



Mini Review

Insights on Micro- and Nano-Plastics Vector Role in Aquatic Metal Transport and Pollution in Sub-Saharan Africa Mining Landscape: A Mini-Scoping Review

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Abstract: Globally, micro- and nano-plastics (MNPs) have emerged as pervasive contaminants in freshwater ecosystems due to their persistence, mobility, and complex interactions with co-pollutants, including metals. In sub-Saharan Africa (SSA), legacy pollution of aquatic ecosystems is largely associated with metal mining and, more recently, with MNPs as emerging contaminants. MNPs exhibit potential as a metal transport vector. However, there is a paucity of evidence on the vector role of MNPs and potential environmental impacts of MNP-metal interactions in SSA aquatic systems. In this mini-scoping review, (1) we documented current evidence on the MNP-metal vector role in SSA aquatic ecosystems; (2) highlighted mechanisms and drivers of MNP-mediated aquatic metal transport; and (3) identified key knowledge gaps for future research in SSA. While global studies provided an in-depth mechanistic understanding of the role of MNPs as metal transport vectors and pollutant dynamics, the few studies in SSA focused primarily on field observations of pollutants, with less emphasis on MNPs in metal mobility. This disparity occurs despite the increased vulnerability to both plastic waste and mining-generated aquatic pollution. The role of MNPs as vectors of metal transport is modulated by polymer characteristics (such as size, morphotype, and abundance), environmental factors (such as pH, ionic strength, temperature, and co-contaminants) and biological factors (such as biofilms and community structure). Despite the emerging evidence of MNPs as vectors for aquatic metal transport in SSA, our understanding of MNP-metal sorption kinetics, bioavailability and trophic implications remains limited. Furthermore, there is insufficient research on the influence of microbial processes and biofilms on MNPs as vectors of metal transport and pollution in the aquatic ecosystems of SSA.

Keywords: micro- and nano-plastics; aquatic pollution; metal transport vector; sorption kinetics; emerging contaminants; sub-Saharan Africa

1. Introduction

Globally, micro- and nano-plastics (MNPs) have emerged as pervasive contaminants in freshwater ecosystems due to their persistence, mobility, and complex interactions with other co-contaminants [1,2]. Increased MNP pollution results from the massive surge in plastic production, which reached 390.7 million metric tons (Mt) in 2021 [3]. Moreover, approximately 13 Mt of plastic entered river systems worldwide in 2021 [4]. This



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scenario presents an emerging environmental concern, as over 250 Mt could have contaminated aquatic systems by 2025 [5]. Even more alarming is the projected surge in global plastic use, from 464 Mt in 2020 to 884 Mt by 2050. Nearly 4725 Mt of plastic stocks are anticipated worldwide in the next three decades [6].

The MNP “plastisphere” (i.e., plastic-microbe-biofilm complex), an emerging microbiome, comprises small-sized (MP < 5 mm; NP < 100 nm), large specific surface area, hydrophobic, and diverse carbon-based functional groups able to adsorb and transport metal ions, and with the potential to modify the environmental behaviour, bioavailability, and toxicity of metals in aquatic environments [7–9]. Several studies have demonstrated the influence of multiple environmental factors, including pH, ionic strength, salinity, dissolved organic matter, ultraviolet-mediated ageing, and physicochemical composition of MNPs, on MNP-metal interactions in aquatic environments [8,10]. Furthermore, the metal adsorption capacity of MNPs enhances both localised and long-distance metal mobility and alters bioaccumulation pathways in aquatic biota, thereby exacerbating ecotoxicological and human health risks across mining landscapes [9,11–13].

In sub-Saharan Africa (SSA), legacy metal pollution of aquatic ecosystems is largely associated with mining and mineral processing [14,15]. Mining waste, including acid mine drainage, smelter emissions, and leachates from mine wastelands, such as tailings storage facilities, continually release metal(loid)s (e.g., Cu, Pb, Cd, As, Zn, and Cr) that pollute surface and groundwater [16–18]. Persistent mine waste pollution adversely affects aquatic biodiversity, ecosystem health and functioning, further threatening water security and the provision of other aquatic ecosystem services [19].

Among the emerging environmental contaminants in SSA are plastics and MNPs [20,21]. Significantly increasing plastic use and waste generation, coupled with poor waste management and disposal systems, have amplified MNP pollution in aquatic ecosystems across SSA [12,22,23]. Globally, research has advanced the understanding of MNPs as potential vectors of metal transport in aquatic environments [24–26]. For instance, Guan et al. [27] examined the roles of MNPs and biofilms in heavy metal transport in freshwater ecosystems. By comparing synthetic polystyrene to natural sediments, the researchers noted a marked increase in the ability of MNPs to attract co-contaminants as biofilms grew on MNP surfaces primarily through complexation. A global review by Bhattacharya and Rajaram [28] observed that the potential vector effect of MNPs facilitates the transport of co-contaminant complexes across biological barriers and trophic levels.

Furthermore, Valiyaveetil Salimkumar et al. [29] documented current knowledge on the adsorption behaviour and interaction of MNPs in soils and aquatic environments. The authors highlighted the factors influencing adsorption, the mechanisms and interactions involved, and the impacts of adsorption on co-contaminant transfer in different environmental matrices. In fact, Narwal et al. [24] emphasise that to effectively tackle and reduce the harmful effects of MNPs and co-contaminants on biodiversity, the underlying mechanisms (e.g., adsorption, desorption, bio-uptake, and synergistic effects) must be fully understood.

However, in SSA, there is a paucity of consolidated evidence on the environmental impacts of MNPs as vectors of metal transport or trophic transfer [22,30]. For instance, Aragaw [22] noted that studies from South Africa and Nigeria dominated research on the environmental impacts of MNPs. The same study also noted a bias towards research on MNP impacts in water and sediment matrices, with less focus on biota, limiting the environmental risk assessment of MNP pollution [22]. Additionally, the impact of the region’s unique climatic and hydrological characteristics (such as tropical rainfall patterns, high temperatures, dynamic flow regimes) and widespread land-use-land-cover changes, coupled with the impacts of climate change, on MNP-metal interactions remains unclear [31,32].

Despite emerging evidence of MNP presence in SSA freshwater systems [33], studies correlating MNP occurrence with trends in aquatic metal pollution in SSA mining landscapes remain both localised and limited [12,22,23]. Given these knowledge gaps in SSA, there is a need to map the current environmental status of MNPs in aquatic systems to understand their nature, interactions with other co-contaminants and environmental implications. Therefore, this review aims to: (1) summarise up-to-date evidence on the MNP-metal vector role and associated environmental impacts on SSA aquatic systems; (2) highlight mechanisms and environmental drivers that influence MNP-mediated aquatic metal pollution in the region; and (3) identify knowledge gaps for future in-depth research on the role of MNPs as vectors of aquatic metal transport and pollution in SSA.

2. Methodological Approach and Synthesis

Considering the emergent and interdisciplinary nature of the MNP-metal interactions in aquatic environments, the scattered evidence, and the limited region-specific studies, a mini-scoping review was undertaken for SSA. Campbell et al. [34] and Khalil et al. [35] advocate using this approach, as it allows broad evidence mapping, conceptual synthesis, and systematic identification of knowledge gaps, without limiting inclusion of specific study designs or requiring data homogeneity, in cognisance of limited evidence.

This mini-scoping review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) protocol [36]. The PRISMA-ScR checklist items, adopted from Tricco et al. [36], are described in Sections 2.1–2.5.

2.1. Article Eligibility Criteria

Studies were included if they (1) were peer-reviewed original research, reviews, or experimental studies published in English between 2019 and 2025; (2) reported on plastics (micro- or nano-) in aquatic environments; (3) examined metal adsorption, desorption, transport, or vector effects of MNPs; (4) focused on mining-impacted aquatic ecosystems or metals commonly associated with mining (e.g., Pb, Cu, Zn, Cd, As, Cr); and (5) were conducted in sub-Saharan Africa or contained mechanistic or experimental findings applicable to the region.

Considerations for exclusion included articles reporting studies that were not relevant to freshwater environments; studies focusing solely on MNPs with no direct or inferred linkage to metals; pollution studies unrelated to mining or metal co-contaminants; grey literature and studies lacking empirical or mechanistic insights on MNP-metal vector relationships.

2.2. Sources of Information

Given the scoping nature of this review, a structured search was conducted to extract the “most relevant” articles from Scopus and Web of Science (WOS) platforms (Appendix A). The search terms combined MNP-metal-related keywords, metal-related keywords, and mining-landscape terminology listed in Section 2.3.

2.3. Article Search Criteria

Article searches were conducted using Boolean operators and a combination of one or more sets of keywords from the general terms. Iterative refining with more specific wording was routinely conducted to extract potentially relevant articles. An example of search strings combination used included: (“microplastics” OR “nanoplastics” OR “plastics”) AND (“metals” OR “heavy metals” OR “trace metals” OR “sorption” OR “transport”) AND (“vector” OR “carrier”) AND (“mining” OR “mining landscape”) AND (“freshwater” OR “rivers” OR “streams”) AND (“Africa” OR “sub-Sahara”). Extended search string paths for Scopus and WOS databases are illustrated in Appendix A. Additionally, based on Wohlin et al. [37], manual citation searches across relevant databases and snowballing searches for highly cited and relevant publications were conducted.

2.4. Article Selection Process

The article search results were exported into Mendeley Reference Manager, where deduplication was done. A further step in Mendeley Reference Manager (ver. 2.144.0) involved manually removing articles with incomplete metadata (title, authors, article type, journal name, year of publication, volume, abstract and doi) even after attempting automated online metadata updates. The titles and abstracts of eligible articles were then screened. Finally, a full-text screening was performed by two independent reviewers for all the included articles. Any disagreements were resolved through consensus.

From Figure 1, 322 articles were identified from the WOS and Scopus databases, and 8 were identified through citation search and snowballing. From the 322 articles, 19 duplicates and 203 publications considered not relevant were removed. The remaining 100 relevant articles were retrieved and fully screened. A final 12 eligible articles were included for full-text review and data charting.

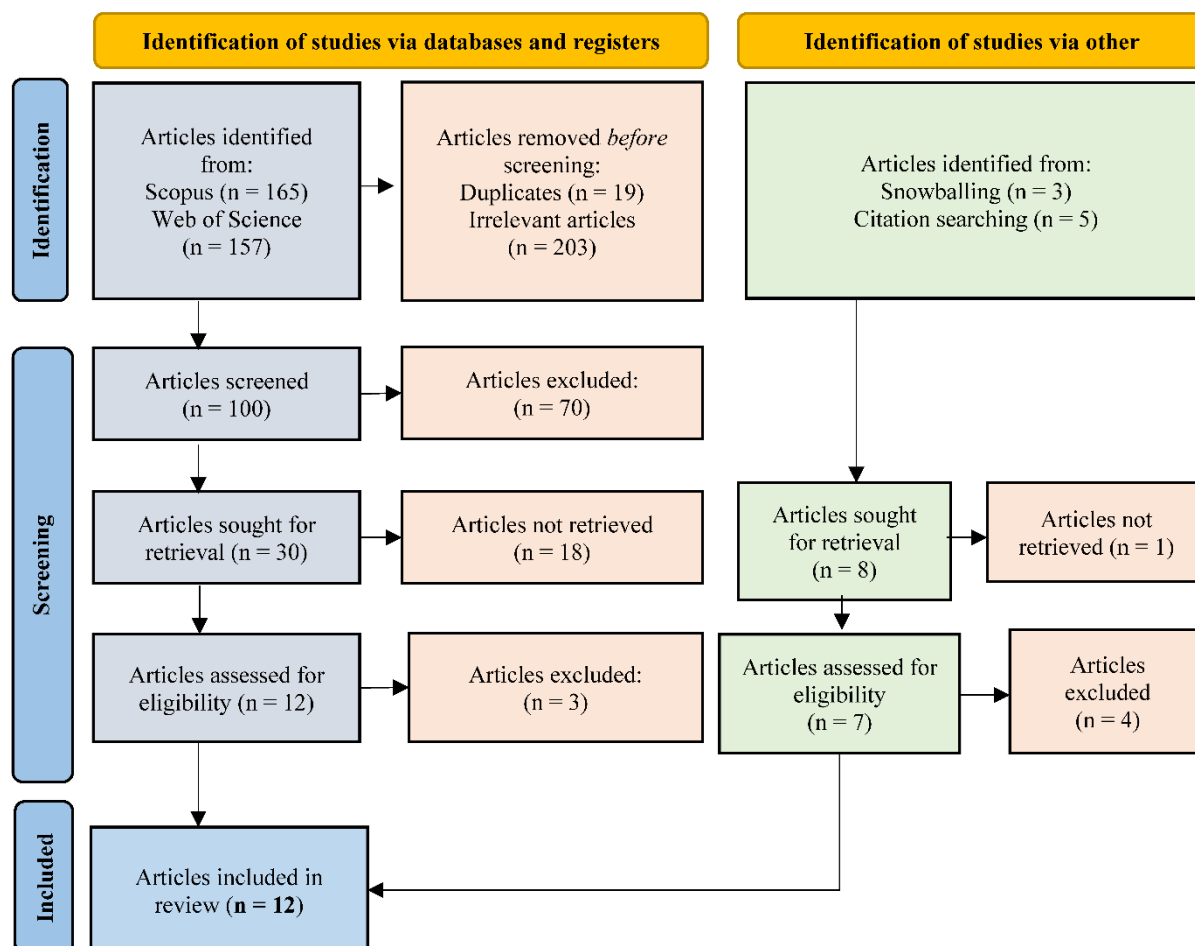


Figure 1. The PRISMA-ScR article selection workflow for the mini-scoping review.

2.5. Data Charting and Synthesis of Results

A standardised data-charting form was developed to extract key elements, including: author(s) and year; country or region; type of study type (field, laboratory, review, modelling); MNP characteristics (polymer type); metal(loid)s involved; methodological approach; key mechanisms (adsorption, desorption, transport, bioaccumulation); environmental drivers and matrices examined; major findings, and knowledge gaps. The data charting process was iterative, allowing continuous refinement of key information elements as new insights emerged.

Due to heterogeneity in the study objectives, methods, and findings, a narrative synthesis was conducted. The findings from the literature review were grouped thematically based on the data-charting elements.

2.6. Overview of Included Articles

Generally, the reviewed studies demonstrated a gradual increase in awareness and scientific interest in MNPs as potential vectors for metal transport in SSA aquatic ecosystems (Table 1). The multi-disciplinary studies comprised laboratory-scale investigations, empirical field research, and regional and global reviews. The global studies were principally mechanistic, focusing on adsorption kinetics, polymer chemistry, and controlled experimental conditions [27,38]. In contrast, studies in SSA were conspicuously field-oriented, observational, and context-specific to environmental contamination scenarios, but lacked the characteristics of a global approach, including long-term ecotoxicological assessments [30,39]. Additionally, these field-based studies were geographically limited, mainly to southern Africa and, to some extent, to West Africa [40–42].

Table 1. Synthesis of 2019–2025 studies on micro- and nano-plastics vector role in transportation and pollution of aquatic ecosystems in the sub-Saharan Africa mining landscape.

Author/Year	Country/Region	MNP Category	Metal	Methodological Approach	Key Mechanisms	Environmental Drivers	Key Findings	Knowledge Gaps
Abduro-Ogo et al., 2022	Global		Pb	Pb-MP synergistic and toxicity bioassay	Adsorption and MNP-metal toxicity	Chlorophyll-a fluorescence, MDA content, soluble sugar and protein; (SOD and POD)	<p>“MP aggravated Pb toxicity on Chl-a and SOD activity under the highest Pb concentration”.</p> <p>“MP-Pb toxicity on physio-biochemical traits of submerged macrophytes synergistic and species-specific”.</p>	
Awe et al., 2025	Cape Town, South Africa	Polypropylene (PP), polyethene (PE), polystyrene (PS), cellulose acetate (CA), synthetic rubbers (SR), polyamides (PA), polyethene terephthalate (PET), styrene acrylonitrile copolymer (SAN), Polyurethanes (PURs), polyvinyl chloride (PVC), natural fibre (NF)	As, Cd, Cr, Co, Cu, Ni, Pb, Zn, Se	UATR-IR spectrometry for MPs; ICP-MS for metals	Adsorption	Hydrology	<p>“Dominance of fragmented plastic items indicates riverine input”.</p> <p>“PS exhibited high metal adsorption capacity”.</p> <p>“PVC and fragmented plastics adsorbed high Pb and Cd concentrations”</p>	<p>“Understanding mechanisms of metal accumulation and fate in foam and fragmented plastics”.</p>
Blankson et al., 2025	Ghana	Polyethene (PE), polypropylene (PP), polystyrene (PS), polyester (PES), and cellophane (CP)	Zn, Cu, Pb	FTIR for MPs; AAS for metals		The vector role of MP in metal transfer to aquatic biota	<p>“MPs potentially act as vectors for Pb in fish”.</p>	
Chaukura et al., 2021	Africa	Natural microfibres, Polyether sulphone, Nylon, PVC		Literature review	Adsorption, ingestion		<p>“River hydrodynamics influence the distribution of MPs”.</p> <p>“MPs can adsorb and transport organic and inorganic pollutants in aqueous environments”.</p> <p>MPs contain toxic fire retardants embedded during manufacture”.</p> <p>“Pollutant-laden MPs negatively impact eco-physiological functions and trophic relationships of aquatic microorganisms”</p>	<p>“Environmental fate of MPs”</p> <p>“MP toxicology under environmentally relevant conditions”.</p> <p>“MP ecotoxicity mechanisms to aquatic biota”,</p> <p>“Organic and inorganic pollutant vector role of MPs in aquatic systems”.</p>

Liu et al., 2021	Global	PE, PP, PS, PVC, PA, PET, EVA,	Cd, Pb, Zn, Cr, Cu	Bibliometric analysis	Ecotoxicity	Water quality, biological attributes	“Environmental and biological factors significantly influence n MPs-metals interactions and combined toxicity”.	“Combined effects of MPs and metals on aquatic biota and human health remain largely unknown”.
							“Microbiota are important vectors in MP-metal interactions in aquatic environments”	“Adsorption capacity of metals by MPs and role of biofilms in multiple environmental factors is unclear”.
								“Studies on the ecotoxic effects of MPs at environmentally relevant concentrations relevant concentrations”.
								“The role of microbes in MP-metal interactions is understudied”
								“Long-term processes involved in biofilm formation and their impact on metal bioavailability”.
Liu et al., 2022	Global	Expanded PS, PE, PP, PS, PA, Plastic pellets, resin pellets, PET, PES	Cd, Co, Ni, Pb, Mn, Fe	Literature review	Adsorption, co-precipitation, mass transfer, weathering or ageing effects	pH, DOM, salinity, UV radiation, chemical oxidation, and thermal degradation	“Adsorption of metals onto MPs involves surface diffusion, pore volume diffusion, and adsorption on accessible active sites”.	“Interactions and regularity between different metals and MPs
							“Ageing of MPs is affected by various environmental conditions, residence time of MPs and metal ions present”.	“Effect of natural ageing on the ability of MPs to adsorb metals”.
							“Combined exposure of MPs and metals adversely affects aquatic biota (e.g., microalgae, fish)”	“Potential ecological impact of metal additives leached from MPs”.
								“Field-based bioaccumulation and biotoxicity of MPs adsorbing metals”

Modekwe et al., 2025	South Africa	Polypropylene (PP)	Fe, Ni	Using polysulfone (PSF) membrane infused with waste plastic-derived multi-walled carbon nanotubes (MWCNTs) for mine wastewater treatment	Adsorption kinetics	hydrophobicity, morphology, thermal stability, hydrophilicity	“Incorporating plastic-derived MWCNTs into matrices of PSF polymer significantly enhanced the properties of fabricated MWCNTs-PSF nanocomposite membranes”.	“Flux and rejection of metals increased with MWCNTs loading”.	“Unknown performance when functionalising surfaces of plastic-derived nanotubes with more hydrophilic materials”.
Narwal et al., 2024	Global	Polyethylene, polyethylene terephthalate	Ag, Fe, Al, Mn, Pb, Cu, Zn, Hg	Literature review	Adsorption, co-precipitation, and plastic degradation.	Salinity, pH, dissolved organic matter, particulate matter, temperature	“HMs can influence MP adsorption characteristics and physicochemical processes”.	“MPs act as a carrier source of HMs deposition”	“Understanding the mechanisms of metal adsorption onto MPs and their subsequent toxicity to aquatic organisms”.
							“0.10 wt% MWCNT loading achieved optimal Fe and Ni rejection of 91% and 74%, respectively”.	“Biofilms enhance the adsorption of HMs through reduced hydrophobicity of PE and supply of functional groups that interact with easily accessible metal ions”.	“Fate of HMs-MPs interaction by-products”
							“Adsorption of HMs to MPs is likely influenced by salinity, pH, dissolved organic and particulate matter, temperature, surface properties, polymer type, exposure duration, size, and concentration”	“Combined effects of both pollutants remains unclear”	
							“Exposure to HMs and MPs is potentially detrimental to aquatic biota (e.g., stunted growth and development, decreased reproduction, elevated stress levels, and altered behaviour”	“Effective remediation strategies for MPs-metal complexes in aquatic environments”	

Tumwesigye et al., 2023	Global	PET, HDPE, PVC, LDPE, PP	Al, Cr, Cu, Fe, Mn, Sn, Ti, Zn, Sb, Br, Hg	Literature review			<p>“Studies on MPs as vectors of chemical and biological agents are limited, especially in freshwaters”.</p> <p>“Polymer type, hydrophobicity, shape, functional groups, size, and spatial structure affect MP interactions with metals coupled with environmental factors (salinity, pH, temperature) and hydrological conditions”.</p>	<p>“Insights on MPs as vectors of chemical and biological agents in aquatic systems and associated ecological risks “.</p> <p>“Environmental scenarios of MPs concentration, shape, size, and ageing. To establish the realistic role of MPs as metal vectors”.</p> <p>“Standardised methodologies for quantification and identification of pollutants sorbed onto MPs and associated assemblages”.</p> <p>“Competitiveness of metals orbbed onto MPs under different environmental conditions”</p>
Vetrimurugan et al., 2020	South Africa	PP, rayon (RY), PC, PES, NY, PAN (polyacrylonitrile), PS, PET, LDPE, HDPE	Si, Al, Fe, Ti, Cu, Zn	SEM/EDS, FTIR analysis	Sorption, ageing, weathering, UV radiation, polymer density	Salinity (Na, Cl), K, Al, C, temperature, hydrology	<p>“MPs disintegrated from the primary plastic products used in domestic and industrial activities”.</p> <p>“Presence of different additives used in the production of the primary plastics (C, Si, Fe, Ca, Mg, Na, K, Ti, S, Cu, Zn)”</p>	

Guan et al., 2020	China	Virgin expanded polystyrene (PS)	Cd, Cu, Zn, Ag, Si, Al, Fe	SEM-EDS, FTIR analysis	Modelling metal adsorption kinetics on virgin and biofilm- covered MPs; vector effects of MPs for HM transport	pH, ionic strength, solid materials (suspended particles, surficial sediment, biofilm-covered MPs, virgin MPs)	<p>“MPs act as anthropogenic vectors of metals in freshwaters”.</p> <p>“Biofilm enhances the adsorption potential of MPs, but not as strongly as natural substrates”.</p> <p>“Biofilms alter the adsorption kinetics and mechanisms of trace metals onto MPs”.</p> <p>“MPs enhance exchange rates of metals between water and solids”.</p>
Mvovo et al., 2025	South Africa	PP, PE, PET, PS	Ni, Cu, Fe	FTIR analysis, stereomicroscopy	Spatiotemporal distribution of MPs and adsorption of HMs in a lotic environment		<p>“MPs deposited on the riverbank adsorbed Cu, Ni, and Fe”.</p> <p>“Wet summer season showed a slightly greater MP abundance in surface waters”.</p> <p>“Sediments had a greater abundance during the dry winter”.</p> <p>“Higher MP abundance in sediments observed in the lower sections of the river in the dry winter season”.</p>

3. Results and Discussion

3.1. Plastic Polymer Categories and Associated Metal Species

From Table 1, polyvinyl chloride (PVC), polyethylene (PE), polypropylene (PP), polystyrene (PS), and polyethylene terephthalate (PET) were the most frequently reported across the studies. These polymers were ubiquitous in both laboratory and field studies, which reflects their widespread use in domestic, industrial, and mining-related applications [30,43]. Regionally, our findings align with Nyaga et al. [33], who reported the prevalence of PE, PP, and PET polymers in Africa's aquatic ecosystems. Globally, the findings also concur with Kochanek et al. [44], who reported that approximately 90% of global plastic polymers were PE, PP, PS, and PVC. They further noted that PE, PP, and PET are the most common polymers worldwide. Other polymers identified in the current study included cellulose acetate (CA), synthetic rubber (SR), polyacrylonitrile (PAN), and low- and high-density PE.

Globally, the metals frequently associated with MNPs in aquatic environments include Cr, Pb, Cd, Cu, Ni, Zn, and Fe [45]. However, field studies in SSA mostly reported Pb, Cd, Cu, and Ni, which commonly represent the underlying geochemical signatures of the SSA mining landscapes [40–42]. The geochemical uniqueness arises because major geological formations, such as the Central African Copperbelt, where mining is dominant, are associated with these elements [46–48].

3.2. Mechanisms of MNP-Metal Interactions and The Role of Biofilms

Adsorption and surface complexation emerge as the dominant mechanisms governing MNP-metal interactions across all studies in sub-Saharan Africa. Results from different studies consistently show that polymer type, surface area, crystallinity, and the presence of oxygen-containing functional groups strongly influence metal sorption capacity [24,49]. Moreover, weathering and ageing processes induced by ultraviolet (UV) radiation, thermal degradation, and chemical oxidation enhance metal adsorption by increasing surface roughness, porosity, and polarity of MNPs [40,49]. These observations conform with several global studies on MNP-metal sorption kinetics [50–55]. For instance, Fred-Ahmadu et al. [54] observed that while MNPs showed potential sorption interactions with metals in sediments, there was a higher Al, Fe, Mn and Zn adsorption capacity of foam plastics (PUR, PS, PEVA) compared to hard plastics (PE, PP, PET). Additionally, Adamu et al. [52] noted the influence of structural factors, such as MNP polymer characteristics (e.g., polarity, crystallinity and size) and the ageing process, as well as pollutant properties (e.g., ionic form and hydrophobicity), on contaminant co-exposure and sorption kinetics. In their study, nanoplastics exhibited higher pollutant exchange rates than microplastics due to their larger surface area and direct proximity to polymers. This observation is also supported by Chen et al. [56]. In another study by Khant et al. [53], PS and PE showed greater adsorption affinity for metals in the aquatic environment. The higher attraction depends on the MNP surface properties, water pH, ionic strength, and salinity. According to Zou et al. [57], the sorption affinities of Pb, Cu, and Cd to PVC, LPE and HPE followed the orders $Pb > Cu > Cd$ and $PVC > HPE > LPE$, respectively. In that study, electrostatic interaction and complexation additionally determined the sorption of the three bivalent metal species.

Our findings further indicate that MNPs in aquatic environments are high-surface-area substrates for biofilm formation by microbial communities [58]. Primarily, the production of exopolymeric substances (EPS) during biofilm formation is a critical factor enhancing contaminant adsorption to aquatic substrates, including MNPs [59]. Fundamentally, EPS reduce the hydrophobicity of MNP surfaces while increasing the abundance of carboxyl and ketones, thereby enhancing MNP adsorption potential [60]. Whereas MNP sorption capacity for metals tends to increase with MNP ageing and maturity of the EPS layer [61], the long-term dynamics of metal concentrations on the EPS-covered MNP surfaces remain underexplored [13].

The review also revealed that biofilm-covered MNPs have a greater capacity for metal sorption than virgin plastics, although their adsorption potential remains lower than that of natural substrates, such as sediments, and Fe and Mn oxides [24,27]. Studies by Stabnikova et al. [62] and Haque et al. [63] similarly reported that biofilms increase metal sorption in aqueous environments. In contrast, other studies have observed that metal adsorption by biofilms can inhibit the co-occurrence of certain microbial communities, such as bacteria [64]. This inhibition is primarily due to the complexity of EPS-metal interactions and growth-limiting physicochemical processes [65,66].

Despite their role as secondary metal sinks in a biofilm-dominated environment, MNPs are instrumental not only for metal mobility but also as reactive surfaces for adsorption, concentration and redistribution in aquatic ecosystems [45,67]. In these ecosystems, microbiological processes generate biofilms on substrates and other surfaces, primarily comprised of EPS and microbial community matrix. Guan et al. [27] observed that biofilm-covered plastics exhibited altered adsorption kinetics, which enhanced metal exchange between water and MNP

surfaces. In the same study, the enhancement of MNP adsorption capacity was primarily due to complexation with functional groups in the biofilms, such as amino, carboxyl, and phenyl-OH. These findings are further supported by Wang et al. [68], who reported that surface complexation and electrostatic interactions significantly influenced the adsorption of metal biofilm-coated MNPs.

In mining-impacted Afrotropical lotic ecosystems, high water temperatures and nutrient-rich environments promote rapid biofilm development, potentially increasing metal adsorption by MNPs [69]. However, Liu et al. [49] and Helmann [70] noted that the role of microbiota in regulating metal bioavailability and toxicity remains poorly understood under environmentally realistic conditions.

3.3. Influence of Environmental Drivers on MNP-Metal Interactions

Environmental drivers, such as water chemistry, hydrology, polymer properties, ageing characteristics, and biologically mediated processes, interactively regulate MNP-metal interactions in aquatic ecosystems (Table 1).

Water chemistry is a key regulator of adsorption processes, particularly in metal-rich mining environments. Liu et al. [49] reported the roles of pH, salinity, dissolved organic matter, and co-existing ions in regulating the adsorption of metal ions onto MNPs, e.g., via surface or pore diffusion, and binding to MNP functional sites. Furthermore, the acidic-to-circumneutral conditions associated with mine drainage can enhance metal adsorption and transport by aged plastics. Narwal et al. [24] further highlighted that dissolved and particulate organic matter may directly or indirectly inhibit metal adsorption onto MNPs.

Hydrology strongly controls the retention, distribution and residence time of metals and MNPs in mining-impacted rivers. Stream hydrodynamics influence MNP fragmentation, resuspension, and downstream transport, increasing the surface area for metal adsorption and translocation [30]. For instance, a study characterising beach plastic litter at Woodbridge Island and Derdesteen area, South Africa, indicated that fragmented plastics, produced by physical degradation from fluvial processes, increase the adsorption capacity of MNPs for metals [39]. Additionally, seasonality was evident in the higher abundance of MNPs and the increase in the suspended sediment concentration in Buffalo River, South Africa, during the wet seasons [42]. In mining catchments, these transitional phases often coincide with elevated metal concentrations, where solid-metal complexes, through adsorption-desorption processes, act as secondary pollution reservoirs or sources [71].

MNP polymer characteristics influence metal affinity [72]. Generally, polystyrene (PE) and polyvinyl chloride (PVC) exhibit higher adsorption capacities, particularly for Pb and Cd. In addition, fragmented plastics exhibit higher metal adsorption due to increased surface area [39]. Environmental ageing further enhances adsorption potential. Liu et al. [49] demonstrated that UV radiation, oxidation, and thermal degradation increase surface roughness and the abundance of oxygen-containing functional groups, thereby enhancing the MNP binding capacity for metals. These processes are particularly relevant under Afrotropical climatic conditions, where intense solar radiation accelerates thermal plastic weathering [73,74]. The presence of metal-containing additives embedded during plastic manufacture further complicates the distinction between sorbed and intrinsic metal concentrations [40].

From the synthesis in Table 1, it is critical to note the following:

1. Documented research consistently identifies MNPs as a significant anthropogenic vector for the aquatic transport of metals (e.g., Pb, Cd, Zn, Cu, and Ni) and their subsequent transfer to aquatic biota, including fish, algae, and macrophytes.
2. The interaction between MPs and metals often results in synergistic toxicity. The co-existence of these co-pollutants tends to aggravate physiological and biochemical stress in aquatic biota, including inhibited growth, reduced antioxidant enzyme activity, and altered behaviour.
3. The capacity of MNPs to sequester metals is not static. MNP ageing via UV radiation and weathering, and biofilm formation on plastic surfaces, significantly increase the affinity of MNPs for adsorbing metal ions.
4. Environmental drivers, such as pH, salinity, dissolved oxygen, and temperature, profoundly influenced the fate and distribution of MNP-metal complexes in aqueous matrices. Hydrological dynamics, such as seasonal variations and flow regimes, also determine the intensity of MNP-metal inputs into the aquatic environment.
5. Metal adsorption by MNPs is highly species-specific and polymer-dependent. Certain plastics, such as Polystyrene (PS) and Polyvinyl Chloride (PVC), often exhibit higher capacities for adsorbing specific toxic metals, including Pb, Cd, Cu, and Ni.

3.4. Research Trends on MNP-Metal Interactions in Aquatic Systems of SSA

To gain preliminary insights on research directions regarding MNP-Metal interactions in the aquatic ecosystems, a keyword clustering and co-occurrence network visualisation (Figure 2) was performed on the selected articles using the VOSviewer (ver. 1.6.20) software [75]. Each node in the figure represents a keyword.

The node size reflects the frequency of keyword occurrence, while link thickness indicates the strength of keyword co-occurrence. For instance, “*Heavy metals*” is the largest and most centrally positioned node, confirming it as the dominant research focus and the network’s primary hub. The three most strongly linked keywords are “*heavy metals*”, “*microplastics*”, and “*micropollutants*”. The strong linkage between “*heavy metals*” and “*microplastics*” emphasises their interconnectivity via physicochemical and environmental processes, including adsorption, transport, and fate. Both contaminants are also strongly associated with other “*micropollutants*”, implying the increasing integration of MNPs into the broader emerging micropollutant assessment frameworks in SSA [20].

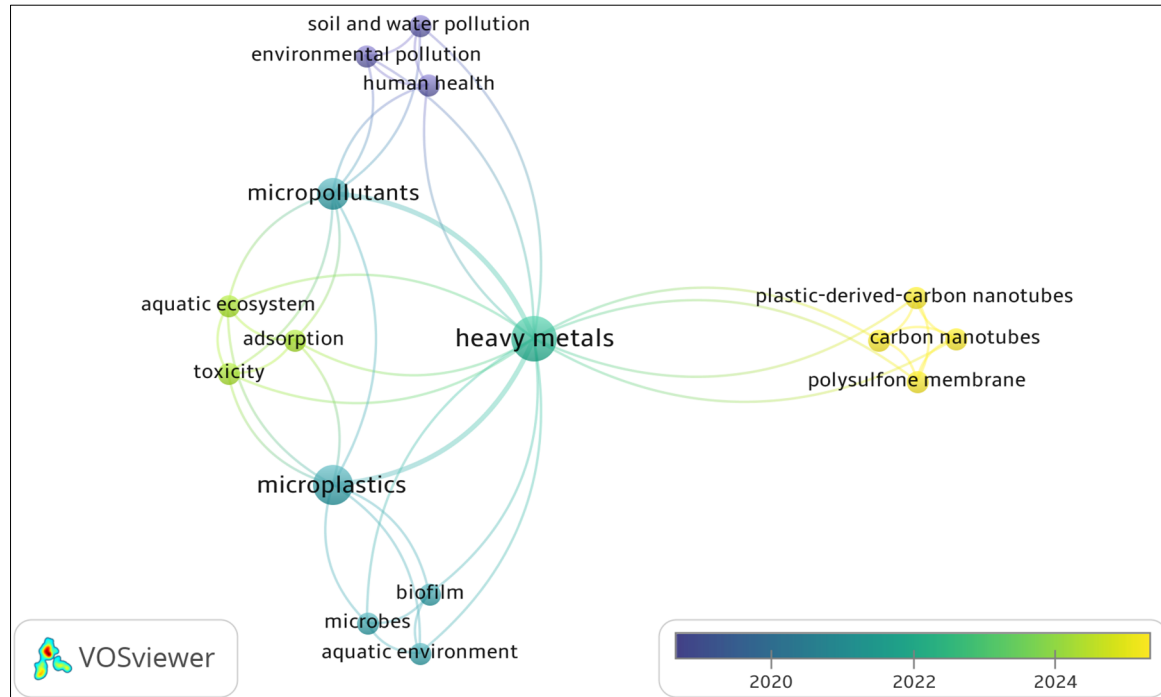


Figure 2. Keyword co-occurrence network and research trends on micro-nano-plastic and metal interactions in aquatic systems of the sub-Saharan Africa mining landscape.

Additionally, Figure 2 shows the average annual progression and focal areas regarding MNP-metal interactions from 2019 to 2025. Early research (2019–2020; blue) is associated with general environmental research themes such as “*environmental pollution*”, “*soil and water pollution*”, and “*human health*”, reflecting broader problem identification and creation of awareness. During this phase, the primary goal was to document the ubiquity of MNPs and metals as independent stressors. This trend reflects the relatively recent emergence of MNPs as contaminants of concern within SSA aquatic systems. For example, Guan et al. [27] noted that while there was awareness of increasing plastic production and use globally (projected to increase from 464 to 884 Mt between 2020 and 2050 [29]), the specific role of MNPs as vectors for other co-contaminants was only beginning to gain regulatory and public attention in SSA.

From 2021 to 2023 (green), there was an apparent shift towards context-specific emerging pollutant themes and mechanistic processes, including “*microplastics*”, “*micropollutants*”, “*adsorption*”, “*toxicity*”, and “*aquatic ecosystem*”. This period marked the deepening understanding of the “Trojan horse” mechanism, in which MNPs serve as vectors for heavy metals in aquatic systems via unique surface properties [76]. Global research during this time also examined the significance of biofilms. The development of the “plastisphere” alters the morphology and physicochemical properties of MPs, typically enhancing their adsorption capacity compared to virgin polymers [27]. For instance, Tang et al. [77] observed that the “plastisphere” reduces the buoyancy and movement of MNPs by increasing their density.

Furthermore, the “plastisphere” enhances the adsorption of co-micropollutants onto MNPs, shifting from intraparticle diffusion to film diffusion. In this regard, the collective metabolism of the “plastisphere” short-circuits natural biogeochemical cycles, introduces and enhances novel pollutant vectors, such as MNPs [78,79]. In essence, via the “microplastics cycle”, the plastisphere paradoxically functions as both a transport vector and a transformation reactor [80].

More recently (2024–2025; yellow), specialised and solution-oriented keywords such as “*carbon nanotubes*”, “*plastic-derived carbon nanotubes*”, and “*polysulfone membrane*” have emerged, suggesting increased awareness and

expanding interest in the environmental implications of MNP-metal interactions, transformation products, and development of advanced materials and nanotechnologies applicable to MNP-metal pollution remediation in SSA [80]. As such, research on MNP-metal interactions is advancing technologies that onboard the synergistic effects of the MNP-metal complex in the aquatic environment [76]. According to Tripathi et al. [81], studies have been conducted to determine efficient techniques for alleviating global MNP and metal pollution. For MNPs, for instance, methods range from physical (e.g., adsorption using adsorbents such as carbon nanotubes and biochar, filtration, and flotation) to chemical (advanced oxidation and thermal degradation) and bioremediation (enzymatic, microbial, and phytoremediation) [81]. Unfortunately, knowledge gaps still exist between simulated laboratory experiments and real-world environmental conditions, as well as material safety [82].

Importantly, the keyword co-occurrence network also exposes several critical knowledge gaps. Keywords related to “*trophic transfer*”, “*bioaccumulation*”, “*human exposure*”, “*risk assessment*”, and “*long-term monitoring*” appear weakly connected or underrepresented, suggesting limited research attention toward ecosystem-scale and public health implications of MNP-metal interactions in SSA. Similarly, the infrequent or absent use of terms linked to “*climate change*”, “*hydrological variability*”, and “*catchment-scale dynamics*” underscores the insufficient integration of environmental variability into current research frameworks, despite the strong influence of seasonal hydrology and tropical climatic conditions on pollutant transport in African river systems. The network therefore reveals that most SSA studies remain localised, short-term, and observational, with comparatively few addressing the long-term ecological consequences, environmentally realistic exposure scenarios, or multi-stressor interactions.

Overall, the keyword co-occurrence analysis illustrates the rapid evolution of research on MNP-metal interactions. The network also highlights a substantial disparity between globally advancing mechanistic studies and the limited scope of current research available in SSA. In retrospect, the analysis underscores the urgent need for integrated regional studies involving ecotoxicology, environmental ecotoxicology, and human health risk assessments. The multifaceted approach will provide a better understanding of the environmental fate and risks of exposure to MNP-metal complexes in the aquatic systems of SSA.

3.5. MNP Vector Role and Implications for Ecosystem and Human Health in SSA

In Table 1, studies indicate that MNPs are vectors that facilitate metal transfer to aquatic biota, thus potentially enhancing bioavailability and toxicity [9,83]. Environmentally driven co-occurrence of MNP and metals in aquatic systems can exacerbate biochemical toxicity to aquatic biota. Under such circumstances, MNPs can act as vectors that translocate metals to biota [8,13].

Synergistic and species-specific toxic effects have occurred in submerged macrophytes and fish, particularly under high metal concentrations [38,41]. For example, Abduro-Ogo et al. [38] demonstrated the synergistic toxicity of Mn and Pb in submerged macrophytes, which expressed reduced chlorophyll a content and altered antioxidant responses. However, other studies, including Martín et al. [84], have also reported both synergistic and antagonistic effects (including reduced toxicity) from co-exposure to MNP-contaminant complexes on aquatic biota. However, Bastante-Rabadán and Boltes [85] argue that the synergistic effects tend to dominate in a multi-contaminant exposure environment. At higher trophic levels, MNPs can act as vectors for Pb transfer into fish, raising concerns for human health in SSA inland fisheries [41]. Similar to Martín et al. [84], our findings also suggest that MNPs function as dynamic vectors that can intensify metal exposure across trophic levels in mining-impacted freshwater systems.

Some studies have attempted to demystify the impacts of MNP-metal co-exposure in aquatic systems. For instance, Chen et al. [86] studied the impact of co-exposure to Pb-NP on the decomposition of stream litter and microbial communities in the Donghe River, China. A co-exposure to 1 mg/L and 10–100 µg/L NP produced non-monotonic, concentration-dependent effects on enzymatic activities and microbial diversity. Similarly, in another study, aged MNPs were reported to decrease the bioavailability of co-occurring Cd to the microalga, *Chlorella vulgaris*, from 85% to 27.6% and 32%. This antagonistic effect caused cell damage, coupled with increased intracellular malonaldehyde (MDA) and superoxide dismutase (SOD) levels [87].

From Figure 2, three interconnected research dimensions emerge: (i) contaminant interactions (“*microplastics*, *heavy metals*, *micropollutants*”), (ii) environmental processes (“*biofilm*, *microbes*, *aquatic environment*, *toxicity*”), and (iii) emerging materials science (“*carbon nanotubes*”, “*plastic-derived carbon nanotubes*”, and “*polysulfone membrane*”) and advanced pollutant treatment approaches (nanotechnology). The strong links between plastics, metals, and biofilm-related terms imply that microbial colonisation enhances metal sorption and mobility, thus increasing exposure risks within aquatic ecosystems. Furthermore, connections

extending toward “human health” indicate potential downstream implications through contaminated water and food-web bioaccumulation and biomagnification.

The co-occurrence of MNPs and metals in aquatic environments represents an emerging environmental and potential human health concern in SSA [12], where mining, rapid urbanisation, and inadequate waste management compound the high dependence on aquatic ecosystems for agro-industrial and municipal uses. Current evidence indicates that MNPs can be potential vectors for metal transport, bioavailability, and biouptake in aquatic environments. This vector role amplifies the existing exposure pathways, exacerbating environmental and potential direct and indirect human health risks [24,88,89].

Figure 3 conceptualises the co-occurrence, fate and associated environmental and potential human health risks of MNPs-metal interactions in aquatic environments. Micro- and nano-plastics originate from both primary sources (e.g., industrial pellets and microbeads) and secondary ageing (e.g., photodegradation, thermodegradation, and biodegradation) [44]. MNPs then enter the aquatic system via terrestrial runoff, wastewater discharge, and atmospheric deposition [90]. On the other hand, metals enter aquatic systems naturally via processes such as weathering and mineralisation, and from anthropogenic activities, including mining, agro-industrial processes, and municipal wastewater effluent and surface runoff [91].

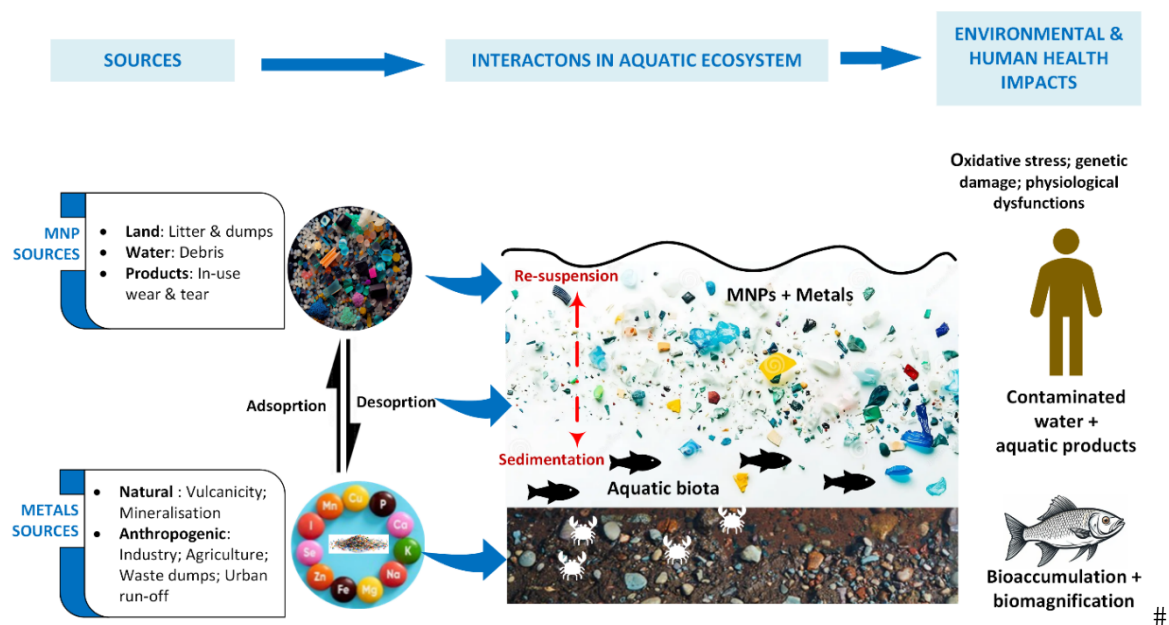


Figure 3. Interaction between metals and MNPs in aquatic ecosystems and associated environmental and human health impacts.

As illustrated in Figure 3, the interaction between MNPs and metals primarily depends on sorption-desorption processes [55]. Additionally, the formation of the biofilm matrix on MNP surfaces accentuates metal sorption, MNP aggregation and deposition to the benthic environment [92]. However, hydrodynamic perturbations such as flooding or turbulence can resuspend and redistribute MNP-metal aggregates within aquatic systems [92]. As such, MNPs in aquatic environments emerge more as transient carriers than metal repositories, in contrast to sediments [55,58,92].

The co-occurrence of MNPs and metals has significant ecological implications, often resulting in either synergistic or non-additive toxic effects. For instance, Yang et al. [93] reported that MNPs enhance the bioavailability of metals to aquatic organisms. Conversely, MNP-bound metals can exacerbate oxidative stress and cellular damage to aquatic biota [93]. The combined effects result in impaired growth, reduced reproductive success, and physiological dysfunction in aquatic biota, including fish and invertebrates [94]. Additionally, co-contamination can disrupt the functioning of microbial communities, the structure of aquatic food webs and nutrient cycling [95]. Moreover, Upadhyay et al. [95] highlighted the potential transfer of MNP-metal complexes via ingestion by aquatic biota, facilitating their entry into the aquatic food webs, bioaccumulation, biomagnification, and toxicity through subsequent trophic levels [96].

Human exposure to MNP-metal complexes may primarily occur through the consumption of contaminated water and key aquatic organisms (e.g., fish and shellfish). For instance, in Europe, mollusc consumers may ingest up to 11,000 MNP particles per year [97]. Once internalised, MNPs can translocate into the circulatory system, secondary organs, and across critical barriers, including the placental and blood-brain barriers [97]. The potential

human health risks associated with such exposure may include oxidative stress, inflammation, genotoxicity, and endocrine disruption [94,98].

Studies suggest that MNPs may enhance the uptake of metals in the gastrointestinal tract, increasing systemic exposure and associated health risks [99]. Nanoplastics are of particular concern due to their ability to cross biological membranes into tissues and the associated potential toxicity [100,101]. The co-occurrence of metal and MNPs may create conditions for enhanced toxicity to aquatic biota and secondary toxicity to consumers of aquatic products, including humans.

In sub-Saharan Africa (SSA), inland fisheries constitute a primary source of protein and livelihood for many communities, including those in mining-intensive regions [102]. MNPs adsorb and concentrate metals, facilitating their potential biomagnification and trophic transfer in aquatic webs, thereby enhancing secondary toxicity [55]. For instance, Blankson et al. [41] demonstrated that MNPs may serve as vectors for Pb accumulation in fish tissues, thereby increasing the susceptibility of indirect human exposure to Pb toxicity. In addition, fragmented high-density, sediment-associated MNPs enriched in metals such as Pb and Cd accumulate in depositional zones and are likely to increase exposure of benthic organisms to metal toxicity [39,42]. Ingestion of exposed benthic biota by secondary and tertiary consumers may elevate dietary co-contaminant exposure [103]. Given the established synergistic neurotoxic, nephrotoxic, and developmental effects of metals such as Pb, Cd and MNPs [104,105], the synergistic effects of MNP-metal dietary exposure represent a significant but poorly quantified emerging potential health risk concern in SSA.

More than 50% of the SSA population relies on untreated or minimally treated freshwater sources for domestic and other uses [106]. Metal-laden plastics suspended in these waters can increase the particulate metal fraction and contribute to chronic ingestion. Evidence from Liu et al. [49] indicates that both aged and biofilm-covered plastics exhibit enhanced metal adsorption, suggesting that environmental MNPs may function as persistent reservoirs of bioavailable metals. In fact, documented Pb toxicity in the SSA mining landscape, including Nigeria and Zambia, provides a vivid case of the probable future threat of MNP-metal-enhanced exposure in drinking water systems [107–109]. Furthermore, MNPs may bypass conventional potable water treatment systems [58]. Although empirical data on MNP-mediated co-contaminant exposure in SSA remain limited, toxicological studies outside SSA suggest that MNP-metal complexes may exacerbate oxidative stress and inflammatory responses, leading to long-term cardiovascular and neurological dysfunctions [110,111].

4. Conclusions, Limitations and Future Perspectives

In this review, we synthesised global and emerging regional insights on the potential role of MNPs in accelerating aquatic metal transport and pollution across the SSA mining landscape. While global studies provided an in-depth mechanistic understanding of MNP-metal vector dynamics, SSA studies focused primarily on pollutant-related field observations with less emphasis on the role of MNPs as vectors of aquatic metal transport.

Nevertheless, we established that MNPs have a high capacity for metal sorption and transportation, which can strongly determine the environmental fate and mobility of legacy mining pollutants in aquatic environments. The role of MNPs as metal transporters is further influenced by polymer characteristics (such as size, morphotype, and abundance), environmental factors (such as pH, salinity, temperature, photoperiodicity, and hydrology) and biological factors (e.g., biofilm characteristics and community structure).

The review further highlights that approximately 90% of global plastic polymers comprise PE, PP, PS, and PVC; findings that align with those documented across SSA. Additionally, the synthesis shows that incorporating 0.10 wt% plastic-derived carbon nanotubes into membranes during advanced water treatment processes can enhance Fe and Ni removal to 91% and 74%, respectively. Studies indicate that metal sorption by MNPs follows specific orders, such as Pb > Cu > Cd for certain MNP categories, providing a quantitative basis for risk assessment.

Despite the emerging evidence that MNPs act as vectors for metal transport and contamination in aquatic environments, knowledge gaps were identified for future research directions in SSA, including: (1) a poor understanding, in the presence of MNPs, of metal adsorption-desorption kinetics, bioavailability and trophic implications at catchment-scale; (2) insufficient integration of microbial processes and the role of biofilms on MNP-metal interactions, metal transport and ecotoxicity to aquatic biota, (3) the extent to which MNP-bound metals desorb within organisms and contribute to internal metal burdens under environmentally realistic conditions, (4) lack of standardised analytical methodologies for quantifying metal adsorption on MNPs.

From the review, emerging evidence across SSA indicates that the direct link between MNP-metal complexes and human health risks are largely unknown. As such, current assessments of potential human health risks in SSA should be interpreted cautiously and regarded as emerging rather than conclusively established events. However,

currently available evidence supports the need for precautionary monitoring and further interdisciplinary research on dietary exposure, trophic transfer, bioaccumulation, and the long-term toxicological implications of MNP-metal interactions in aquatic ecosystems in SSA.

4.1. Limitations of the Review

A key limitation of this mini-scoping review is the relatively narrow evidence base available from sub-Saharan Africa. In Sections 2.4–2.6, from the 330 records initially identified, only 12 studies met the eligibility criteria for an in-depth synthesis, with most studies concentrated in a few countries in Southern and West Africa. Subsequently, the current understanding of MNP-metal interactions in SSA remains geographically uneven and is largely based on localised field observations. Therefore, while this review identifies important emerging patterns regarding MNPs as potential vectors of metal transport and likely associated ecological and human health risks, these findings should not be interpreted as definitive for all SSA aquatic ecosystems. Rather, the outputs represent currently available evidence of MNPs as metal transport vectors and highlight plausible risk pathways. Furthermore, the emerging concerns require validation through broader geographical coverage, long-term monitoring programmes, and region-specific ecosystem-level studies under environmentally realistic conditions.

4.2. Future Perspectives

In light of the above, the following future research directions are recommended:

- (1) Methodological standardisation: There is an urgent need for standardised analytical protocols to identify and quantify metals specifically sorbed onto MNPs versus those intrinsic to the polymer.
- (2) Mechanistic studies on MNP-metal-biofilm interactions: Future research should integrate the role of microbial processes and biofilms, as they significantly alter MNP-metal adsorption kinetics and bioavailability but remain poorly resolved.
- (3) Catchment-scale MNP-metal dynamics in aquatic ecosystems: Research should shift from sporadic localised observations to long-term catchment-scale studies that track the transport, trophic transfer, competitive adsorption of multiple metals, and environmental and potential human health risks from dietary exposure.

Future multifaceted studies integrating environmental monitoring, ecotoxicology, and public health investigations are particularly necessary to quantify environmentally realistic exposure thresholds for MNP-metal complexes and associated health outcomes.

Author Contributions

K.O.O. and S.S. contributed equally to the conceptualisation, data curation, original drafting, reviewing, and editing of the manuscript. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

Publicly available data from the references cited in this manuscript were used in this review. No new data were generated in this manuscript.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

Appendix A. Boolean Operators for Article Search in Scopus and Web of Science

Appendix A.1. Scopus

("microplastics" OR "nanoplastics" OR "plastics") AND ("metals" OR "heavy metals" OR "trace metals" OR "sorption" OR "transport") AND ("vector" OR "carrier") AND ("mining" OR "mining landscapes") AND ("freshwater" OR "rivers" OR "streams") AND ("Africa") AND PUBYEAR > 2019 AND PUBYEAR < 2025 AND (LIMIT-TO (AFFILCOUNTRY, "South Africa") OR LIMIT-TO (AFFILCOUNTRY, "Nigeria") OR LIMIT-TO (AFFILCOUNTRY, "Kenya") OR LIMIT-TO (AFFILCOUNTRY, "Ethiopia") OR LIMIT-TO (AFFILCOUNTRY, "Uganda") OR LIMIT-TO (AFFILCOUNTRY, "Tanzania") OR LIMIT-TO (AFFILCOUNTRY, "Cameroon") OR LIMIT-TO (AFFILCOUNTRY, "Zambia") OR LIMIT-TO (AFFILCOUNTRY, "Sudan") OR LIMIT-TO (AFFILCOUNTRY, "Mozambique") OR LIMIT-TO (AFFILCOUNTRY, "Malawi") OR LIMIT-TO (AFFILCOUNTRY, "Botswana")) AND (LIMIT-TO (DOCTYPE, "re") OR LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (LANGUAGE, "English"))).

Appendix A.2. Web of Science (WOS)

Query link: <https://www.webofscience.com/wos/woscc/summary/b0b1795a-4ab8-420b-b8a8-ebbf953ff53-01b3b9f62e/relevance/1>

TS = (microplastics OR nanoplastics OR plastics) AND TS = (metal* OR heavy metal* OR trace metal* OR trace element*) AND TI = (vector* OR carrier* OR transport*) OR TI = (freshwater* OR surface water* OR inland water* OR aquatic* OR river* OR lake* OR wetland*) AND CU = (Africa OR sub-Sahara*) and Article or Review Article (Document Types) and Article or Review Article (Document Types) and Environmental Sciences Ecology (Research Areas) and Environmental Sciences Ecology or Water Resources or Biodiversity Conservation (Research Areas) and BOTSWANA or CAMEROON or ETHIOPIA or KENYA or MOZAMBIQUE or NIGERIA or TANZANIA or UGANDA or ZAMBIA or ZIMBABWE or SOUTH AFRICA (Countries/Regions).

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