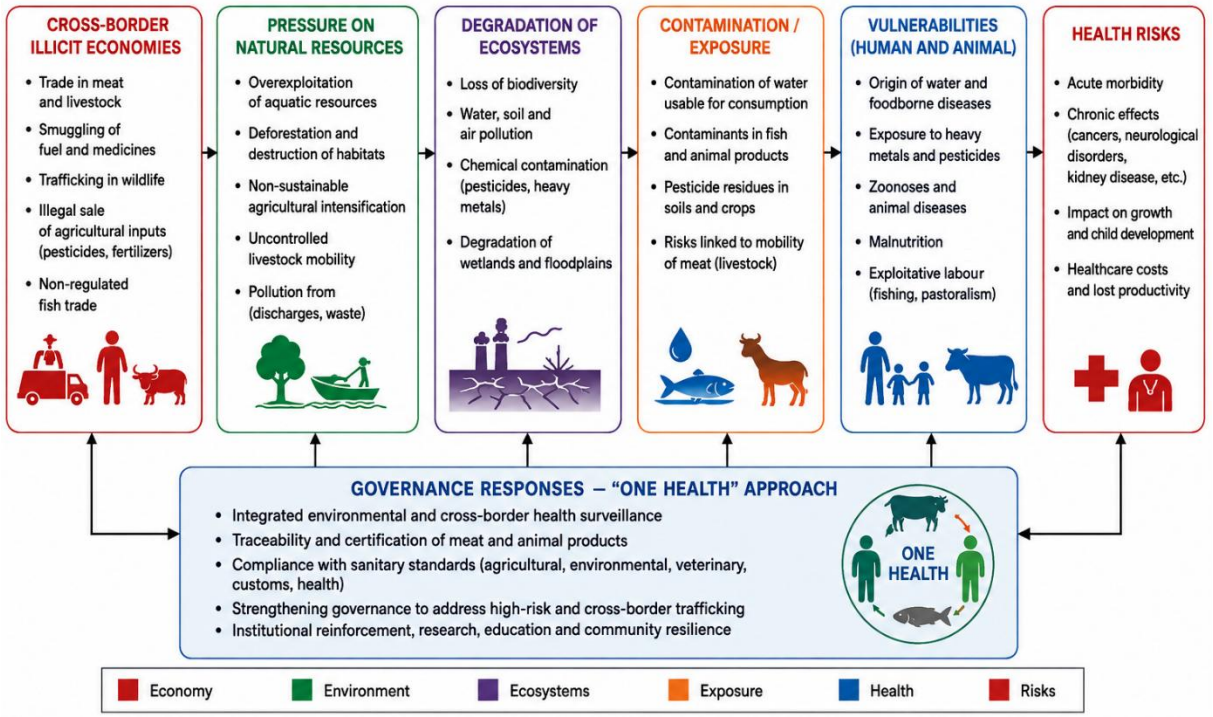


Figure 3. Conceptual framework of the interactions between illicit economies, environment, human health and animal health in the Lake Chad Basin

Figure 4 focuses on this dynamic by showing the main areas of cross-border circulation of resources and goods. It highlights the many corridors connecting commercial centres, markets, pastoral areas and fishing zones. These corridors are not exclusively criminal: they are also essential spaces for economic and social mobility. But, the lack of regulation and monitoring can facilitate the coexistence of legal, informal and illicit flows. The porosity of borders and the overlapping of economic routes therefore increase the difficulties of tracing livestock, food products, fishery resources and certain goods.

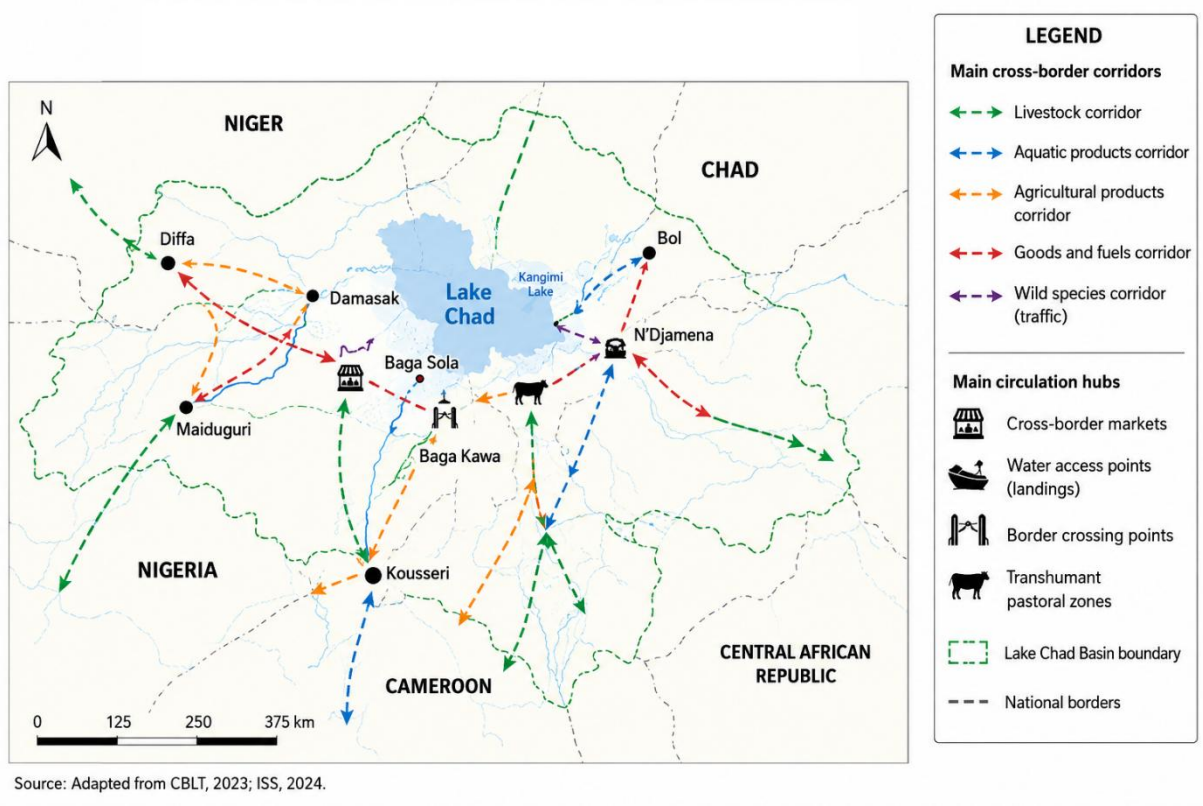


Figure 4. Main cross-border circulation routes of goods and resources in the Lake Chad Basin

Towards a 'One Health' Governance of Transboundary Illicit Economies

Responding to these challenges requires an integrated governance model. Security forces alone cannot address the environmental and health externalities generated by transboundary economies. Similarly, environmental agencies cannot intervene effectively without understanding mobility, markets and insecurity.

Firstly, a One Health strategy for the Lake Chad Basin should strengthen transboundary environmental and health surveillance. Water quality, fish contamination, animal diseases, pesticide residues and food safety should be monitored through interoperable regional systems. Secondly, veterinary and health authorities should improve livestock identification and traceability among Cameroon, Chad, Niger and Nigeria.

Thirdly, border markets should become spaces for integrated surveillance rather than merely security checkpoints. Market inspections could bring together customs services, veterinary services, food safety authorities and environmental health administrations. Such an approach would help reduce the fragmentation that aids the movement of goods between legal and illicit channels with limited traceability.

Fourthly, regional institutions should distinguish vulnerable informal economies from organized criminal markets. Uniform repression of informal trade may weaken livelihoods and push populations towards more dangerous routes. The objective should instead be to formalize low-risk trade while targeting high-risk activities such as trafficking in protected species, livestock theft, the circulation of hazardous products and goods used to finance criminal activities.

Finally, the LCBC and national governments should integrate health indicators into conventional security indicators. The success of regional policies should not be measured solely through seizures, arrests or border patrols, but also through changes in water quality, food security, animal disease surveillance, environmental degradation and community health.

Conclusion

Transboundary illicit economies in the Lake Chad Basin constitute more than a security and governance challenge. They are embedded within a socio-ecological environment in which livelihoods, ecosystems, mobility and health are interdependent. Fishing, livestock farming, agriculture and cross-border trade support millions of people, but weak regulation and criminal exploitation can amplify environmental pressures and health vulnerabilities.

The available evidence does not justify the view that illicit trade directly causes environmental contamination or disease. Rather, it shows that the ecological systems within which these economies operate are already exposed to contamination, overexploitation and governance weaknesses. The challenge is therefore to identify and regulate the mechanisms through which environmental and health risks become connected to informal and illicit economic flows.

A One Health approach provides a relevant framework for achieving this. It encourages decision-makers to connect environmental surveillance, human health, veterinary surveillance, food safety and transboundary governance. For the Lake Chad Basin, such an approach would make it possible to move from a predominantly reactive and security-oriented regional model towards a preventive model centred on ecological resilience, health protection and the sustainability of livelihoods.

The future of environmental health in the Lake Chad Basin depends not only on controlling illicit economies, but also on addressing the socio-economic conditions that sustain them. A sustainable response must therefore combine environmental protection, public health, facilitation of legal trade, community resilience and coordinated transboundary governance. Accordingly, tackling illicit economies is also a means of working towards healthier ecosystems and healthier border communities.

References

[1] Pachova, N. I., Nakayama, M., & Jansky, L. (Eds.)., 2008, *International water security: Domestic threats and opportunities*. (Tokyo: United Nations University Press)

[2] Ndimele, P. E., Akanni, A., Ositimehin, K. M., Shittu, J. A., Ojewole, A. E., & Ayeni, Y. Z., 2024, Fostering international and trans-boundary cooperation in the management of Lake Chad fisheries, wildlife and flora: The role of a trans-boundary Ramsar conservation area. *Aquatic Living Resources* **37**, Article 6. https://doi.org/10.1051/alr/2024004

[3] Nwadiogbu, C. C. N., 2026, Hybrid threats in the Lake Chad Basin: The nexus between terrorism, illicit wealth, and transborder crime. *Journal of Terrorism Studies* **8**(1), Article 7. https://doi.org/10.7454/jts.v8i1.10104

[4] Ojewale, O., & Tayo, R. S., 2025, *Evolution and dynamics of informal money transfer systems in the Lake Chad Basin* (ENACT Research Paper, Issue 60). (Pretoria: Institute for Security Studies). http://enact-africa.s3.amazonaws.com/uploads/pages/1764147930499-2025-11-26-ENACT-money-transfers-in-LCB-paper.pdf

[5] Wakdok, S. S., & Bleischwitz, R., 2021, Climate change, security, and the resource nexus: Case study of Northern Nigeria and Lake Chad. *Sustainability* **13**(19), Article 10734. https://doi.org/10.3390/su131910734

[6] Greter, H., Batil, A. A., Ngandolo, B. N., Alfaroukh, I. O., Moto, D. D., Hattendorf, J., Utzinger, J., Zinsstag, J., 2017, Human and livestock trematode infections in a mobile pastoralist setting at Lake Chad: Added value of a One Health approach beyond zoonotic diseases research. *Transactions of the Royal Society of Tropical Medicine and Hygiene* **111**(6), 278–284. https://doi.org/10.1093/trstmh/trx051

[7] Zenn, J., 2021, Boko Haram's Factional Feuds: Internal Extremism and External Interventions. *Terrorism and Political Violence* **33**(3), 616–648. https://doi.org/10.1080/09546553.2019.1566127

[8] Dzawanda, B., Matsa, M. M., Gumbo, E. B., Runokunda, J. C., & Nicolau, M. D., 2025, A systematic review of informal cross-border trade in African economies towards vision 2030. *Discover Sustainability* **7**(1), Article 84. https://doi.org/10.1007/s43621-025-02443-8

[9] Bawa, S., Afolabi, M., Abdelrahim, K., Abba, G., Ningi, A., Tafida, S. Y., Tegegne, S. G., Warigon, C., Nomhwange, T., Umar, S. A., Aregay, A., Fanti, A., Ahmed, B., Nsubuga, P., Adamu, U., Braka, F., Wondimagegnehu, A., & Shuaib, F., 2018, Transboundary nomadic population movement: A potential for import-export of poliovirus. *BMC Public Health* **18**(4), Article 1316. https://doi.org/10.1186/s12889-018-6190-2

[10] Lake Chad Basin Commission, 2008, *Strategic action programme for the Lake Chad Basin: Agreed by the LCBC member states of Cameroon, Central African Republic, Chad, Niger, and Nigeria*. https://iwlearn.net/resolveuid/2cc8f6b24b896184e77164ab75cbf7b1

[11] Mozer, A., & Prost, S., 2023, An introduction to illegal wildlife trade and its effects on biodiversity and society. *Forensic Science International: Animals and Environments* **3**, Article 100064. https://doi.org/10.1016/j.fsiae.2023.100064

[12] Kidd, K. A., Stern, G., & Lemoalle, J., 2004, Mercury and other contaminants in fish from Lake Chad, Africa. *Bulletin of Environmental Contamination and Toxicology* **73**(2), 249–256. https://doi.org/10.1007/s00128-004-0420-2

[13] Crampon, M., Copard, Y., Favreau, G., Raux, J., Merlet-Machour, N., Le Coz, M., Ibrahim, M., Peulon-Agasse, V., & Portet-Koltalo, F., 2014, Occurrence of 1,1′-dimethyl-4,4′-bipyridinium (Paraquat) in irrigated soil of the Lake Chad Basin, Niger. *Environmental Science and Pollution Research* **21**(18), 10601–10613. https://doi.org/10.1007/s11356-014-3064-8

[14] Shuaibu, A., Kalin, R. M., Phoenix, V., Banda, L. C., & Lawal, I. M., 2025, Potentially toxic elements source identification and associated health risks in the groundwater of transboundary Komadugu-Yobe Basin, Lake Chad region: An integrated approach using chemometric analysis and index-based models. *Journal of Hydrology: Regional Studies* **59**, Article 102439. https://doi.org/10.1016/j.ejrh.2025.102439

[15] Office of the United Nations High Commissioner for Human Rights, 2026, UN expert calls for urgent action in Chad to combat impunity for trafficking in persons, especially children (February 26). https://www.ohchr.org/en/press-releases/2026/02/un-expert-calls-urgent-action-chad-combat-impunity-trafficking-persons

[16] Commission du Bassin du Lac Tchad, 2022, *Programme d'action stratégique (PAS) 2023–2037 : Pour l'inversion de la tendance de dégradation des terres et des écosystèmes dans le bassin du Lac Tchad*. N'Djamena : Commission du Bassin du Lac Tchad (CBLT). https://cblt.org/wp-content/uploads/2026/02/Programme-Daction-Strategique-du-Bassin-du-Lac-Tchad-PAS-2023-2037.pdf

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Floristic Diversity, Forest Structure and Above-ground Carbon Stocks of the Mbamba Forest, Kwilu Province, Democratic Republic of the Congo

Patience Loso Alik [1,2,a], Pisco Menga Munkolo [1,b], Crispin Balo Ilunga [1,c], Jean-Paul Koto-Te-Nyiwa Ngbolua [3,d,*], Godéfroid Yaya Yemweni [1,2,e], Félicien Lukoki Luyeye [1,f], Bonaventure Masens Da-Musa Yung [1,g]

[1] *Laboratory of Plant Biodiversity, Ecology and Ethnobotany, Life Sciences Section, University of Kinshasa, P.O. Box 190, Kinshasa XI, Democratic Republic of the Congo*

[2] *Higher Pedagogical Institute of Kikwit, Kwilu Province, Democratic Republic of the Congo*

[3] *Laboratory of Ethnobiology and Medical Phytochemistry, Life Sciences Section, University of Kinshasa, Kinshasa, Democratic Republic of the Congo*

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[a] **ORCID:** *0009-0002-6897-1834*; **Email:** *losoalik327@gmail.com*

[b] **ORCID:** *0009-0000-5565-566X*; **Email:** *mengapisco@yahoo.fr*

[c] **ORCID:** *0009-0009-8999-6222*; **Email:** *balocrispin7@gmail.com*

[d] **ORCID:** *0000-0002-0066-8153*; **Email:** *jpngbolua@unikin.ac.cd*

[e] **ORCID:** *0000-0001-9153-1410*; **Email:** *godefroidyaya16@gmail.com*

[f] **ORCID:** *0000-0002-1233-9699*; **Email:** *felicien.lukoki@unikin.ac.cd*

[g] **ORCID:** *0009-0008-0646-9500*; **Email:** *bonaventuremasens2024@gmail.com*

*__Corresponding author:__ Jean-Paul Koto-Te-Nyiwa Ngbolua, **Email:** *jpngbolua@unikin.ac.cd*; **Tel.:** (+243) 816879527

Graphical Abstract

This study characterizes the floristic diversity, forest structure and above-ground carbon stocks of the Mbamba forest. The results reveal high floristic diversity and structural heterogeneity, with distinct floristic groups and a strong contribution of dominant species to forest structure. The forest also stores substantial above-ground biomass and carbon, highlighting its ecological importance and the need to conserve floristic diversity, structurally important species and large trees.



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Abstract: This study characterizes the floristic diversity, forest structure and above-ground carbon stocks of the forest within the Sisters of Mary concession in Mbamba, Kwilu Province, Democratic Republic of the Congo. The inventory was conducted in 18 plots of 25 × 25 m, covering 1.125 ha. It recorded 536 woody individuals belonging to 101 taxa and 32 families, with high floristic diversity (H' = 3.701; Simpson = 0.942; Pielou = 0.802). *Staudtia kamerunensis*, *Dichostemma glaucescens* and *Brachystegia laurentii* accounted for 34.70% of individuals, and stems of 10–30 cm diameter represented 75.1%. Multivariate analyses distinguished two floristic groups, with differences in composition (PERMANOVA: pseudo-$F_{1,16}$ = 4.216; R^2 = 0.209; p < 0.001) and dispersion (PERMDISP: $F_{1,16}$ = 8.501; p = 0.010). Mean above-ground biomass was 423.24 ± 77.50 Mg ha^{-1}, corresponding to 198.92 ± 36.43 Mg C ha^{-1}. These results highlight a floristically diverse forest with substantial above-ground biomass and carbon stocks, supporting its conservation and temporal monitoring.

Keywords: *Floristic diversity, Forest structure, Above-ground carbon stocks*

Introduction

African tropical forests are major reservoirs of biodiversity and carbon. Congo Basin forests store considerable carbon, but their net sink function is increasingly threatened by socio-economic and climatic pressures [1].

The Democratic Republic of the Congo (DRC) contains the largest share of Congo Basin forests, yet data on diversity, structure and carbon stocks remain geographically uneven. Forest–savannah transition zones are particularly under-documented despite agriculture, fuelwood use, fires and fragmentation [2,3].

Kwilu forests occur in this transitional context, where floristic composition and structure influence biomass [4]. In African tropical forests, biomass may be concentrated in a few dominant species or large trees [5,6], depending on tree size, density, basal area, wood density and species composition [7].

The Mbamba forest in the Sisters of Mary concession retains well-developed woody vegetation, but its floristic composition, structure and above-ground carbon stocks remain poorly quantified.

This study characterizes floristic diversity, forest structure and above-ground carbon stocks, identifies floristic groups and characteristic species, and quantifies biomass and carbon.

Materials and Methods

Study Area

The study was conducted in the Sisters of Mary concession forest at Mbamba, Imbongo Sector, Bulungu Territory, Kwilu Province, DRC (Figure 1).

The region has a tropical climate, with a rainy season mainly from August to May and a dry season from May to August. Annual rainfall is about 1,600 mm and mean relative humidity 78% [4]. Soils are mainly sandy to sandy-clayey over sandstone substrates [8,9].

The site belongs to the Guineo-Congolian domain within a forest–savannah mosaic. Masens *et al.* [4] reported terra firme forests dominated by *Brachystegia laurentii.*

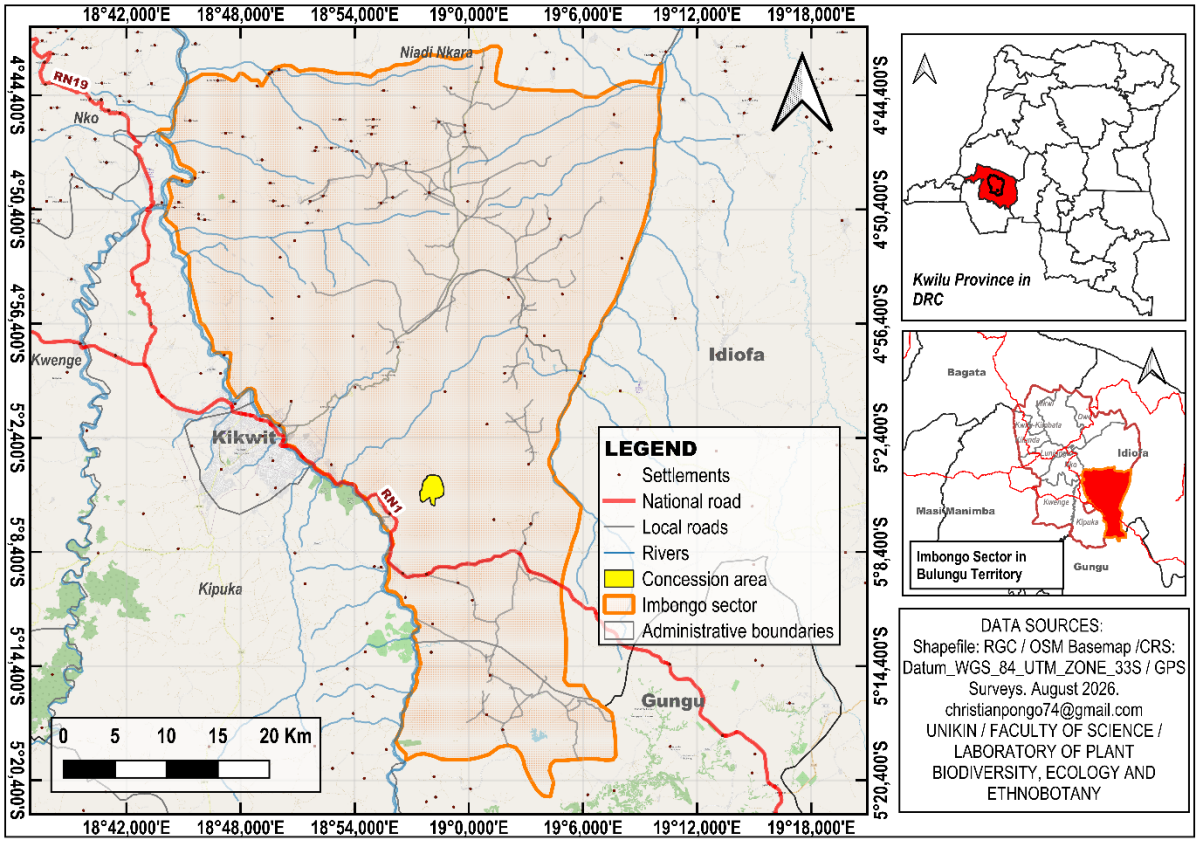


Figure 1. Location of the forest within the Sisters of Mary concession in Mbamba, Kwilu Province, Democratic Republic of the Congo.

Sampling Design and Data Collection

Following a preliminary survey, 18 purposively selected 25 × 25 m plots (625 m²) were established across forest sectors representing physiognomic variability, but avoiding edges, tracks, savannahs and recently disturbed areas. All woody individuals with DBH ≥ 10 cm were inventoried and identified to species level when possible using botanical expertise and taxonomic references.

Trunk circumference was measured at 1.30 m above ground, or immediately above buttresses, swellings or deformities, following tropical forest inventory recommendations [10,11]. Diameter at breast height (DBH) was then calculated from circumference using the following formula (1)

$$DHP = \frac{C}{\pi} \quad (1)$$

where **C** represents the trunk circumference (cm) and $\boldsymbol{\pi}$ **= 3.1416**

Floristic Diversity and Structural Parameters

Species richness was the number of taxa recorded at site and plot levels. Floristic diversity was quantified using Shannon–Wiener, Simpson and Pielou indices [12]. The Shannon–Wiener index (H') was calculated as follows (2) :

$$H' = -\sum_{i=1}^{S} p_i \, ln(p_i) \quad (2)$$

where S represents the total number of species and p_i the proportion of individuals belonging to species i. Simpson's diversity index ($1-D$) was expressed as follows (3):

$$1 - D = 1 - \sum_{i=1}^{S} p_i^2 \quad (3)$$

Pielou's evenness (J') was obtained as follows (4):

$$J' = \frac{H'}{ln(S)} \quad (4)$$

These indices described diversity and evenness. Sampling representativeness was examined with a species accumulation curve based on cumulative richness across plots. Because each plot covered 0.0625 ha, richness was expressed against the cumulative sampled area.

Stand structure was described using density, diameter distribution and basal area [10]. Density (D) was calculated as follows (5):

$$D = N/S \quad (5)$$

where N corresponds to the number of trees recorded and S to the sampled area in hectares. The individual basal area (ST_i) was calculated from DBH as follows (6):

$$ST_i = \frac{\pi \, DHP^2}{4} \quad (6)$$

with DBH expressed in metres. The basal area of the stand (ST) was then obtained by summing the individual basal areas and expressing the result per hectare (7):

$$ST = \frac{\sum \quad ST_i}{S} \quad (7)$$

and expressed in $m^2\ ha^{-1}$. Diameter-class distributions described horizontal stand structure.

The structural role of species was assessed through relative density, relative dominance, relative frequency and the Importance Value Index [13]. Relative density (DR_i) was calculated as follows (8):

$$DR_i = \frac{N_i}{N} \, x \, 100 \quad (8)$$

Relative dominance (DoR_i) was obtained from basal area (9):

$$DoR_i = \frac{ST_i}{ST_{total}} \, x \, 100 \quad (9)$$

Relative frequency (FR_i) was calculated as follows (10):

$$FR_i = \frac{F_i}{\sum \quad F_i} \, x \, 100 \quad (10)$$

The Importance Value Index was then obtained by adding these three components (11):

$$IVI_i = DR_i + DoR_i + FR_i \quad (11)$$

This index made it possible to identify the species playing the most important role in the structure of the stand.

Analysis of Floristic Structure

The floristic structure of the plots was explored using hierarchical cluster analysis (HCA) based on Bray–Curtis dissimilarities calculated from species abundances [14]. A second classification based on the Jaccard index, after transforming abundance data into presence–absence data, was performed to assess the stability of the groupings when only species occurrence was considered.

Variation in floristic composition among plots was examined using NMDS (Non-metric Multidimensional Scaling) based on Bray–Curtis dissimilarities [15,16]. A DCA (Detrended Correspondence Analysis) was used as a complementary approach to characterize the main gradients of floristic variation.

Differences in floristic composition between groups were tested using PERMANOVA, based on Bray–Curtis dissimilarities and 9,999 permutations [17]. Homogeneity of multivariate dispersions was assessed in parallel using PERMDISP, based on the distances of plots from the centroid of their respective group [18].

Species characteristic of the floristic groups were identified using IndVal analysis, which combines species specificity and fidelity to groups **[19].** A SIMPER (Similarity Percentage) analysis, based on Bray–Curtis dissimilarities, was then used to identify the species contributing most to the differentiation between groups.

Estimation of Biomass and Carbon Stock

Individual above-ground biomass was estimated using an allometric equation developed by Fayolle *et al.* [20] for trees in African tropical forests, incorporating diameter and wood density:

$$\mathbf{AGB_p = \exp\left[0.046 + 1.156 \log(\rho) + 1.123 \log(DHP) + 0.436 (\log(DHP))^2 - 0.045 (\log(DHP))^3\right]} \quad (12)$$

where ***AGBp*** represents the above-ground biomass of the tree (kg), ***DBH*** the diameter at breast height (cm), $\boldsymbol{\rho}$ the wood density (g cm^{-3}), ***log*** the natural logarithm, and ***exp*** the exponential function. Wood density (ρ, g cm^{-3}) was assigned to each taxon using the `getWoodDensity()` function of the R package BIOMASS, based on the Global Wood Density Database v.2 [21,22]. Total above-ground biomass was obtained by summing the individual biomass values of all trees recorded in the plots and was then converted into tonnes per hectare (t/ha) [4].

Above-ground carbon stock (*C*) was estimated from above-ground biomass (*AGB*), considering a carbon fraction of 0.47 (13).

$$\mathbf{C = AGB \times 0{,}47} \quad (13)$$

where *C* represents the above-ground carbon stock (Mg C ha^{-1}) and *AGB* the above-ground biomass (Mg ha^{-1}). Total carbon stock was obtained by summing the individual carbon stocks of all trees recorded in the plots. The CO_2 equivalent was then calculated from the ratio of the molecular masses of CO_2 and carbon (14):

$$CO_{2eq} = C \; x \; 3{,}667 \quad (14)$$

The results were expressed in Mg ha^{-1} for above-ground biomass, Mg C ha^{-1} for carbon stock and Mg CO_2 ha^{-1} for CO_2 equivalent.

Statistical Analyses

Analyses were performed in R 4.6.1. Quantitative variables were summarized by mean, standard deviation, median, range and coefficient of variation. Vegan [23] was used for multivariate analyses; indicspecies for IndVal; car for Levene's test; effectsize for Hedges' g; stats for UPGMA; dendextend [24] for dendrograms; and ggplot2/ggrepel for graphics. Floristic groups were compared for richness, density, basal area and AGB.

Results

Floristic Composition and Diversity

A total of 536 woody individuals belonging to 101 taxa and 32 families were recorded in the 1.125 ha sampled area. *Staudtia kamerunensis* was the most abundant species, with 90 individuals (16.79%), followed by *Dichostemma glaucescens* with 73 individuals (13.62%) and *Brachystegia laurentii* with 23 individuals (4.29%). Together, these three species represented 34.70% of the recorded individuals. Seventy taxa were represented by fewer than five individuals and together accounted for 21.08% of the total abundance (Table 1).

Table 1. Relative abundance and density of the main woody species

Species	No. of individuals	Relative abundance (%)	Density (individuals ha^{-1})
Staudtia kamerunensis Warb.	90	16.79	80.00
Dichostemma glaucescens Pierre	73	13.62	64.89
Brachystegia laurentii (De Wild.) Hoyle	23	4.29	20.44
Anisophyllea polyneura Engl.	16	2.99	14.22
Mammea africana Sabine	15	2.80	13.33
Parinari excelsa Sabine	15	2.80	13.33
Pentadesma butyracea Sabine	13	2.43	11.56
Scorodophloeus zenkeri Harms	13	2.43	11.56
Xylopia staudtii Engl. & Diels	13	2.43	11.56
Sacoglottis gabonensis (Baill.) Urb.	12	2.24	10.67
Tessmannia africana Harms	12	2.24	10.67
Lophira alata Banks ex C.F.Gaertn.	9	1.68	8.00
Maranthes chrysophylla (Oliv.) Prance	9	1.68	8.00
Symphonia globulifera L.f.	9	1.68	8.00
Distemonanthus benthamianus Baill.	8	1.49	7.11
Scyphocephalium mannii (Benth.) Warb.	8	1.49	7.11
Strombosia pustulata Oliv.	8	1.49	7.11
Xylopia hypolampra Mildbr.	8	1.49	7.11
Detarium macrocarpum Harms	6	1.12	5.33
Hannoa klaineana Pierre & Engl.	6	1.12	5.33
Prioria balsamifera (Vermoesen) Breteler	6	1.12	5.33

Pterocarpus mildbraedii Harms	6	1.12	5.33
Annonidium mannii (Oliv.) Engl. & Diels	5	0.93	4.44
Anthrocaryon klaineanum Pierre	5	0.93	4.44
Dacryodes klaineana (Pierre) H.J.Lam	5	0.93	4.44
Entandrophragma angolense (Welw.) C.DC.	5	0.93	4.44
Entandrophragma candollei Harms	5	0.93	4.44
Lebruniodendron leptanthum (Harms) J.Léonard	5	0.93	4.44
Nesogordonia papaverifera (A.Chev.) Capuron	5	0.93	4.44
Pentaclethra macrophylla Benth.	5	0.93	4.44
Trichilia welwitschii C.DC.	5	0.93	4.44
Other taxa (70)	**113**	**21.08**	**100.44**
Total	**536**	**100.00**	**476.44**

At the taxonomic level, the 101 taxa were distributed among 32 families. Fabales was the most species-rich order, with 22 species (21.78%), followed by Malpighiales and Sapindales, each with 21 species (20.79%). In terms of abundance, Malpighiales was dominant, with 180 individuals (33.58%), followed by Magnoliales with 133 individuals (24.81%) and Fabales with 106 individuals (19.78%) (Table 2)

Table 2. Taxonomic composition and abundance of recorded orders

Order	No. of families	No. of species	Species (%)	No. of individuals	Density (individuals ha^{-1})	Relative abundance (%)
Malpighiales	11	21	20.79	180	160.00	33.58
Magnoliales	2	11	10.89	133	118.22	24.81
Fabales	1	22	21.78	106	94.22	19.78
Sapindales	5	21	20.79	57	50.67	10.63
Cucurbitales	1	1	0.99	16	14.22	2.99
Santalales	1	3	2.97	11	9.78	2.05
Gentianales	2	7	6.93	10	8.89	1.87
Ericales	3	6	5.94	8	7.11	1.49
Malvales	1	2	1.98	6	5.33	1.12
Rosales	2	3	2.97	5	4.44	0.93
Apiales	1	1	0.99	1	0.89	0.19
Arecales	1	1	0.99	1	0.89	0.19
Lamiales	1	1	0.99	1	0.89	0.19
Ranunculales	1	1	0.99	1	0.89	0.19
Total	**32**	**101**	**100.00**	**536**	**476.44**	**100.00**

Fabaceae was the most species-rich family, with 22 species (21.78%), followed by Meliaceae with 10 species (9.90%), Annonaceae with seven species (6.93%), Apocynaceae with six species (5.94%) and Burseraceae with five species (4.95%) (Table 3; Figure 2). Myristicaceae, although

represented by only four species, accounted for 91 individuals (16.98%). Euphorbiaceae comprised 73 individuals (13.62%).

Table 3. Species richness, abundance and density of the main botanical families

Family	No. of species	Species (%)	No. of individuals	Relative abundance (%)	Density (individuals ha^{-1})
Fabaceae	22	21.78	106	19.78	94.22
Myristicaceae	4	3.96	91	16.98	80.89
Euphorbiaceae	2	1.98	73	13.62	64.89
Calophyllaceae	2	1.98	28	5.22	24.89
Chrysobalanaceae	3	2.97	28	5.22	24.89
Meliaceae	10	9.90	28	5.22	24.89
Annonaceae	7	6.93	27	5.04	24.00
Burseraceae	5	4.95	17	3.17	15.11
Anisophylleaceae	1	0.99	16	2.99	14.22
Humiriaceae	1	0.99	12	2.24	10.67
Irvingiaceae	4	3.96	11	2.05	9.78
Olacaceae	3	2.97	11	2.05	9.78
Ochnaceae	1	0.99	9	1.68	8.00
Clusiaceae	1	0.99	9	1.68	8.00
Apocynaceae	6	5.94	8	1.49	7.11
Other families (17)	**29**	**28.71**	**72**	**13.43**	**64.00**
Overall total	**101**	**100.00**	**536**	**100.00**	**476.44**

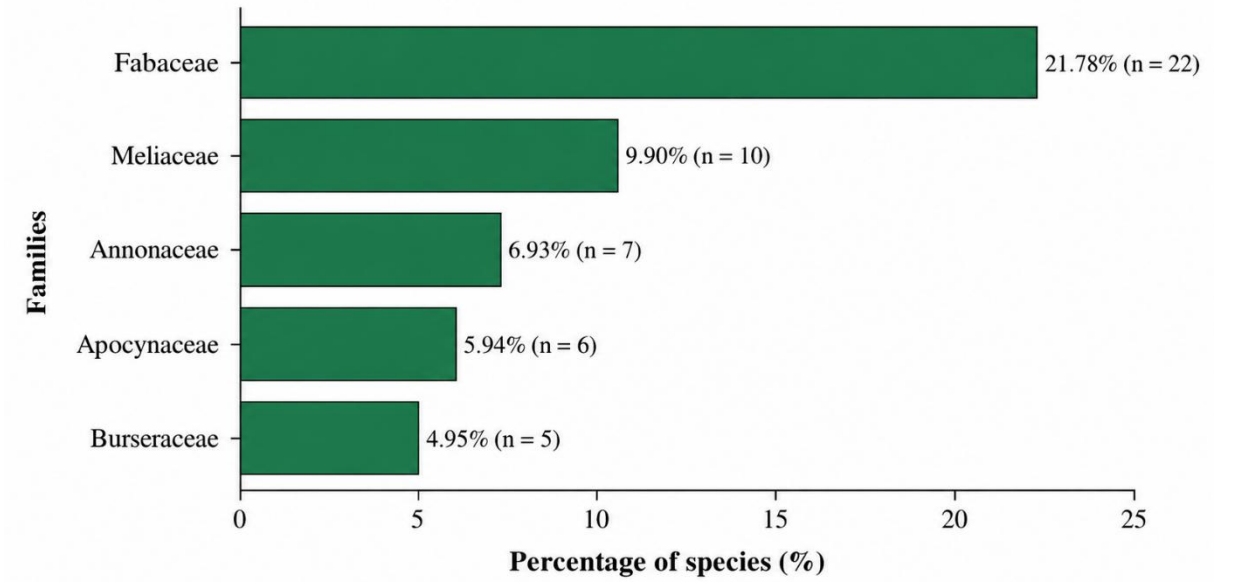


Figure 2. Distribution of the five most species-rich families.

The species accumulation curve increased progressively with sampled area, with a gradual slowing towards the end of sampling (Figure 3). Mean cumulative richness reached 95.77 species at 1.00 ha, 98.45 species at 1.0625 ha and 101 species at the total sampled area of 1.125 ha (Table 4).

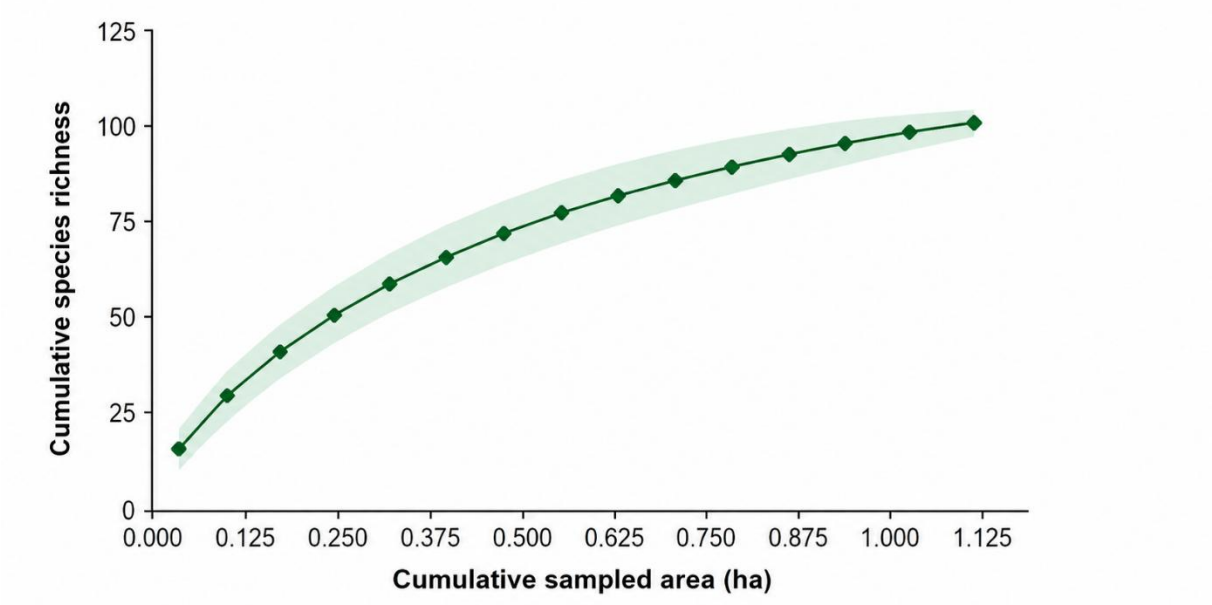


Figure 3. Species accumulation curve as a function of cumulative sampled area.

Table 4. Mean cumulative species richness and associated variability according to sampled area

No. of plots	Sampled area (ha)	Mean species richness	Standard deviation	Lower limit	Upper limit
1	0.0625	15.37	4.02	11.35	19.39
2	0.1250	26.68	4.87	21.81	31.55
3	0.1875	35.95	5.41	30.54	41.36
4	0.2500	43.96	5.52	38.45	49.48
5	0.3125	50.93	5.48	45.45	56.41
6	0.3750	57.06	5.37	51.70	62.43
7	0.4375	62.53	5.23	57.30	67.76
8	0.5000	67.41	5.06	62.35	72.47
9	0.5625	71.87	4.83	67.03	76.70
10	0.6250	76.03	4.57	71.46	80.60
11	0.6875	79.83	4.32	75.50	84.15
12	0.7500	83.42	4.16	79.27	87.58
13	0.8125	86.78	3.80	82.99	90.58
14	0.8750	90.01	3.57	86.44	93.58
15	0.9375	93.01	3.20	89.81	96.22

16	1.0000	95.77	2.73	93.03	98.50
17	1.0625	98.45	1.98	96.47	100.43
18	1.1250	101.00	0.00	101.00	101.00

The ecological spectra showed a predominance of mesophyllous species, which represented 83.96% of individuals. Sarcochores were the dominant dispersal type (51.49%), followed by ballochores (32.46%) and barochores (11.01%). Guineo-Congolian and Lower Guineo-Congolian elements together represented most of the recorded individuals (Figure 4).

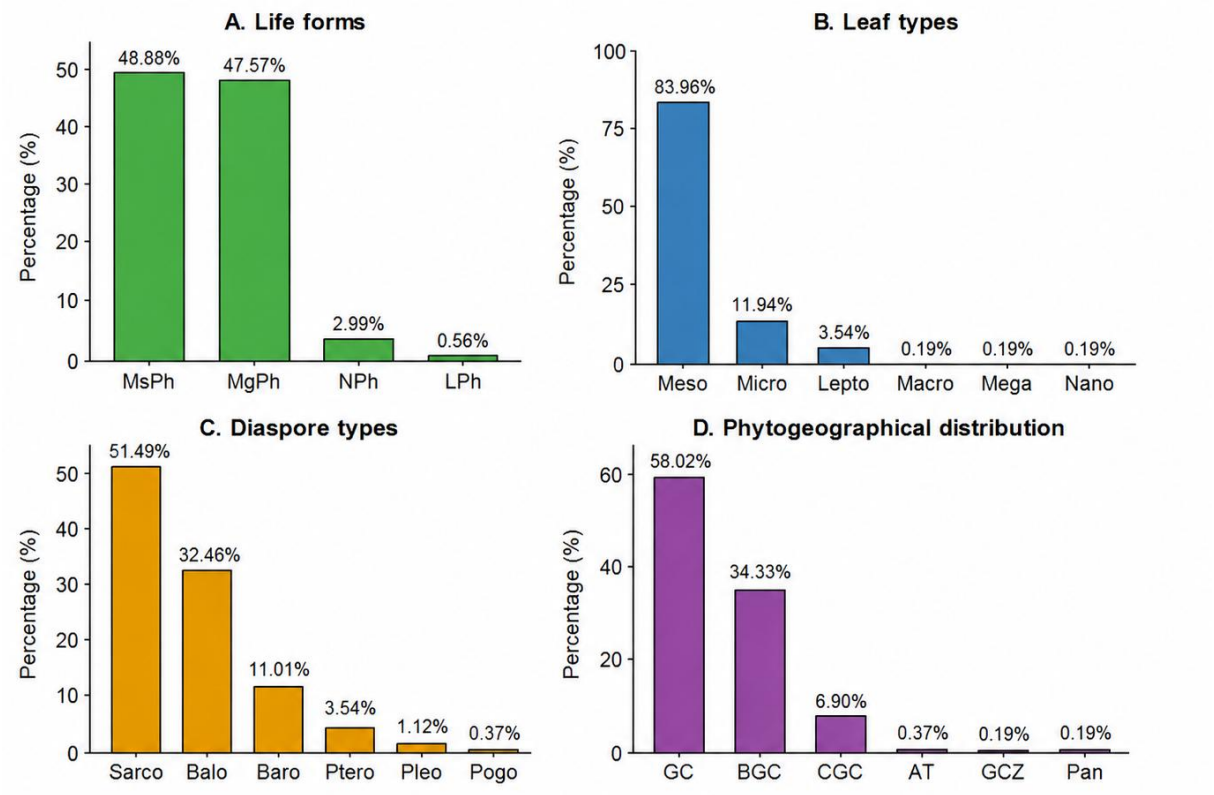


Figure 4. Ecological and phytogeographical spectra of the woody flora studied.

Overall floristic diversity was high, with a Shannon index (H') of 3.701, Simpson index ($1-D$) of 0.942 and Pielou evenness (J') of 0.802 (Table 5). Diversity varied among plots. Species richness ranged from six species in P8 to 23 species in P10. Shannon diversity ranged from 1.090 in P8 to 2.822 in P10. Pielou evenness ranged from 0.608 in P8 to 0.951 in P16 (Table 6).

Table 5. Overall floristic diversity indices

Level	Area (ha)	Abundance (N)	Richness (S)	Shannon (H′)	Simpson (1−D)	Pielou (J′)
Overall	1.125	536	101	3.701	0.942	0.802

Table 6. Floristic diversity indices calculated for the different 625 m² (0.0625 ha) plots

Plot	Abundance (N)	Richness (S)	Shannon (H′)	Simpson (1−D)	Pielou (J′)
P1	28	13	2.296	0.875	0.895
P2	26	17	2.578	0.896	0.910
P3	32	15	2.471	0.895	0.913
P4	31	19	2.729	0.916	0.927
P5	30	18	2.656	0.909	0.919
P6	27	10	1.886	0.796	0.819
P7	27	12	2.073	0.823	0.834
P8	28	6	1.090	0.536	0.608
P9	23	13	2.279	0.858	0.889
P10	40	23	2.822	0.913	0.900
P11	22	12	2.220	0.851	0.893
P12	28	16	2.481	0.885	0.895
P13	30	14	2.375	0.882	0.900
P14	37	20	2.711	0.904	0.905
P15	28	18	2.698	0.916	0.934
P16	30	18	2.748	0.927	0.951
P17	31	14	2.380	0.885	0.902
P18	38	19	2.728	0.920	0.926

Forest Structure and Ecological Importance of Species

Tree density varied among the 18 inventory plots (Figure 5a). Mean density was 476.4 stems ha^{-1}, with values ranging from 352 stems ha^{-1} in P11 to 640 stems ha^{-1} in P10 (Table 7). The mean number of individuals per plot was 29.8 ± 4.7, with the highest numbers recorded in P10 (40 individuals), P18 (38 individuals) and P14 (37 individuals) (Figure 5b).

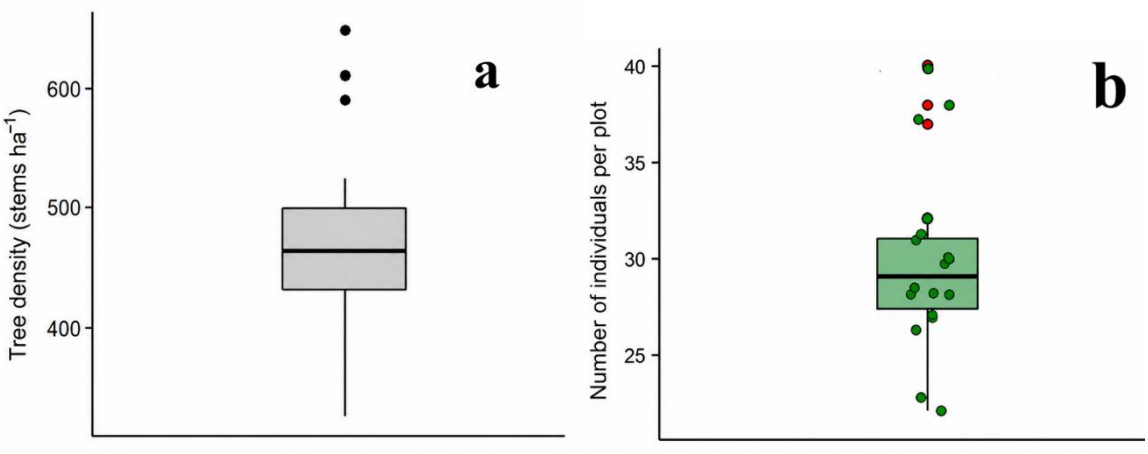


Figure 5. Distribution of (a) tree density (stems ha^{-1}) and (b) number of individuals per plot across the 18 inventory plots.

The diameter distribution was characterized by a predominance of individuals in the smaller diameter classes (Figure 6). The [10–20 cm[and [20–30 cm[classes represented 45.8% and 29.3% of individuals, respectively. Together, these two classes accounted for 75.1% of the recorded stems. From the [30–40 cm[class onwards, relative frequency decreased markedly, reaching 9.2%, then 6.5% in the [50–60 cm[class.

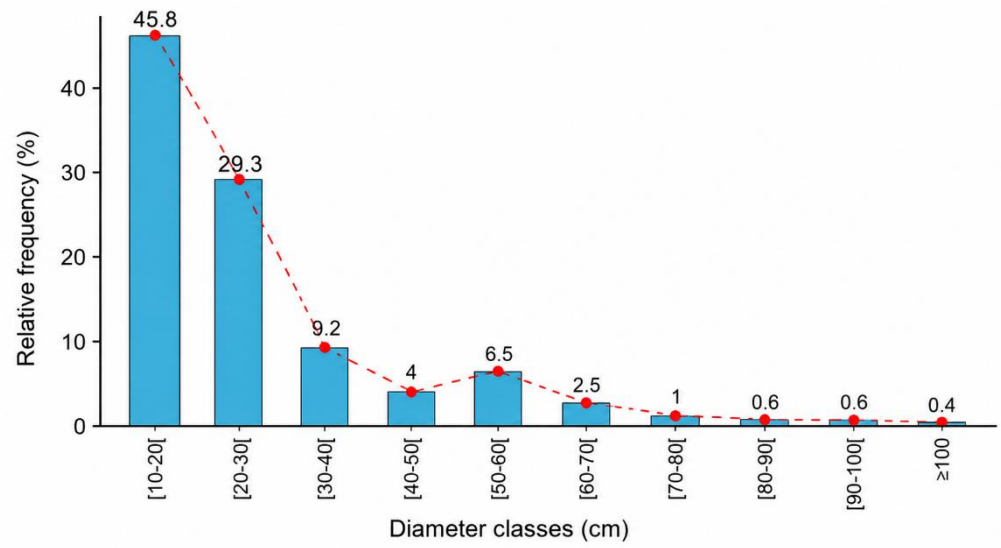


Figure 6. Distribution of individuals according to diameter classes.

Basal area also varied among plots, with a mean value of 36.37 m² ha^{-1}. The highest basal area was recorded in P8 (83.50 m² ha^{-1}), followed by P1 (56.83 m² ha^{-1}) and P2 (56.41 m² ha^{-1}), whereas the lowest value was recorded in P6 (19.63 m² ha^{-1}).

Table 7. Number of individuals, density and basal area of the inventoried stands

Plot	Number of individuals	Density (individuals ha^{-1})	Basal area (m^2)	Basal area (m^2 ha^{-1})
P1	28	448	3.55	56.83
P2	26	416	3.53	56.41
P3	32	512	1.28	20.54
P4	31	496	2.80	44.76
P5	30	480	1.96	31.30
P6	27	432	1.23	19.63
P7	27	432	1.42	22.64
P8	28	448	5.22	83.50
P9	23	368	1.81	28.96
P10	40	640	1.29	20.68
P11	22	352	1.94	31.12
P12	28	448	2.17	34.76
P13	30	480	1.83	29.29
P14	37	592	2.67	42.68
P15	28	448	1.85	29.62
P16	30	480	1.31	21.04
P17	31	496	2.05	32.84
P18	38	608	3.00	48.06
Mean ± SD	**29.8 ± 4.7**	**476.4 ± 75.8**	**2.27 ± 1.02**	**36.37 ± 16.39**

The Importance Value Index (IVI) showed differences in the structural importance of species. *Staudtia kamerunensis* had the highest IVI (32.81), with a relative density of 16.79%, relative dominance of 9.52% and relative frequency of 6.50%. *Brachystegia laurentii* ranked second (IVI = 24.46), with the highest relative dominance (18.37%), followed by *Dichostemma glaucescens* (IVI = 23.21). The remaining species had lower IVI values (Table 8).

Table 8. Structural parameters and Importance Value Index (IVI) of the main species

Species	Density (individuals ha^{-1})	BA (m^2 ha^{-1})	RD (%)	RDo (%)	RF (%)	IVI
Staudtia kamerunensis Warb.	80.00	3.46	16.79	9.52	6.50	32.81
Brachystegia laurentii (De Wild.) Hoyle	20.44	6.68	4.29	18.37	1.81	24.46
Dichostemma glaucescens Pierre	64.89	1.65	13.62	4.54	5.05	23.21
Mammea africana Sabine	13.33	1.11	2.80	3.06	3.25	9.10
Parinari excelsa Sabine	13.33	0.84	2.80	2.30	3.97	9.07
Xylopia staudtii Engl. & Diels	11.56	1.03	2.43	2.83	2.89	8.15
Tessmannia africana Harms	10.67	0.80	2.24	2.21	2.53	6.97
Scorodophloeus zenkeri Harms	11.56	0.97	2.43	2.66	1.81	6.89
Prioria balsamifera (Vermoesen) Breteler	5.33	1.48	1.12	4.06	1.44	6.63
Distemonanthus benthamianus Baill.	7.11	0.97	1.49	2.68	2.17	6.34
Pentadesma butyracea Sabine	11.56	0.62	2.43	1.70	2.17	6.29

Anisophyllea polyneura Engl.	14.22	0.50	2.99	1.37	1.81	6.16
Pterocarpus mildbraedii Harms	5.33	1.42	1.12	3.90	1.08	6.10
Symphonia globulifera L.f.	8.00	0.84	1.68	2.30	1.81	5.78
Sacoglottis gabonensis (Baill.) Urb.	10.67	0.43	2.24	1.19	2.17	5.59
Lophira alata Banks ex C.F.Gaertn.	8.00	0.62	1.68	1.71	1.81	5.19
Detarium macrocarpum Harms	5.33	0.95	1.12	2.61	1.08	4.81
Piptadeniastrum africanum (Hook.f.) Brenan	3.56	0.94	0.75	2.58	1.44	4.77
Hannoa klaineana Pierre & Engl.	5.33	0.51	1.12	1.39	2.17	4.68
Maranthes chrysophylla (Oliv.) Prance	8.00	0.28	1.68	0.77	2.17	4.62
Scyphocephalium mannii (Benth.) Warb.	7.11	0.53	1.49	1.46	1.44	4.40
Xylopia hypolampra Mildbr.	7.11	0.40	1.49	1.10	1.44	4.04
Anthrocaryon klaineanum Pierre	4.44	0.48	0.93	1.33	1.44	3.71
Klainedoxa gabonensis Pierre ex Engl.	3.56	0.53	0.75	1.47	1.44	3.66
Strombosia pustulata Oliv.	7.11	0.31	1.49	0.86	1.08	3.44
Lebruniodendron leptanthum (Harms) J.Léonard	4.44	0.49	0.93	1.34	1.08	3.35
Entandrophragma candollei Harms	4.44	0.29	0.93	0.80	1.44	3.17
E. cylindricum (Sprague) Sprague	2.67	0.54	0.56	1.49	1.08	3.13
Pentaclethra macrophylla Benth.	4.44	0.38	0.93	1.04	1.08	3.05
Annonidium mannii (Oliv.) Engl. & Diels	4.44	0.09	0.93	0.24	1.81	2.98
Other species (71 species)	108.44	6.23	22.76	17.13	37.54	77.44
Total	**476.44**	**36.37**	**100.00**	**100.00**	**100.00**	**300.00**

Floristic Differentiation and Characteristic Species

Hierarchical cluster analysis based on Bray–Curtis dissimilarities distinguished two floristic groups (Figure 7a). Group 1 comprised 11 plots, whereas Group 2 comprised seven plots. The classification based on Jaccard dissimilarity, using presence–absence data, was also examined to assess the grouping of plots when only species occurrence was considered (Figure 7b).

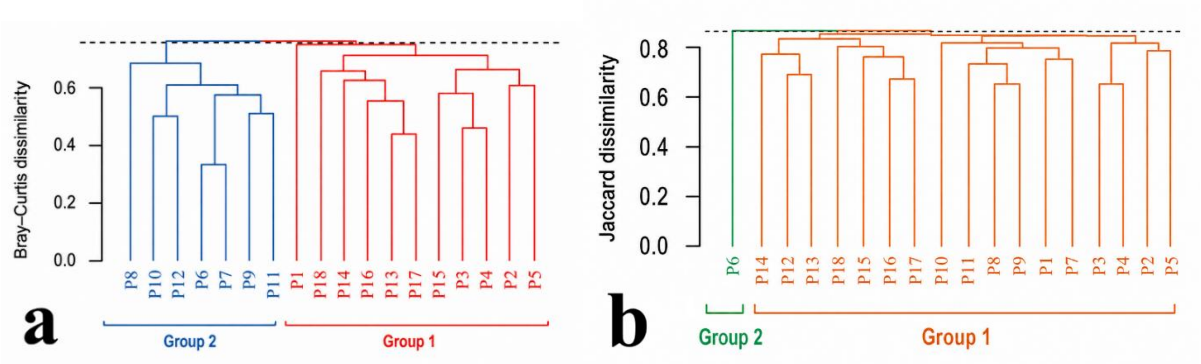


Figure 7. Hierarchical cluster analysis of the plots based on (a) Bray–Curtis dissimilarity using the unweighted pair group method with arithmetic mean (UPGMA), and (b) Jaccard dissimilarity calculated from presence–absence data.

NMDS ordination showed the distribution of the plots according to the two floristic groups derived from the Bray–Curtis hierarchical classification (Figure 8a). The Shepard diagram showed the relationship between observed Bray–Curtis dissimilarities and the distances represented by the NMDS ordination (Figure 8b). DCA provided a complementary representation of the floristic differentiation between plots and groups (Figure 8c).

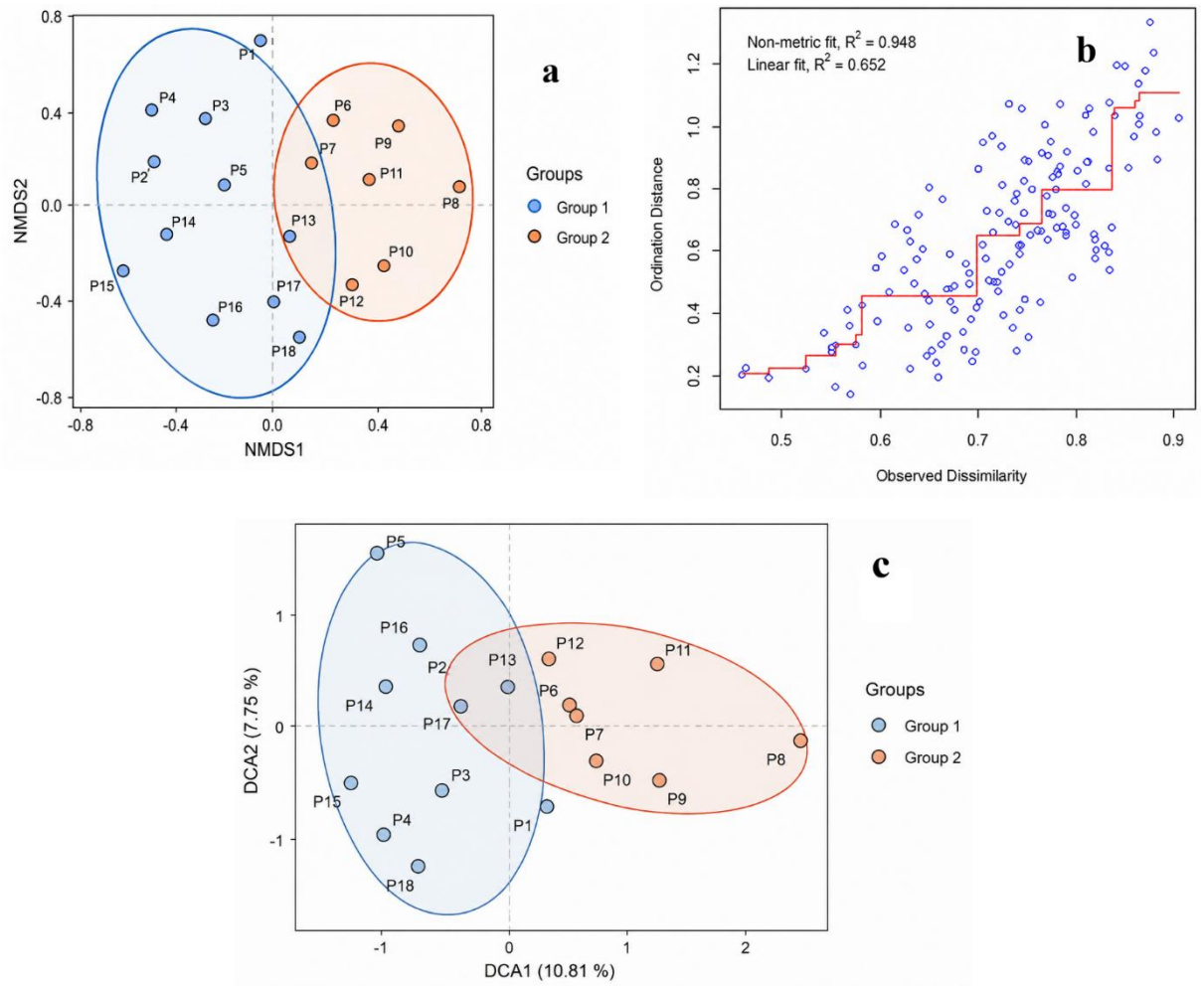


Figure 8. Floristic ordination of the plots: (a) NMDS ordination showing the floristic groups derived from the Bray–Curtis hierarchical classification; (b) Shepard diagram showing the relationship between observed Bray–Curtis dissimilarities and distances represented by the NMDS ordination; and (c) DCA ordination showing the floristic groups derived from the Bray–Curtis hierarchical classification.

PERMANOVA indicated a significant difference in floristic composition between the two groups (pseudo-$F_{1,16}$ = 4.216; R^2 = 0.209; p < 0.001). The PERMDISP test also indicated a significant difference in dispersion between the two groups ($F_{1,16}$ = 8.501; p = 0.010; 9,999 permutations), with mean distances to the centroid of 0.4607 for Group 1 and 0.3939 for Group 2 (Table 9; Figure 9).

Table 9. Effect of group on floristic composition and multivariate dispersion based on Bray–Curtis dissimilarities.

Analysis	Source of variation	df	Sum of squares	R^2	F	p	Distance to centroid
PERMANOVA	Group	1	0.9107	0.2085	4.2157	< **0.001**	–
	Residuals	16	3.4565	0.7915	–	–	–
PERMDISP	Group	1	0.0191	–	8.5014	**0.010**	–
	Residuals	16	0.0359	–	–	–	–
Dispersion	Group 1	–	–	–	–	–	0.4607
	Group 2	–	–	–	–	–	0.3939

Note. n = 18 plots. Differences in floristic composition were assessed using PERMANOVA, and the homogeneity of multivariate dispersions was assessed using PERMDISP. A p-value < 0.05 was considered statistically significant

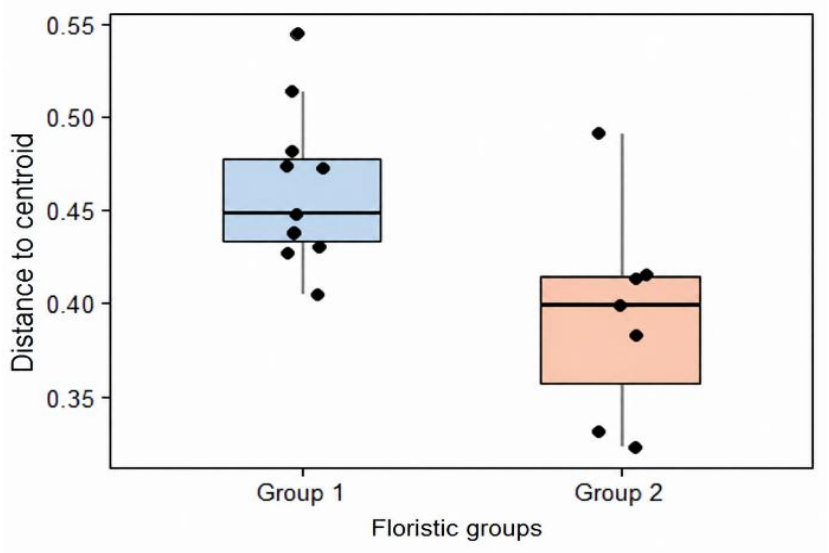


Figure 9. Distribution of distances to the centroid for the two floristic groups defined by the Bray–Curtis classification.

Indicator species analysis identified three species significantly associated with the floristic groups. *Dichostemma glaucescens* was associated with Group 2 (IndVal = 80.64%; $p = 0.0013$), whereas *Staudtia kamerunensis* was associated with Group 1 (IndVal = 66.30%; $p = 0.0087$). *Brachystegia laurentii* was also associated with Group 2 (IndVal = 55.54%; $p = 0.0284$). No other species showed a statistically significant association with either group at the 5% significance level (Table 10).

Table 10. Significant indicator species of the floristic groups identified by the Bray–Curtis classification.

Species	Indicator group	Abundance G1	Abundance G2	Frequency G1 (%)	Frequency G2 (%)	IndVal (%)	*p*
Dichostemma glaucescens	Group 2	20	53	63.64	100.00	80.64	0.0013
Staudtia kamerunensis	Group 1	68	22	100.00	100.00	66.30	0.0087
Brachystegia laurentii	Group 2	1	22	9.09	57.14	55.54	0.0284

Note. Only species with $p < 0.05$ are reported.

The first three species identified by SIMPER also corresponded to the three significant indicator species identified by the IndVal analysis, although the two methods do not measure the same aspect of floristic structure. *Dichostemma glaucescens* contributed 13.05% to the dissimilarity between groups, followed by *Staudtia kamerunensis* (8.20%) and *Brachystegia laurentii* (7.08%). Together, these three species accounted for 28.32% of the floristic dissimilarity between Groups 1 and 2 (Table 11).

Table 11. Contribution of the main species to floristic dissimilarity between Groups 1 and 2 according to the SIMPER analysis.

Species	Mean G1	Mean G2	Mean contribution	SD	Ratio	Contribution (%)	Cumulative (%)	*p*
Dichostemma glaucescens	1.82	7.57	0.0988	0.035	2.827	13.05	13.05	0.0001
Staudtia kamerunensis	6.18	3.14	0.0621	0.037	1.663	8.20	21.24	0.0064
Brachystegia laurentii	0.09	3.14	0.0536	0.104	0.515	7.08	28.32	0.0280
Anisophyllea polyneura	0.73	1.14	0.0238	0.028	0.842	3.15	31.47	0.3258
Scorodophloeus zenkeri	1.18	0.00	0.0204	0.028	0.727	2.69	34.16	0.3318
Mammea africana	1.18	0.29	0.0189	0.018	1.070	2.50	36.66	0.2719
Xylopia staudtii	0.64	0.86	0.0179	0.018	0.987	2.36	39.02	0.4774
Pentadesma butyracea	0.91	0.43	0.0176	0.019	0.918	2.32	41.34	0.7973
Sacoglottis gabonensis	0.55	0.86	0.0172	0.018	0.936	2.27	43.61	0.3157
Tessmannia africana	0.55	0.86	0.0171	0.017	0.992	2.26	45.86	0.2773
Parinari excelsa	0.73	1.00	0.0156	0.012	1.254	2.06	47.92	0.3539
Symphonia globulifera	0.82	0.00	0.0144	0.021	0.682	1.91	49.83	0.4151
Maranthes chrysophylla	0.45	0.57	0.0140	0.018	0.799	1.85	51.68	0.3432
Lophira alata	0.82	0.00	0.0137	0.019	0.736	1.81	53.49	0.2977

Strombosia pustulata	0.55	0.29	0.0134	0.026	0.515	1.77	55.26	0.4914
Xylopia hypolampra	0.55	0.29	0.0129	0.020	0.637	1.70	56.96	0.5258
Scyphocephalium mannii	0.36	0.57	0.0128	0.019	0.666	1.69	58.65	0.3297
Distemonanthus benthamianus	0.55	0.29	0.0109	0.012	0.883	1.44	60.09	0.8403
Pterocarpus mildbraedii	0.45	0.14	0.0098	0.021	0.462	1.29	61.38	0.5276
Anthrocaryon klaineanum	0.18	0.43	0.0093	0.013	0.714	1.23	62.61	0.2304
Prioria balsamifera	0.55	0.00	0.0092	0.013	0.697	1.21	63.82	0.4569
Detarium macrocarpum	0.55	0.00	0.0089	0.016	0.561	1.18	65.00	0.6683
Dacryodes klaineana	0.36	0.14	0.0081	0.019	0.424	1.07	66.07	0.4127
Hannoa klaineana	0.45	0.14	0.0078	0.009	0.923	1.03	67.10	0.2553
Annonidium mannii	0.45	0.00	0.0078	0.009	0.898	1.03	68.14	0.0577
Lebruniodendron leptanthum	0.45	0.00	0.0078	0.014	0.580	1.03	69.17	0.6306
Nesogordonia papaverifera	0.45	0.00	0.0077	0.011	0.681	1.02	70.18	0.4313

Aboveground Biomass and Carbon Stocks

Mean above-ground biomass was 423.24 ± 77.50 Mg ha^{-1}, with values ranging from 313.44 to 564.96 Mg ha^{-1} and a coefficient of variation of 18.31%. Mean carbon stock was 198.92 ± 36.43 Mg C ha^{-1}, ranging from 147.32 to 265.53 Mg C ha^{-1}. The corresponding mean CO_2 equivalent was 729.38 ± 133.57 Mg CO_2 ha^{-1}, with values ranging from 540.17 to 973.62 Mg CO_2 ha^{-1} (Table 12).

Table 12. Descriptive statistics of above-ground biomass, carbon stock and CO_2 equivalent of the inventoried woody stands

Variable	Mean ± SD	Median	Min	Max	CV (%)
Above-ground biomass (Mg ha^{-1})	423.24 ± 77.50	413.04	313.44	564.96	18.31
Carbon stock (Mg C ha^{-1})	198.92 ± 36.43	194.13	147.32	265.53	18.31
CO_2 equivalent (Mg CO_2 ha^{-1})	729.38 ± 133.57	711.81	540.17	973.62	18.31

Above-ground biomass, carbon stock and CO_2 equivalent differed in their mean values between the two floristic groups. Group 1 had a mean above-ground biomass of 451.08 ± 66.71 Mg ha^{-1}, corresponding to 212.01 ± 31.35 Mg C ha^{-1} and 777.37 ± 114.96 Mg CO_2 ha^{-1}. Group 2 had lower mean values, with 379.50 ± 77.12 Mg ha^{-1} of above-ground biomass, 178.36 ± 36.25 Mg C ha^{-1} of carbon and 653.99 ± 132.91 Mg CO_2 ha^{-1} (Table 13).

Table 13. Above-ground biomass, carbon stock and CO_2 equivalent by vegetation group

Vegetation group	*n*	Above-ground biomass (Mg ha^{-1})	Carbon stock (Mg C ha^{-1})	CO_2 equivalent (Mg CO_2 ha^{-1})
Entire study site	18	423.24 ± 77.50	198.92 ± 36.43	729.38 ± 133.57
Group 1	11	451.08 ± 66.71	212.01 ± 31.35	777.37 ± 114.96
Group 2	7	379.50 ± 77.12	178.36 ± 36.25	653.99 ± 132.91

The contribution to above-ground biomass varied among species. *Staudtia kamerunensis* had the highest contribution, with 66.12 Mg ha^{-1}, representing 15.62% of total AGB, followed by *Dichostemma glaucescens* with 38.95 Mg ha^{-1} (9.20%) and *Brachystegia laurentii* with 33.22 Mg ha^{-1} (7.85%). Together, these three species accounted for 32.67% of total above-ground biomass. The 30 main woody species accounted for 80.22% of total AGB, whereas the remaining 71 species contributed 19.78%. The total values for the inventoried stands were 423.24 Mg ha^{-1} for AGB, 198.92 Mg C ha^{-1} for carbon stock and 729.38 Mg CO_2 ha^{-1} for CO_2 equivalent (Table 14).

Table 14. Contribution of the 30 main woody species to above-ground biomass, carbon stock and CO_2 equivalent.

Species	AGB (Mg ha^{-1})	Contribution (%)	C (Mg C ha^{-1})	CO_2 eq. (Mg CO_2 ha^{-1})
Staudtia kamerunensis Warb.	66.12	15.62	31.08	113.95
Dichostemma glaucescens Pierre	38.95	9.20	18.31	67.12
Brachystegia laurentii (De Wild.) Hoyle	33.22	7.85	15.61	57.25
Mammea africana Sabine	12.97	3.06	6.10	22.35
Scorodophloeus zenkeri Harms	11.95	2.82	5.62	20.59
Parinari excelsa Sabine	11.79	2.79	5.54	20.32
Tessmannia africana Harms	10.94	2.59	5.14	18.85
Symphonia globulifera L.f.	10.46	2.47	4.92	18.03
Anisophyllea polyneura Engl.	9.96	2.35	4.68	17.16
Pterocarpus mildbraedii Harms	9.16	2.16	4.31	15.79
Xylopia staudtii Engl. & Diels	8.94	2.11	4.20	15.41
Pentadesma butyracea Sabine	8.86	2.09	4.16	15.27
Sacoglottis gabonensis (Baill.) Urb.	8.72	2.06	4.10	15.03
Lophira alata Banks ex C.F.Gaertn.	8.68	2.05	4.08	14.96
Distemonanthus benthamianus Baill.	8.19	1.94	3.85	14.11

Prioria balsamifera (Vermoesen) Breteler	7.98	1.89	3.75	13.75
Detarium macrocarpum Harms	7.24	1.71	3.40	12.48
Strombosia pustulata Oliv.	6.31	1.49	2.97	10.87
Piptadeniastrum africanum (Hook.f.) Brenan	6.02	1.42	2.83	10.37
Maranthes chrysophylla (Oliv.) Prance	5.90	1.39	2.77	10.17
Scyphocephalium mannii (Benth.) Warb.	5.88	1.39	2.76	10.13
Xylopia hypolampra Mildbr.	5.43	1.28	2.55	9.36
Klainedoxa gabonensis Pierre ex Engl.	5.16	1.22	2.43	8.89
Lebruniodendron leptanthum (Harms) J.Léonard	5.04	1.19	2.37	8.69
Hannoa klaineana Pierre & Engl.	4.84	1.14	2.27	8.34
Anthrocaryon klaineanum Pierre	4.81	1.14	2.26	8.29
Pentaclethra macrophylla Benth.	4.66	1.10	2.19	8.03
Entandrophragma candollei Harms	3.95	0.93	1.86	6.81
Entandrophragma cylindricum (Sprague) Sprague	3.85	0.91	1.81	6.63
Guarea thompsonii Sprague & Hutch.	3.56	0.84	1.67	6.14
Other species (71 species)	**83.70**	**19.78**	**39.34**	**144.24**
Total	**423.24**	**100.00**	**198.92**	**729.38**

Comparison of the two floristic groups showed higher mean values in Group 1 for species richness, density, basal area and AGB (Figure 10). Mean species richness was 16.82 ± 2.40 species plot^{-1} in Group 1 and 13.14 ± 5.30 in Group 2. Density was 496.00 ± 58.13 and 445.71 ± 93.95 individuals ha^{-1}, respectively.

Table 15. Comparison of species richness, forest structure and above-ground biomass between floristic groups

Variable	Group 1 (n = 11), mean ± SD	Group 2 (n = 7), mean ± SD	Welch (*t*, df)	Welch *p*	Wilcoxon (*W*)	Wilcoxon *p*	Hedges' *g*
Species richness (species plot^{-1})	16.82 ± 2.40	13.14 ± 5.30	1.724 (7.59)	0.125	61.5	**0.041**	—
Density (individuals ha^{-1})	496.00 ± 58.13	445.71 ± 93.95	1.270 (8.96)	0.236	60.0	0.055	0.65
Basal area (m² ha^{-1})	37.57 ± 12.95	34.47 ± 22.35	0.333 (8.60)	0.747	51.0	0.277	0.17
AGB (Mg ha^{-1})	451.08 ± 66.71	379.50 ± 77.12	2.022 (11.51)	0.067	60.5	**0.047**	0.96

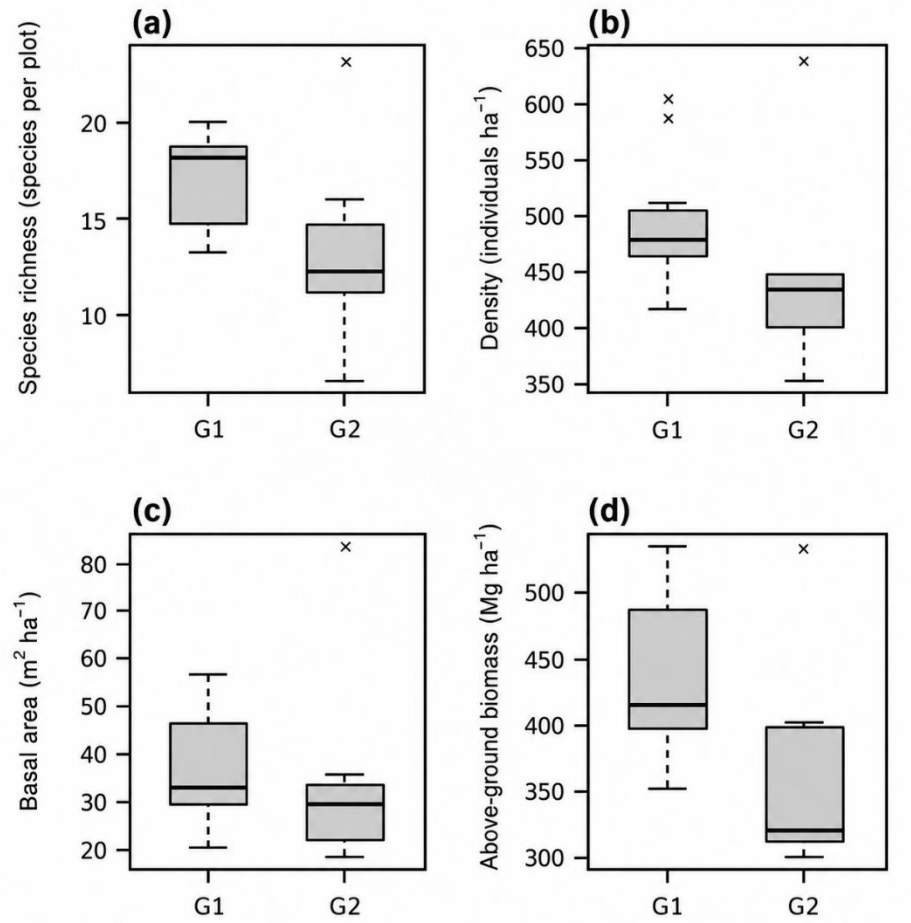


Figure 10. Distribution of above-ground biomass (AGB), basal area, density and species richness between the two floristic groups. The boxplots represent the median, interquartile range and values extending up to 1.5 times the interquartile range.

Welch's test showed no significant differences between groups for species richness (p = 0.125), density (p = 0.236), basal area (p = 0.747) or AGB (p = 0.067) (Table 15).

Discussion

The 536 individuals represented 101 taxa but were unevenly distributed: *Staudtia kamerunensis*, *Dichostemma glaucescens* and *Brachystegia laurentii* comprised 34.70% of stems, whereas 70 taxa with fewer than five individuals comprised 21.08%. Such coexistence of high richness and dominance is typical of tropical forests [6]. *Staudtia kamerunensis* accounted for 16.79% of stems and had the highest IVI (32.81), making it a major structural species. *Brachystegia laurentii* represented only 4.29% of stems but 18.37% of relative dominance and had the second-highest IVI (24.47), illustrating the structural influence of large individuals [25].

Overall Shannon (3.701), Simpson (0.942) and Pielou (0.802) indices indicate high diversity despite species dominance; interpretation should also consider richness and sampling completeness

[24]. Plot richness ranged from 6 to 23 species and Shannon diversity from 1.090 to 2.822, showing marked spatial heterogeneity. The accumulation curve slowed progressively, reaching a mean of 95.77 species at 1 ha versus 101 observed. This suggests good coverage but not exhaustiveness; formal assessment would require coverage and richness extrapolation [26].

Mesophylls predominated (83.96%), consistent with relatively humid conditions, although leaf size also reflects canopy position and species traits. Sarcochores comprised 51.49% of individuals, followed by ballochores (32.46%) and barochores (11.01%), suggesting an important role for animal-mediated dispersal that requires direct confirmation. Guineo-Congolian and Lower Guineo-Congolian elements comprised 92.35% of individuals, confirming the forest-domain affinity reported by Masens *et al.* [4].

Mean density was 476.4 stems ha^{-1}, close to 426 ± 11 stems ha^{-1} reported for African tropical forests by Lewis *et al.* [5]. Mean basal area was 36.37 m^2 ha^{-1} (19.63–83.50), showing that density alone does not explain structure. Contrasts between P10 and P8 highlight the importance of large trees, which can contribute disproportionately to biomass [6].

Bray–Curtis classification distinguished two floristic groups, and PERMANOVA confirmed differentiation (pseudo-$F_{1,16}$ = 4.216, R^2 = 0.209, $p < .001$). PERMDISP also differed between groups ($F_{1,16}$ = 8.501, p = .010), with greater dispersion in Group 1; PERMANOVA must therefore be interpreted in light of dispersion heterogeneity [18]. Environmental conditions or disturbance history may contribute to this heterogeneity, but these hypotheses require environmental data. *Dichostemma glaucescens* was associated with Group 2 (IndVal 80.64%, p = .0013; SIMPER 13.05%), as was *B. laurentii* (55.54%, p = .0284; 7.08%). These three species explained 28.32% of dissimilarity, but 27 species were needed to reach about 70%, indicating a broader multispecies contribution.

Mean AGB was 423.24 ± 77.50 Mg ha^{-1}, near the upper range for African tropical forests and close to 395.7 Mg ha^{-1} reported by Lewis *et al.* [5], consistent with high basal area and large trees. Mean carbon stock was 198.92 ± 36.43 Mg C ha^{-1} versus 162 ± 20 Mg C ha^{-1} reported for old-growth Yangambi forest [27]. AGB ranged from 313.44 to 564.96 Mg ha^{-1} (CV 18.31%), partly reflecting the distribution of large trees [6].

Group 1 had higher means for richness, density, basal area and AGB, but Welch's tests detected no significant differences; compositional differentiation was therefore clearer than structural differentiation. Density and basal area did not differ significantly (p = 0.236 and 0.747). The AGB

contrast may partly reflect composition because the three main differentiating species account for 32.67% of total AGB, but biomass also depends on size, abundance and wood density.

IVI ranked *Staudtia kamerunensis* (32.81), *Brachystegia laurentii* (24.46) and *Dichostemma glaucescens* (23.21) highest. The 30 leading species accounted for 80.22% of AGB, and *Staudtia kamerunensis, Dichostemma glaucescens* and *Brachystegia laurentii* for 32.67%, consistent with disproportionate biomass concentration in tropical forests [6,25]. *Staudtia kamerunensis* contributed 15.62% of AGB and had the highest abundance and IVI; *B. laurentii* contributed 7.85% of AGB despite only 4.29% of stems. Biomass contribution therefore depends on size and structure as well as abundance [6,25].

Conservation should jointly protect floristic diversity, large trees and dominant biomass-contributing species; the three leading species alone account for 32.67% of AGB [6]. The two floristic groups also demonstrate internal heterogeneity, which should be incorporated into management rather than treating the forest as uniform.

Conclusion

The Mbamba forest is floristically diverse and internally heterogeneous: 536 woody individuals in 1.125 ha represented 101 taxa, with a few dominant species and many poorly represented taxa. Two floristic assemblages were distinguished, notably associated with *Staudtia kamerunensis*, *Dichostemma glaucescens* and *Brachystegia laurentii*. Compositional differences were clearer than structural differences. Richness and AGB comparisons were method-sensitive. These values represent standing carbon, not sequestration rates, and exclude some estimation uncertainty. Repeated inventories with environmental and disturbance data are needed to assess carbon dynamics and explain heterogeneity.

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Ethical considerations

The study used floristic inventories and non-destructive dendrometric measurements, with no human participants or animal experimentation; ethics committee approval was therefore not

applicable. Fieldwork was authorized by the Sisters of Mary concession managers and followed applicable site-access and plant-resource rules.

Patience Loso Alik: Conceptualization, Methodology, Investigation, Data curation, Writing – original draft; **Pisco Menga Munkolo:** Methodology, Formal analysis, Data curation, Writing – review & editing; **Jean-Paul Ngbolua:** Methodology, Formal analysis, Data curation, Writing – review & editing; **Crispin Balo Ilunga:** Formal analysis, Validation. **Godefroid Yaya:** Investigation, Data curation; **Félicien Lukoki Luyeye:** Validation, Writing – review & editing; **Bonaventure Masens Da Musa Yung:** Investigation, Validation, Supervision; All authors read, reviewed and approved the final version of the manuscript.

REFERENCES

[1] Hubau, W., Lewis, S. L., Phillips, O. L., Affum-Baffoe, K., Beeckman, H., Cuní-Sanchez, A., Daniels, A. K., Ewango, C. E. N., Fauset, S., Mukinzi, J. M., Sheil, D., Sonké, B., Sullivan, M. J. P., Sunderland, T. C. H., Taedoumg, H., Thomas, S. C., White, L. J. T., Abernethy, K. A., Adu-Bredu, S., Amani, C. A., Baker, T. R., Banin, L. F., Baya, F., Begne, S. K., Bennett, A. C., Benedet, F., Bitariho, R., Bocko, Y. E., Boeckx, P., Boundja, P., Brienen, R. J. W., Brncic, T., Chezeaux, E., Chuyong, G. B., Clark, C. J., Collins, M., Comiskey, J. A., Coomes, D. A., Dargie, G. C., de Haulleville, T., Djuikouo Kamdem, M. N., Doucet, J.-L., Esquivel-Muelbert, A., Feldpausch, T. R., Fofanah, A., Foli, E. G., Gilpin, M., Gloor, E., Gonmadje, C., Gourlet-Fleury, S., Hall, J. S., Hamilton, A. C., Harris, D. J., Hart, T. B., Hockemba, M. B. N., Hladik, A., Ifo, S. A., Jeffery, K. J., Jucker, T., Kasongo Yakusu, E., Kearsley, E., Kenfack, D., Koch, A., Leal, M. E., Levesley, A., Lindsell, J. A., Lisingo, J., Lopez-Gonzalez, G., Lovett, J. C., Makana, J.-R., Malhi, Y., Marshall, A. R., Martin, J., Martin, E. H., Mbayu, F. M., Medjibe, V. P., Mihindou, V., Mitchard, E. T. A., Moore, S., Munishi, P. K. T., Nssi Bengone, N., Ojo, L., Evouna Ondo, F., Peh, K. S.-H., Pickavance, G. C., Dalberg Poulsen, A., Poulsen, J. R., Qie, L., Reitsma, J., Rovero, F., Swaine, M. D., Talbot, J., Taplin, J., Taylor, D. M., Thomas, D. W., Toirambe, B., Tshibamba Mukendi, J., Tuagben, D., Umunay, P. M., van der Heijden, G. M. F., Verbeeck, H., Vleminckx, J., Willcock, S., Wöll, H., Woods, J. T., & Zemagho, L., 2020, Asynchronous carbon sink saturation in African and Amazonian tropical forests. *Nature* **579**(7797), 80–87. https://doi.org/10.1038/s41586-020-2035-0

[2] Megevand, C., 2013, *Dynamiques de déforestation dans le bassin du Congo : Réconcilier la croissance économique et la protection de la forêt***.** Directions in Development: Environment and Sustainable Development. (Washington, DC: World Bank). https://doi.org/10.1596/978-0-8213-9742-8

[3] Tyukavina, A., Hansen, M. C., Potapov, P., Parker, D., Okpa, C., Stehman, S. V., Kommareddy, I., & Turubanova, S., 2018, Congo Basin forest loss dominated by increasing smallholder clearing. *Science Advances* **4**(11), eaat2993. https://doi.org/10.1126/sciadv.aat2993

[4] Masens, Y. B. da-M., Ngbolua, K.- te-N., Masens, M., Tembeni, J. M. T., & Bongo, G. N., 2020, Assessment of Phytoecological Parameters of Forest Massifs in the Kwilu Province in the Democratic Republic of the Congo. *Asian Plant Research Journal* **6**(4), 8–18. https://doi.org/10.9734/aprj/2020/v6i430134

[5] Lewis, S. L., Sonké, B., Sunderland, T., Begne, S. K., Lopez-Gonzalez, G., van der Heijden, G. M. F., Phillips, O. L., Affum-Baffoe, K., Baker, T. R., Banin, L., Bastin, J.-F., Beeckman, H., Boeckx, P., Bogaert, J., De Cannière, C., Chezeaux, E., Clark, C. J., Collins, M., Djagbletey, G., Djuikouo, M. N. K., Droissart, V., Doucet, J.-L., Ewango, C. E. N., Fauset, S., Feldpausch, T. R., Foli, E. G., Gillet, J.-F., Hamilton, A. C., Harris, D. J., Hart, T. B., de Haulleville, T., Hladik, A., Hufkens, K., Huygens, D., Jeanmart, P., Jeffery, K. J., Kearsley, E., Leal, M. E., Lloyd, J., Lovett, J. C., Makana, J.-R., Malhi, Y., Marshall, A. R., Ojo, L., Peh, K. S.-H., Pickavance, G., Poulsen, J. R., Reitsma, J. M., Sheil, D., Simo, M., Steppe, K., Taedoumg, H., Talbot, J., Taplin, J. R. D., Taylor, D., Thomas, S. C., Toirambe, B., Verbeeck, H., Vleminckx, J., White, L. J. T., Willcock, S., Woell, H., & Zemagho, L., 2013, Above-ground biomass and structure of 260 African tropical forests. *Philosophical Transactions of the Royal Society B: Biological Sciences* **368**(1625), 20120295. https://doi.org/10.1098/rstb.2012.0295

[6] Bastin, J.-F., Barbier, N., Réjou-Méchain, M., Fayolle, A., Gourlet-Fleury, S., Maniatis, D., de Haulleville, T., Baya, F., Beeckman, H., Beina, D., Couteron, P., Chuyong, G., Dauby, G., Doucet, J.-L., Droissart, V., Dufrêne, M., Ewango, C., Gillet, J.-F., Gonmadje, C. H., Hart, T., Kavali, T., Kenfack, D., Libalah, M., Malhi, Y., Makana, J.-R., Pélissier, R., Ploton, P., Serckx, A., Sonké, B., Stevart, T., Thomas, D. W., De Cannière, C., & Bogaert, J., 2015, Seeing Central African forests through their largest trees. *Scientific Reports* **5**, Article 13156. https://doi.org/10.1038/srep13156

[7] Chave, J., Réjou-Méchain, M., Búrquez, A., Chidumayo, E., Colgan, M. S., Delitti, W. B. C., Duque, A., Eid, T., Fearnside, P. M., Goodman, R. C., Henry, M., Martínez-Yrízar, A., Mugasha, W. A., Muller-Landau, H. C., Mencuccini, M., Nelson, B. W., Ngomanda, A., Nogueira, E. M., Ortiz-Malavassi, E., Pélissier, R., Ploton, P., Ryan, C. M., Saldarriaga, J. G., & Vieilledent, G., 2014, Improved allometric models to estimate the aboveground biomass of tropical trees. *Global Change Biology* **20(**10), 3177–3190. https://doi.org/10.1111/gcb.12629

[8] Nicolaï, H., 1963, *Le Kwilu : Étude géographique d'une région congolaise*. (Bruxelles, Belgique : CEMUBAC).

[9] Mutungu, K., Mudiji, M. B., Kakesa, P., Intinga, V. V., Mboma, M. N., Mwadi, S. S., Muluba, K. C., & Mwamba, T. C., 2009, *Monographie de la ville de Kikwit*. (Kikwit, République démocratique du Congo : Institut Supérieur Pédagogique de Kikwit [ISP/Kikwit])

[10] Kent, M., 2012, *Vegetation description and data analysis: A practical approach* (2nd ed.). (Chichester, UK: Wiley-Blackwell).

[11] Menga, P., Nasi, R., Bayol, N., & Fayolle, A., 2012, Phénologie et diamètre de fructification du wengé (*Millettia laurentii* De Wild.): implications pour la gestion. *Bois et Forêts des Tropiques* **312**(2). https://doi.org/10.19182/bft2012.312.a20501

[12] Mbete, P., Leckoundzou, A., Sosthene, O. C., Moukilou, G., Goma, G. F., & Koubouana, F., 2019, Évaluation des potentialités ligneuses de l'Assiette Annuelle de Coupe (AAC) 2018 dans l'Unité Forestière d'Exploitation (UFE) Mpoukou-Ogooué. *International Journal of Biological and Chemical Sciences* **13**(1), 265–276. https://doi.org/10.4314/ijbcs.v13i1.22

[13] Menga, P., 2012, *Écologie des peuplements naturels de Millettia laurentii De Wild. dans la région du lac Maï-Ndombe, en RD Congo : Implications pour la gestion durable d'une espèce exploitée* [Thèse de doctorat, Université de Kinshasa].

[14] Bray, J. R., & Curtis, J. T., 1957, An ordination of the upland forest communities of southern Wisconsin. *Ecological Monographs* **27**(4), 325-349. https://doi.org/10.2307/1942268

[15] Kruskal, J. B., 1964, Multidimensional scaling by optimizing goodness of fit to a nonmetric hypothesis. *Psychometrika* **29**(1), 1–27. https://doi.org/10.1007/BF02289565

[16] Kindlund, Y. K., & Tyler, T., 2023, Magnitude and drivers of plant diversity loss differ between spatial scales in Scania, Sweden 1957–2021. *Applied Vegetation Science* **26**, e12730. https://doi.org/10.1111/avsc.12730

[17] Anderson, M. J., 2001, A new method for non-parametric multivariate analysis of variance. *Austral Ecology* **26**(1), 32–46. https://doi.org/10.1111/j.1442-9993.2001.01070.pp.x

[18] Anderson, M. J., 2006, Distance-based tests for homogeneity of multivariate dispersions. *Biometrics* **62**(1), 245–253. https://doi.org/10.1111/j.1541-0420.2005.00440.x

[19] De Cáceres, M., & Legendre, P., 2009, Associations between species and groups of sites: Indices and statistical inference. *Ecology* **90**(12), 3566–3574. https://doi.org/10.1890/08-1823.1

[20] Fayolle, A., Ngomanda, A., Mbasi, M., Barbier, N., Bocko, Y., Boyemba, F., Couteron, P., Fonton, N., Kamdem, N., Katembo, J., Kondaoule, H. J., Loumeto, J., Maïdou, H. M., Mankou, G., Mengui, T., Mofack, G. II, Moundounga, C., Moundounga, Q., Nguimbous, L., Nsue Nchama, N., Obiang, D., Ondo Meye Asue, F., Picard, N., Rossi, V., Senguela, Y.-P., Sonké, B., Viard, L., Yongo, O. D., Zapfack, L., & Medjibe, V. P., 2018, A regional allometry for the Congo basin forests based on the largest ever destructive sampling. *Forest Ecology and Management* **430**, 228–240. https://doi.org/10.1016/j.foreco.2018.07.030

[21] Fischer, F.J., Chave, J., Zanne, A., Jucker, T., Fajardo, A., Fayolle, A., de Lima, R.A.F., Vieilledent, G., Beeckman, H., Hubau, W., De Mil, T., Wallenus, D., Aldana, A.M., Alvarez-Dávila, E., Alves, L.F., Apgaua, D.M.G., Arcanjo, F., Bastin, J.-F., Bilous, A., Birnbaum, P., Blyshchyk, V., Borah, J., Boukili, V., Camarero, J.J., Casas, L., Cazzolla Gatti, R., Chambers, J.Q., Fabiano, E.C., Choat, B., Conti, G., Cornwell, W., Dar, J.A., Das, A.K., Dobler, M., Dougabka, D., Edwards, D.P., Evans, R., Falster, D., Fearnside, P., Flores, O., Fyllas, N., Gérard, J., Goodman, R.C., Guibal, D., Henao-Diaz, L.F., Hervé, V., Hietz, P., Homeier, J., Ibanez, T., Ilic, J., Jansen, S., Kalita, R.M., Kenzo, T., Kindermann, L., Kothandaraman, S., Kotowska, M., Kubota, Y., Langbour, P., Lawson, J., de Lima, A.L.A., Link, R.M., Linstädter, A., López, R., Macinnis-Ng, C., Magnago, L.F.S., Martin, A.R., Matheny, A.M., McCarthy, J.K., Miller, R.B., Nath, A.J., Nelson, B.W., Njana, M., Nogueira, E.M., Oliveira, A., Oliveira, R., Olson, M., Onoda, Y., Paul, K., Piotto, D., Radtke, P., Razafindratsima, O., Ramananantoandro, T., Read, J., Richardson, S., de la Riva, E.G., Rodríguez-Reyes, O., Rolim, S.G., Rolo, V., Rosell, J.A., Salguero-Gómez, R., Santini, N.S., Schuldt, B., Schwendenmann, L., Sellin, A., Staples, T., Stevenson, P.R., Sundarapandian, S., van der Sande, M.T., Thibaut, B., Tng, D.Y.P., Torezan, J.M.D., Villanueva, B., Weiskittel, A., Wells, J., Wright, S.J. & Zieminska, K., 2026, Beyond species means – the intraspecific contribution to global wood density variation. *New Phytologist* **249**, 2630-2651. https://doi.org/10.1111/nph.70860

[22] Fischer, F. J., Chave, J., Zanne, A. E., Jucker, T., Fajardo, A., Fayolle, A., Ferreira de Lima, R. A., Vieilledent, G., Beeckman, H., Hubau, W., De Mil, T., Wallenus, D., Aldana, A. M., Alvarez-Davila, E., Alves, L. F., Mattos Guimarães Apgaua, D., Arcanjo, F., Bastin, J. F., Bilous, A., Birnbaum, P., Blyshchyk, V., Borah, J., Boukili, V., Camarero, J. J., Casas Caro, L. F., Cazzolla Gatti, R., Chambers, J. Q., Chimbioputo Fabiano, E., Choat, B., Conti, G., Cornwell, W., Dar, J. A., Das, A. K., Dobler, M., Dougabka, D., Edwards, D. M., Evans, R., Falster, D., Fearnside, P., Flores, O., Fyllas, N. M., Gérard, J., Goodman, R. C., Guibal, D., Henao-Diaz, L. F., Hervé, V., Hietz, P., Homeier, J., Ibanez, P., Ilic, H., Jansen, S., Kalita, R. M., Kenzo, T., Kindermann, L., Kothandaraman, S., Kotowska, M. M., Kubota, Y., Langbour, P., Lawson, J., Alves de Lima, A. L., Link, R. M., Linstädter, A., López, R.,

Macinnis-Ng, C., Magnago, L. F. S., Martin, A. R., Matheny, A. M., McCarthy, J., Miller, R. B., Nath, A. J., Nelson, B. W., Njana, M. A., Nogueira, E. M., De Oliveira, A. A., Oliveira, R. S., Olson, M. E., Onoda, Y., Paul, K., Piotto, D., Radtke, P., Razafindratsima, O., Ramananantoandro, T., Read, J., Richardson, S. J., de la Riva, E. G., Rodríguez-Reyes, O., Rolim, S., Rolo, V., Rosell, J. A., Salguero-Gómez, R., Santini, N. S., Schuldt, B., Schwendenmann, L., Sellin, A., Staples, T. L., Stevenson, P. R., Sundarapandian, S., van der Sande, M., Thibaut, B., Tng, D. Y. P., Torezan, J. M., Villanueva, B., Weiskittel, A. R., Wells, J., Wright, S. J., & Zieminska, K., 2026, *Global Wood Density Database v.2 (GWDD v.2)* [Data set]. University of Bristol. https://doi.org/10.5281/zenodo.16919509

[23] Oksanen, J., Simpson, G. L., Blanchet, F. G., Kindt, R., Legendre, P., Minchin, P. R., O'Hara, R. B., Solymos, P., Stevens, M. H. H., Szoecs, E., Wagner, H., Barbour, M., Bedward, M., Bengtsson, H., Bolker, B., Borcard, D., Carvalho, G., Chirico, M., De Caceres, M., Durand, S., Evangelista, H. B. A., FitzJohn, R., Friendly, M., Furneaux, B., Hannigan, G., Heida, I., Hill, M. O., Lahti, L., Martino, C., McGlinn, D., Ouellette, M.-H., Ribeiro Cunha, E., Smith, T., Stier, A., Ter Braak, C. J. F., & Weedon, J., 2026, *vegan: Community ecology package* (Version 2.7-5) [R package]. R Foundation for Statistical Computing. https://doi.org/10.32614/CRAN.package.vegan

[24] Galili, T., 2015, dendextend: An R package for visualizing, adjusting and comparing trees of hierarchical clustering. *Bioinformatics* **31**(22), 3718–3720. https://doi.org/10.1093/bioinformatics/btv428

[25] Fauset, S., Johnson, M. O., Gloor, M., Baker, T. R., Monteagudo M., A., Brienen, R. J. W., Feldpausch, T. R., Lopez-Gonzalez, G., Malhi, Y., ter Steege, H., Pitman, N. C. A., Baraloto, C., Engel, J., Pétronelli, P., Andrade, A., Camargo, J. L. C., Laurance, S. G. W., Laurance, W. F., Chave, J., Allie, E., Núñez Vargas, P., Terborgh, J. W., Ruokolainen, K., Silveira, M., Aymard C., G. A., Arroyo, L., Bonal, D., Ramirez-Angulo, H., Araujo-Murakami, A., Neill, D., Hérault, B., Dourdain, A., Torres-Lezama, A., Marimon, B. S., Salomão, R. P., Comiskey, J. A., Réjou-Méchain, M., Toledo, M., Licona, J. C., Alarcón, A., Prieto, A., Rudas, A., van der Meer, P. J., Killeen, T. J., Marimon Junior, B.-H., Poorter, L., Boot, R. G. A., Stergios, B., Vilanova Torre, E., Costa, F. R. C., Levis, C., Schietti, J., Souza, P., Groot, N., Arets, E., Chama Moscoso, V., Castro, W., Honorio Coronado, E. N., Peña-Claros, M., Stahl, C., Barroso, J., Talbot, J., Guimarães Vieira, I. C., van der Heijden, G., Thomas, R., Vos, V. A., Almeida, E. C., Álvarez Davila, E., Aragão, L. E. O. C., Erwin, T. L., Morandi, P. S., Almeida de Oliveira, E., Valadão, M. B. X., Zagt, R. J., van der Hout, P., Alvarez Loayza, P., Pipoly, J. J., Wang, O., Alexiades, M., Cerón, C. E., Huamantupa-Chuquimaco, I., Di Fiore, A., Peacock, J., Pallqui Camacho, N. C., Umetsu, R. K., Barbosa de Camargo, P., Burnham, R. J., Herrera, R., Quesada, C. A., Stropp, J., Vieira, S. A., Steininger, M., Reynel Rodríguez, C., Restrepo, Z., Esquivel Muelbert, A., Lewis, S. L., Pickavance, G. C., & Phillips, O. L., 2015, Hyperdominance in Amazonian forest carbon cycling. *Nature Communications* **6**, Article 6857. https://doi.org/10.1038/ncomms7857

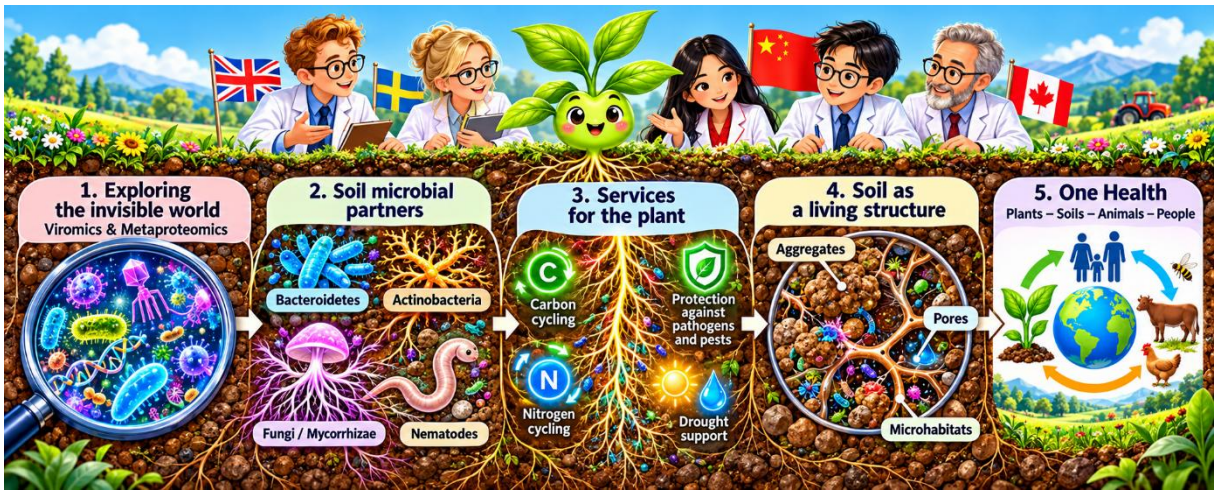
[26] Chao, A., Gotelli, N. J., Hsieh, T. C., Sander, E. L., Ma, K. H., Colwell, R. K., & Ellison, A. M., 2014, Rarefaction and extrapolation with Hill numbers: A framework for sampling and estimation in species diversity studies. *Ecological Monographs* **84**(1), 45–67. https://doi.org/10.1890/13-0133.1

[27] Kearsley, E., Hufkens, K., Verbeeck, H., Bauters, M., Beeckman, H., Boeckx, P., & Huygens, D., 2019, Large-sized rare tree species contribute disproportionately to functional diversity in resource acquisition in African tropical forest. *Ecology and Evolution* **9**(8), 4349-4361. https://doi.org/10.1002/ece3.4836

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BOOK REVIEW

Understanding and utilising soil microbiomes for a more sustainable agriculture, **edited by** Kari E. Dunfield. Cambridge, UK: Burleigh Dodds Science Publishing, 2025. xxiv + 424 pp. Hardback, £155.00. Hardback. ISBN 978-1-80146-474-1. eISBN 978-1-80146-476-5. DOI: 10.19103/AS.2024.0136



What an extraordinary feeling it is to begin reading this book! So richly documented is this guide to soil microbiomes that it quickly carried me away, to the point of living the story in detail within the imagination of an invisible underground world beneath our feet, and looking through the eyes of a young plant growing in a soil already inhabited and so finely coordinated.

Larafa, Fall, Nannipieri *et al.* reveal the secret codes of viromics and metaproteomics that allow us to unlock the great door to this invisible universe (pp. 3–37), and to become acquainted with its inhabitants and their functions. Technology has considerably advanced these means of access through sequencing, as well as mass spectrometry and bioinformatics. At first sight, one can distinguish the dominant microbial community and its virome (pp. 12–15). The relationship between these two partners is never uniform: a virus may represent a catastrophe for one

bacterium and a formidable enemy when it is able to infect it; yet, for another antagonistic bacterium, it may be perceived as a means of eliminating rivals and freeing space and nutrients. Yes, but the possible advantages are not always systematic. And for the ecosystem? The outcome depends on a multitude of factors, including the identity of the species affected, their interactions and the local ecological conditions. In this world, so meticulously structured and organized, the soil remains the chronicler of the "tasks performed", the guardian of memory and traceability. Every task carried out is recorded in the archive of each inhabitant's activities, and this archive can be deciphered only through metaproteomics (pp. 27–37).

During the official ceremonies marking the young plant's visit to this buried world, sixteen scientists from four countries — the United Kingdom, Sweden, China and Canada — stand in line. These scholars, coming from different horizons, form three delegations of scientific ambassadors: (1) Lidbury *et al.*, experts in resource transformation (pp. 45–73); (2) Bao *et al.*, specializing in bacterial diversity (pp. 73–84); and (3) Weerasuriya *et al.*, responsible for relations between fungi and plants (pp. 89–113).

The delegations are then invited to present their discoveries to our young plant.

The Lidbury *et al.* delegation proposes a visit to the processing factories and the carbon and phosphorus supply stations. It explains that skilful workers are active in these factories: the "Bacteroidetes". This is a bacterial group, some members of which possess remarkable molecular equipment enabling them to transform complex carbon resources. Some also have mechanisms for acquiring organic phosphorus. The work is organized into several specialized workshops, because not all Bacteroidetes possess the same metabolic skills.

Some workshops even possess genuine genetic plans known as PULs (Polysaccharide Utilisation Loci) (p. 52) for exploiting complex resources. These are groups of genes involved in the recognition, degradation and acquisition of polysaccharides (pp. 50–53). The delegation acknowledges that many functions still remain to be deciphered, particularly under real soil conditions.

When the second delegation takes the floor, our young plant discovers, to her surprise, that some inhabitants of this bacterial community look strangely like fungi. But appearances are deceptive: Actinobacteria are all bacteria. They display great morphological, genetic and

metabolic diversity. Some are distinguished by a misleading filamentous, almost fungal appearance (pp. 73–84).

These bacteria are adapted to inhabit different environments, but their establishment is not left to chance: pH, moisture, temperature, organic resources and vegetation all help determine their abundance and distribution. Actinobacteria are very helpful and sociable, living in close interaction with the other inhabitants of this underground world. They perform a wide range of functions within the community. Some willingly put their talents to work in defence through their ability to produce antibiotics, antifungals and other secondary metabolites; some can be mobilized for biological control; others undertake remediation operations. Still others work in recycling, breaking down complex plant residues and thereby contributing to the carbon cycle.

The third delegation could not have found a better moment to show the young plant who the true fungi are, and what role they play in this underground society (pp. 89–113). It is as if, without even realizing it, the previous delegations had, through the questions they left unresolved, prepared a perfect introduction to their intervention. At last, the plant meets her mycobiome (pp. 95–99), the species most intimately associated with her roots, with which she continuously exchanges resources in mycorrhizae (p. 97), until they become indispensable to one another. But not every encounter between plant and fungus ends in a happy alliance: everything depends on who meets whom, and under what conditions.

The third delegation believes it is instructing a naïve plant about her own root neighbourhood, when in fact the plant herself plays an active part in its selection. Regmi *et al.* come to reveal her little secret: is she not herself chairing the “Host selection” council (p. 131) and helping to organize this community around her own roots? She even possesses an entire chemical arsenal, released by her roots, capable of influencing those who come to settle in her neighbourhood. The rhizosphere is a highly mysterious and extremely dynamic zone. One can almost read it in her eyes, even as she tries to deny it. And it is difficult for her to hide the game: this is a genuine scientific inspection brigade, capable of spying on her influence through omics approaches (pp. 155–158).

The plant quickly wants to change the subject and divert attention towards the tiny inhabitants moving through the soil: the nematodes. “Oh! How charming they are!” she exclaims, as if nothing were happening. The reality is that some of them are plant parasites capable of attacking her roots. These tiny creatures are great eaters, but each group has its own menu: some are

bacterivores, others fungivores, plant parasites, predators or omnivores; these “charming ones” in fact belong to several trophic groups. Ruess presents them to our star as highly widespread multicellular organisms, present in virtually all habitats, with very diverse lifestyles and functions (pp. 175–176).

The Jetter and Schäfer delegation nevertheless remains suspicious and keeps wondering: but after all, who does this plant work for? For herself, for the inhabitants of the soil, for the ecosystem… or for all this little world at once? The answer takes them far beyond her roots alone: in this society, the health of some cannot be considered independently from that of others. It is here that the concept of One Health takes on its full meaning (pp. 205–220).

It is now time to present the catalogue of services. At the fourth station (pp. 231–322), our young plant cannot help but feel proud, because the offer proves to be more generous than she had imagined: carbon management (pp. 231–250), nitrogen management (pp. 255–265), protection against pathogens and pests (pp. 271–283), and assistance in the face of drought (pp. 293–321). Our young plant finally begins to understand everything she gains from maintaining good relations with all her neighbours. And when the activity of this underground society departs from the ordinary, she now knows that something may not be quite right (pp. 231–250).

Shi arrives at just the right moment to remind our young plant that an offer exists only when one responds to demand, and that the most lasting relationships are those in which each gives at least as much as is being received. He illustrates this through the example of soil (pp. 335–356). He first explains that soil is not simply a support. In one direction, its texture, particles, aggregates and pores, together with the circulation of water, air and resources, create a multitude of microhabitats for the microbiota. The size and organization of the pores also influence the distribution, movement and interactions of microorganisms. In the other direction, microorganisms themselves help to assemble and stabilize the aggregates that structure the soil.

The young plant had long admired the services provided by her neighbours, and all the sacrifices and assistance they so generously offer, yet at the same time she remains convinced that all of this is not enough to guarantee a sustainable and optimized life.

The final two delegations, coordinated by Whalen and Mendes *et al.* (pp. 365–419), perhaps give her the most important lesson of all: this invisible society can be profoundly disturbed by our own interventions, by our own agricultural and fertilization practices intended to increase

yields. Optimizing the soil therefore no longer means simply growing a plant; it means learning to consider and care for the living world that makes that plant grow and that lies beneath her feet.

And I, because I like to move forward with clarity, find myself trapped in an endless circle beside the delegation of the two German scientists, Jetter and Schäfer, at once suspicious and questioning, still waiting for an answer to these questions: but after all, who does this plant work for? For herself, for the inhabitants of the soil, for the ecosystem… or for all this little world at once? And in the end, who works for whom? We work for her, she works for others, the others work among themselves… and here I am back at my starting point.

Fortunately, one single expression was enough to escape this mechanism: One Health. Perhaps it was simply necessary to understand that there was no "who works for whom", but rather "everyone works with everyone". In this society, each gives, receives and depends on the others; the health of some cannot be considered independently from that of others. One Health may be a relatively recent term, but the story it tells is immemorial: beneath our feet as above them, the health of some has always been built together with that of others (pp. 205–220).

Indeed, this book conveys the same advice: let us walk gently upon the earth, because beneath our steps the balance is very fragile, life works in silence, and the hope of future generations depends upon it; that hope, too, is already beginning to germinate.

From its inhabitants to their functions, from their alliances to their rivalries, from their services to their fragile balances, this extraordinary underground society seemed to have carried me away with it, delightfully. Our young plant slowly disappears between the pages as the end approaches, unfortunately. After such a journey beneath our feet, so well accompanied, I still want her to remain. For although all these secrets have now been unlocked, another question still remains. Beneath her roots, yes, she seems to have solved every mystery; but in the very title of the book, one riddle still resists me, and I keep asking myself the same question: why "utilising" rather than "using" [1–3]? As Eric Partridge states, '**utilize, utilization** are, 99 times out of 100, much inferior to *use, v. [verb]* and *n. [noun[;* the one other time, it is merely inferior [4].

References

[1] Centers for Disease Control and Prevention, 2003, *CDC style guide*. U.S. Department of Health and Human Services. https://www.cdc.gov/nceh/clearwriting/writing-tips/pdfs/2025/Utilize-vs-Use-H.pdf

[2] Hotaling, S., 2020, Simple rules for concise scientific writing. *Limnology and Oceanography Letters* **5**(6), 379–383. https://doi.org/10.1002/lol2.10165

[3] Tanaka, H., & Seals, D. R., 2024, Scientific writing in physiology: Confused/misused terms and phrases. *Journal of Applied Physiology* **136**(2), 401–407. https://doi.org/10.1152/japplphysiol.00868.2023

[4] Partridge, Eric, Usage and Abusage: a Guide to Good English (London: Hamish Hamilton), 1947, 6th ed. 1965, rev 1979, p., 353

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nadia.boutaleb@fstm.ac.ma

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BOOK REVIEW

Wild Orcas: A Deep Dive into the World of Killer Whales, edited by Strager, H., & DeNardo, C., Princeton: Princeton University Press, USA, 2026, 256 pp., US$35.00 (hardback), ISBN: 978-0-691-26984-9.

Before the nineteenth century, it was generally believed that species existed in the state in which they had been created, retaining all their characteristics through time. The living world was thus perceived through the dominant lens of fixism. Soon afterwards, remarkable theories followed one another, each bringing new and particular concepts and mechanisms: first transformism, then Darwinism, and finally modern theories founded on advances in contemporary science [1].

Reading *Wild Orcas: A Deep Dive into the World of Killer Whales*, one begins to see a new theory integrating several dimensions: culture, traditions, social life, learning, transmission, and a range of factors that are indeed observable in the living world. In *Wild Orcas*, Strager and DeNardo provide evidence that these dimensions may even exert selective pressure, contribute to the reproductive isolation of social groups and thus may influence gene flow across population boundaries (pp. 194–213).

The authors acknowledge that this does not necessarily apply to all species and remains to be demonstrated; but it is certain that orcas exhibit specific dialects, hunting techniques, food preferences and social structures that play a determining role in ‘evolution’ (pp. 197, 207–213).

Although orcas are commonly called ‘killer whales’, *Orcinus orca* is the largest member of the Delphinidae, and therefore an odontocete cetacean. It is a marine mammal that breathes at the surface and is remarkably adapted to swimming, diving and predation. The book explains their extraordinary geographical distribution and ecotypes, devoting considerable attention to their distribution and to distinct populations, sometimes reproductively isolated, displaying particular behaviours, diets, social structures and, in some cases, morphological characteristics. Chapter 3, ‘*In the Field*’ (pp. 64–93) reveals the scientific methods used to encounter, observe and listen to

them in the field: photo-identification, hydrophones, biopsies, biologging tags (*biologging* and D-tags), GPS tracking, drones, aerial photogrammetry and even breath sampling.

Like other cetaceans, they live in complex social environments and depend on acoustic communication, but orcas are distinguished by the diversity of their socially acquired behaviours. In *Wild Orcas*, these remarkably complex animals manifest sacrifice, cooperation, teamwork and generosity (pp. 109, 112–114, 156, 165, 197, 204, 230, 237). Whether these result from thinking and moral choice is debatable. Anthropomorphizing animals is risky. There are three striking areas (Figure 1).

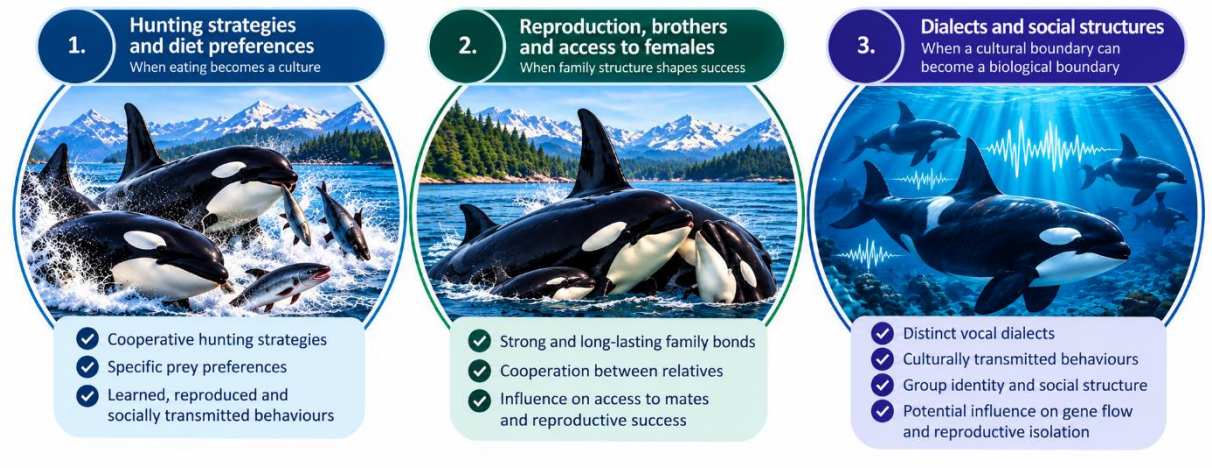


Figure 1. Culture in orcas: three pathways linking socially transmitted behaviour to evolutionary processes

The first and most convincing example is that of the cooperative hunting strategies used by *killer whales*. The orca is a highly specialized apex predator, and members of a hunting group are capable of coordinating their movements to surround, pursue, isolate or destabilize prey. The hunting techniques generally used are neither standard nor uniform; they constitute a ‘profession’ learned, reproduced and socially transmitted from previous generations. Hunting thus becomes a cultural tradition of the group rather than an individual and independent behaviour.

Know-how and problem-solving skills are transmitted and even learned from one another (pp. 94–119, 200–204). These creatures go beyond what we might imagine: they have fixed mealtimes! They know when it is time to ‘come to the table’, what to eat, and whom to follow and hunt. Fish, squid, seabirds, seals, sea lions and even other cetaceans — all of these prey may appear on the menu, but not all orcas eat the same thing. The nature of the food is itself a tradition: one does not necessarily eat what others eat or whatever happens to be available, even if it may be considered edible from another point of view (pp. 119, 202–204). A meal is an art, a culture, a tradition. Culture may therefore contribute to creating different selective environments for different groups. Among

orcas, there are groups of hunters specializing in fish and others specializing in marine mammals. There are even hunters specializing in seals! In Patagonia, some go so far as to beach themselves to capture young sea lions (pp. 57–58), a technique as spectacular as it is risky. Can intention be perceived in a refined use of body mass, instincts and skills to secure a meal? Since the risk must be considered, something very close to thinking and choice is apparent.

Certain food cultures of human beings have long functioned in this way, with each group having its own habits and specialities, and our dishes enriched by locally available natural resources. The habits specific to each population must be preserved and maintained for future generations [2]. Globalization tends to homogenize food practices, which further contributes to devaluing food and cultural identity [3].

This first example is not the most striking. Strager and DeNardo describe the lifelong attachment of young orcas to their natal groups. Older females within these families play an important social role in protection and transmission. Reproduction and relationships between related males are illuminating (pp. 140–165). The cooperation between brother orcas is touching. A true example of sacrifice and of enduring family bonds! Some males may devote an important part of their social lives to supporting their relatives, without necessarily reproducing themselves, helping a brother to reach the female he desires and, ultimately, contributing to his reproductive success. Thus, the orcas' social organization can have consequences for who reproduces and who passes genes on to the next generation (pp. 145, 148–157, 197, 213). Is this not sufficient evidence of an influence on gene flow across population boundaries (pp. 197, 207–213)?

This is, of course, a disputable notion. If there is no real choice or intention in a sense evident in mankind, can orcas not be governed merely by 'the logic' of 'the selfish gene'? In many parts of the world still today, mankind lives often in extended families, where brothers, sisters, grandparents, uncles and aunts all participated in mutual support, education and transmission [4]. This pattern contributes to psychological balance and to the development of the 'useful' individual. Today, socio-economic causes –notably urbanization – have profoundly affected family life. We may gain in autonomy, but how united is society?

The third example, magnificently presented by the authors, is that of vocal dialects as a component of orca culture, alongside hunting strategies, greeting ceremonies, beach rubbing and other socially differentiated behaviours (pp. 125, 127, 132, 136, 143, 145, 197, 200, 204–205). Not all orcas speak the same language: each group has its own dialect and behavioural characteristics that persist across generations and contribute fully to its social identity (pp. 197, 200, 204–205). Underwater, sound is a major biological tool for communication and perception. Orcas produce calls and clicks, among other sounds; echolocation enables them to obtain information about their environment and their

prey. Some calls are learned, and some repertoires are specific to particular groups. The authors devote an entire chapter to this subject, *Listening in on Killer Whales* (pp. 120–139). On p. 73, the authors transcribe one of the sounds heard underwater: 'Yeeeeee-oooo-ee'. We can listen to orcas and recognize their calls and dialects. An equally well-developed reference work resembling the *Oxford Dictionary of English* (ODE) [5] is not yet available for this language. Is one indeed possible?

The authors also evoke possible interactions with the human world (pp. 43, 220). Recently, repeated interactions between Iberian orcas and boats have been reported off the Spanish and Portuguese coasts. The orcas' motivation for this behaviour remains uncertain, but its spread between individuals raises the question of possible social transmission [6]. Will it persist over time and be transmitted within the group?

If we are to speak seriously about the conservation of this species, the orca is a mobile, social and acoustically sophisticated animal whose family structures and natural behaviours are difficult to reproduce in an artificial environment. The authors are against the capture of orcas and their confinement to an artificial life. The final chapter, *Saving Killer Whales* (pp. 218–243), studies the major categories of threats: declining prey availability, contaminants and pollution, underwater noise, habitat disturbance, small population sizes and reproductive problems. The contrast between the Southern Residents (<75) and Northern Residents (~300) is telling, showing that some orca populations are considerably more vulnerable and directly affected by the challenges associated with biodiversity.

Darwin taught us to look at how the environment selects living organisms. Orcas are 'wild', but their world is neither disordered nor without rules. This book about *wild orcas* teaches us many lessons. It shows us the power of what surrounds us and its importance in our own development: everything also depends on our ability to interact, understand and learn. This book deserves a place in the reflective history of evolutionary thought.

References

[1] Dagg, J. L., & Derry, J. F., 2022, Patrick Matthew's synthesis of catastrophism and transformism. *Notes and Records: The Royal Society Journal of the History of Science* **78**(1), 167–188. https://doi.org/10.1098/rsnr.2022.0019

[2] Boukherouk, M., & Bousbaa, C., 2026, The Unseen UNESCO Kitchen: Informal Foodways, Socio-Economic Power, and Jemaa Lfna's Living Heritage. In *International Conference on Economic Development and Social Sustainability* (pp. 501-516). (Cham: Springer Nature Switzerland).

[3] Hawkes, C., 2006, Uneven dietary development: Linking the policies and processes of globalization with the nutrition transition, obesity and diet-related chronic diseases. *Globalization and Health* **2**, Article 4. https://doi.org/10.1186/1744-8603-2-4

[4] Jæger, M. M., 2012, The Extended Family and Children's Educational Success. *American Sociological Review* **77**(6), 903-922. https://doi.org/10.1177/0003122412464040

[5] Stevenson, A. (Ed.)., 2010, *Oxford Dictionary of English* (3rd ed.). (Oxford: Oxford University Press)

[6] Castro, J., Cid, A., Martins, M. P., Estrela, G., Pieters, A., & Quirin, A., 2026, Insights into a disruptive behavior of Iberian killer whales (*Orcinus orca*) with boats: Perspective from multiple interactions with a research vessel. *Marine Mammal Science* **42**(4), e70247. https://doi.org/10.1111/mms.70247

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b.bahlaouan@ispitscasa.ac.ma

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