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Nature-based Solutions to Wastewater Treatment of Microplastics: Technologies, Challenges, and Prospects

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Review

Nature-Based Solutions to Wastewater Treatment of Microplastics: Technologies, Challenges, and Prospects

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Abstract

Microplastic pollution has emerged as a serious societal concern, posing risks to the environment, human health, and economies. Conventional wastewater treatment processes remove microplastics at various levels from physical removal (primary), biological degradation (secondary), and contaminant-specific removal (tertiary treatment). Nature-based solutions (NbS) offer an ecologically friendly alternative that utilizes nature to wastewater treatment. This study provides an overview of the sources and impacts of microplastic pollution, NbS technologies for microplastic removal, challenges and prospects in utilizing NbS, and the knowledge gaps. Primary sources of microplastics are intentionally produced at microscopic sizes, while secondary sources originate from the disintegration of larger plastic debris. Among the NbS technologies are constructed wetlands (horizontal subsurface flow, vertical flow, surface flow, microbial fuel cells, multistage) with up to 100% efficiency; green infrastructures (bioretention systems, green walls, permeable pavements, retention ponds) with up to 99% efficiency; macrophytes and microphytes with up to 94% microplastic removal rate. Despite the ecosystem services provided by NbS, they are challenged by the decrease in efficiency in removing other contaminants, detection and evaluation of NbS performance, and non-technical factors (operations and maintenance, public acceptance, climate risks, financing). The findings present insights on further research and implications for the successful adoption of NbS to wastewater treatment.

Keywords: constructed wetlands; microplastics; nature-based solutions; water resource management; wastewater treatment

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1. Introduction

Plastic pollution is one of the major problems the world is facing today. Due to its significant contribution to both human well-being and the economy through various applications, more than 430 million tonnes of plastic are produced annually and are expected to reach 736 million tonnes by 2040 [1]. However, about two-thirds of plastics are short-lived products that soon become waste, with a large portion ending up in rivers, lakes, and oceans. filling the ocean and, often, working their way into the human food chain [2]. This pollution disrupts natural processes, harms wildlife, and contributes to climate change [1]. Microplastics are among the most damaging and long-term contributors to this pollution crisis. Microplastics are polymers with a diameter smaller than 5 mm that pose a growing threat to human and planetary health [1,3]. They come from various sources and processes, which, if not managed properly, microplastic pollution will lead to severe and widespread ecological, health, and economic consequences.

Various levels of treatment processes are utilized to remove microplastics. The removal rates of these processes are summarized in Table 1. The primary treatment focuses on the physical removal of large microplastics, such as fragments and beads, solids, and other floating materials from wastewater [4]. This includes sedimentation, which settles large solids at the bottom of the primary tank, forming primary sludge, coagulation, which destabilizes microplastics, and flocculation, which promotes the clumping of these destabilized particles into larger flocs that can be easily removed through settling [5,6]. This process can remove up to 98.4% of microbeads, 71.8% of fibers, and 62.7% of other microplastics [5–8]. Secondary treatment focuses on biologically degrading soluble organic compounds and suspended solids that survive the primary treatment such as trickling filters, activated sludge processes, intermittent sand filters, and stabilization ponds [9–11]. This stage is particularly effective for removing larger microplastics (2–5 mm), but less efficient on fibers and smaller particles (<500 μm) [12,13]. Particularly, it can remove up to 100% of microbeads and 96.9% or other microplastics, but only up to 57.8% of fibers [5,6,14,15]. Tertiary treatment is an advanced stage that targets the removal of specific contaminants that primary and secondary treatments cannot eliminate. Among the tertiary treatment techniques are microfiltration, ultrafiltration, chemical coagulation, and advanced oxidation processes [5,6,16,17]. These methods include dissolved air flotation, membrane bioreactors, disc filters, and rapid sand filtration [12,17–19]. These techniques can remove up to 99.9% microbeads, 57.7% fibers, and 95% other microplastics [12,17,20,21]. Moreover, there are advanced technologies used to remove microplastics, including nanotechnologies, advanced oxidation processes, and hybrid systems that combine different methods, such as membrane bioreactors and ultrafiltration/reverse osmosis, coagulation and ozonation, and constructed wetlands [18,19,22].

Table 1. Microplastics removal rate for different levels of wastewater treatment.

Treatment Technology	Microbeads	Fibers	Other Microplastics	Sources
Primary Treatment	> 98.4%	> 71.8%	> 62.7%	[5–8]
Secondary Treatment	> 100%	> 57.8%	> 96.9%	[5,6,14,15]
Tertiary Treatment	> 99.9%	> 57.7%	> 95%	[12,17,20,21]

Despite the efficiencies of conventional wastewater treatment processes, they also face several limitations, leading to the need for advanced treatment techniques and other alternatives. For instance, residues removed after the treatment process may accumulate in soil and affect terrestrial ecosystems, posing risks to the environment [19]. They can also escape wastewater treatment plants and enter the environment, which can eventually pose environmental and human health risks [23]. Moreover, these technologies may be costly, particularly to communities in developing countries that lack the financing mechanisms and expertise in operating wastewater treatment plants [24].

Another promising alternative is nature-based solutions (NbS) to treat wastewater. NbS are innovative approaches that leverage natural processes to address various socioeconomic and environmental challenges, including the treatment of wastewater. In terms of water management, NbS are effective in managing water quality, reducing flood risks, and addressing droughts through methods like wetland restoration and sustainable agriculture [25]. With an eco-friendly and cost-efficient approach, various NbS technologies are utilized in wastewater treatment [26,27]. Furthermore, NbS are also used to remove microplastics in wastewater and other bodies of water [28].

Several studies discuss the role of NbS technologies in removing microplastics. For instance, Li, et al. [29] evaluated the tolerance and efficiency of different submerged macrophytes for optimization as NbS for operational aquatic microplastic retention practice. Cole, et al. [30] analyzed the efficiency of mussels as biofilters to remove waterborne microplastics in aquatic ecosystems and return them into biodeposits to be further captured and removed. Falkenberg, Cornet and Joyce [28] also utilized mussels to eliminate microplastics and transfer them into biodeposits, which can be transported to other parts of benthic areas, or collected and removed from the environment. In another study, Büngener, et al. [31] analyzed a large pilot-scale green wall as NbS to treat greywater (a mix of water collected from washing machines, toilet showers, kitchen sinks, baths, and synthetic greywater) and

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its potential for microplastics removal. Moreover, Mancini, et al. [32] investigated the role of an interspersed lagoon surrounded by aquatic plants, a constructed wetland (CW), in retaining microplastics and found that CWs trap microplastics from several sources.

With the growing number of studies in NbS for microplastics removal in wastewater, various literature reviews have already been conducted. For instance, Zhang, et al. [33] presented a comprehensive review of the microplastics removal through CWs and how their accumulation affects the treatment performance for other nutrients such as nitrogen, phosphorus, and carbon. In another review, Ahmad, et al. [34] analyzed different green infrastructure technologies for sustainable stormwater management, such as permeable pavements, CWs, bioretention systems, and stormwater ponds for effectively removing microplastics. Moreover, García-Haba, et al. [35] reviewed the role of sustainable drainage systems, including sedimentation-based systems such as wetlands or ponds, filtration-based systems such as bioretention cells or gardens, and permeable pavements as NbS to microplastic pollution from urban runoff. Meanwhile, Fakhri, et al. [36] reviewed the utilization of bio-based materials, such as bioflocculants, modified biopolymers, and bio-based aerogels, in capturing and eliminating microplastics, with particular focus on mechanisms, effectiveness, practicality, and interactions under various environmental conditions. Most literature either focuses broadly on NBS for wastewater, technological solutions for microplastics, or NbS for microplastics on water resources, but rarely connects them systematically.

This study aims to contribute to the literature by presenting an overview of NbS technologies for the treatment of wastewater containing microplastics. Specifically, the study aims to (1) discuss the sources of microplastic pollution on the bodies of water and its impacts on humans and the environment; (2) review the NbS technologies for microplastic removal; (3) analyze the challenges in adopting NbS technologies and their prospects for utilization; and (4) identify the knowledge gaps, which can serve as a basis for future research directions. The findings also present several insights for policymakers, practitioners, project planners, and local communities on the sustainable implementation of NbS towards achieving SDG 6 (Clean Water and Sanitation), SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), SDG 14 (Life Below Water), and SDG 15 (Life on Land).

2. Sources and Impacts of Microplastic Pollution

2.1. Sources of Microplastic Pollution

Microplastic pollution is a significant environmental issue with various sources contributing to its widespread presence in marine, freshwater, and terrestrial ecosystems (see Figure 1). The sources of microplastics can be categorized into primary and secondary sources. Plastics that are intentionally produced at microscopic sizes (< 5mm) are termed primary microplastics, while small plastic fragments that originate from the disintegration of larger plastic debris are secondary microplastics [37].

The most common source of microplastic pollution from primary sources are clothing and textiles. For instance, microfibers from laundry sewage, fishery activities, and waste textiles dominate other plastic types in more than 65% of samples collected from various water sources such as domestic sewers, surface water, sediments, and effluents of treatment plants [38]. Another source of microplastic pollution is the vehicle tire wear or the plastic fragments from mechanical abrasion of car tires on pavements that are washed by rain, snow melt, and street cleaning into natural and municipal drainage systems [39]. This contributes from one-third to half of microplastics unintentionally released into the soil, aquatic resources, and a small percentage becomes airborne [40]. Personal care, cosmetics, and beauty products are another source, which are usually made up of thermosets, thermoplastics, and silicones used as skin conditioners, emulsion stabilizers, film formers, viscosity regulators, and several other uses [41]. Microplastics are added to different products, including rinse-off (whitening products, hair-coloring and -nourishing products, shampoos, shower gels, and soaps) and leave-on (lotions, makeup, lip care, deodorants, sun care, hair-care, and nail-care products) cosmetics [41].

Microplastics from paints and coatings are another source of pollution that, despite their prevalence, are often excluded from microplastics audits [42]. Paint particles from the land come from damaged or deteriorating coatings on the built environment, roads, and establishments that are transported to the different bodies of water through runoff, wastewater, and atmospheric deposition. On the other hand, paint particles in the ocean come from marine vessels and the blue economy industry [43]. Moreover, plastics that are created through the polymerization of by-products from fossil fuels are liquified at high temperatures and undergo several processes to produce various shapes of plastic products. These processes release microplastics to wastewaters, which will eventually drain down to different bodies of water [44].

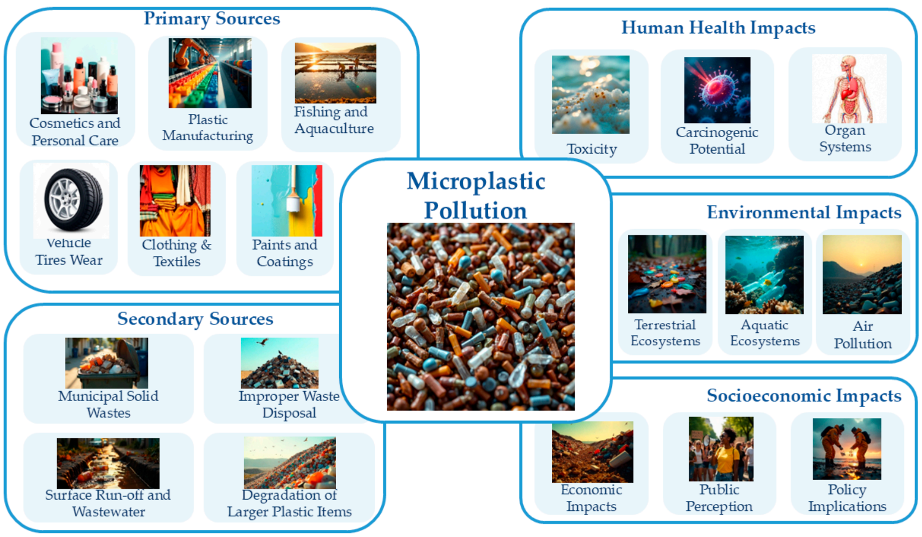

Figure 1. Sources and impacts of microplastic pollution.

In terms of secondary sources, microplastic pollution comes from municipal solid waste (MSW) and landfills. A study revealed a notable concentration of microplastics on the fine fraction of MSW, with the predominance of microplastics smaller than 1 mm (80%), indicating a high tendency to leak from treatment systems and contaminate terrestrial ecosystems, including agricultural soil [45]. Another study found that rainfall concentrates microplastics in the landfill leachates infiltrating the surrounding landfill groundwater [46]. Weathering of plastic wastes in the landfill generates microplastics, which can be transported into the landfill leachate and seep into the soil and groundwater. Without proper protection and management, conventional landfills can be sources of microplastics and other pollutants that are harmful to the surrounding environment, especially groundwater [47]. While recycling of MSW reduces plastic pollution, mechanical recycling processes without wastewater treatment may result in higher emissions of microplastics, posing risks to the surrounding aquatic environments [48].

The combination of weathering and natural hazards is another secondary source of microplastic pollution. Typhoons, hurricanes, monsoons, heavy rains, and flash floods significantly contribute to microplastic pollution through surface runoff and wind transport. Particle redistribution caused by agitated waves and fragmentation under intense abrasion forces is further exacerbated by severe weather conditions that have the potential to scatter larger and more diverse types of microplastics [49]. Meanwhile, microplastics from domestic wastewater, industrial effluents, and stormwater that are treated in municipal wastewater treatment plants contribute to 25% of microplastics in the oceans [50]. The study also found that American and Canadian households dispose of an average of 533 million microfibers annually from laundry into water and wastewater systems [50]. This is supported

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by another study highlighting that the untreated wastewater from laundry contained 10,029±1421 microfibers per liter and that 1 kg of polyester-cotton blend fabric can generate 336,833 microfibers per wash. These values were reduced to 191.5 ± 109.4 microfibers per liter and 6367 microfibers/kg polyester after treatment, implying an impressive efficiency of 98.09% microfiber removal from wastewater [51]. On the other hand, cotton and wool, and other sources of microplastics such as acrylic, polyester, polyamide, polypropylene, and viscose/rayon were identified in the inflow and outflow samples in textile wastewater treatment plants, which may drain into the sewers and then pollute the receiving bodies of water [52].

2.2. Impacts of Microplastic Pollution

Microplastic pollution has become a challenging societal and environmental issue due to its pervasive presence in various ecosystems and adverse impacts on humans and the environment. For instance, in textile industries, manufacturing processes (e.g., cutting and sewing) contribute to a considerable amount of particulate pollution (fine particles and microfibers) accumulated in a working environment with poor ventilation [53]. They can also enter the human body systems through ingestion of food, including dairy products, honey, salt, seafoods, drinking water, and air, posing severe health risks [52]. Microplastics can affect body systems, such as the cardiovascular, respiratory, neurological, gastrointestinal, immunological, and reproductive systems [54].

Inhalation of microplastic fibers, particularly in working areas with high levels fiber contamination, can lead to respiratory discomfort, which reflects inflammatory responses in the airways and interstitium [55]. Due to their small size, these particles pass through the body's natural defenses and enter the alveoli in the lungs, which causes respiratory inflammation and tissue damage such as asthma, chronic bronchitis, and even lung fibrosis [53]. Meanwhile, microplastic exposure to the gastrointestinal tract is linked to the ingestion of food and water that are contaminated with microplastics. Initial exposures may cause inflammation, dysbiosis, constipation, as well as alteration in intestinal absorbency, while prolonged exposures may result in chronic inflammation, such as irritable bowel syndrome and inflammatory bowel disease [54]. Microplastics can also spread in the cardiovascular system, which causes cardiac toxicity and leads to inflammation, oxidative stress, and pyroptosis. These may further contribute to heart disease and stroke [56]. Microplastics can also elicit immunological reactions within the body. They can trigger excessive inflammation or change immune responses, causing the body to be more susceptible to infections or autoimmune conditions. These include autoimmune disorders and immunosuppression [53,54]. They can penetrate physiological barriers and bypass the blood–brain barrier, leading to damage in the central nervous system. These damages may result in neurodegenerative diseases such as Parkinson's, Alzheimer's, multiple sclerosis, and amyotrophic lateral sclerosis [57]. Moreover, microplastics inhibits the neuroendocrine system, which can affect the production of sex hormones via the hypothalamic–pituitary–gonadal axis and reproductive health, such as impaired spermatogenesis in males as well as dysfunctions in the placenta, uterus, and ovary, in females [54].

Microplastics affect the environment, particularly terrestrial and aquatic ecosystems. Weathering of microplastics through chemical, mechanical, and ultraviolet radiation alters their properties and characteristics, forming finer fragments [58]. These fragments interact with soil components, such as minerals, organic matter, and microorganisms, resulting in different levels of toxicity. While they tend to accumulate in the upper soil layers due to their size, bioturbation caused by earthworms and other organisms carries these particles into the deeper parts of the soil [59]. The contamination of soil with microplastics affects its physical, chemical, and biological properties and influences the functions and structures of soil microflora, causing serious damage to the agricultural soil [60]. Any microplastic pollution in air, water, and soils can eventually be transferred to livestock such as ruminants, aquaculture, and poultry, causing changes in their intestinal microbial population and other internal organs, resulting in biochemical changes, structural destruction, malfunction, and diseases [61]. Microplastics from land- and sea-based activities, particularly in highly populated urbanized and industrialized regions with considerable impact of anthropogenic activities on the

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environment, can also contaminate mollusks [62]. These mollusks are important pathways for transporting microplastics to larger organisms in food chains such as fisheries and marine mammals that can drastically reduce their population size and, in worst cases, lead to the extinction of vulnerable populations [63,64]. When contaminated mollusks are ingested by these animals, the toxic and mechanical effects of microplastics may result to several problems, such as reduced food intake, suffocation, behavioral changes, and genetic alterations [3].

Microplastic pollution can also impact the socioeconomic conditions of communities. Blue economy industries such as ecotourism and fishing are negatively affected leading to economic losses due to the contamination of marine environments, limitation of several aquatic tourism activities, lower fish catch, and the high costs of clean-up efforts [65]. Beaches contaminated with microplastics may reduce tourist influx and decrease revenue generation [66]. Moreover, microplastic pollution in fishery zones raises concerns over the safety of fisheries and seafood, which potentially impacts both local livelihoods and public health [67]. These concerns and public perception of microplastic pollution as a serious risk have driven political actions and regulatory measures to mitigate and address their environmental, human health, and socioeconomic impacts.

3. Nature-based Solutions to Wastewater Treatment of Microplastics

The International Union for Conservation of Nature (IUCN) defined NbS as the actions that protect, sustainably manage, and restore natural or modified ecosystems to effectively address challenges in society while providing benefits to both human well-being and biodiversity [68]. As a convenient umbrella concept, NbS encompasses many related concepts such as ecosystem services, natural capital, ecosystem-based adaptation, and ecological engineering [69]. It involves strategies that utilize natural processes and ecosystems to tackle societal challenges such as climate change, biodiversity loss, and water management [69,70]. NbS provides several ecosystem services, including the provisioning, regulating, cultural, and supporting services to humans and the environment [71,72]. Due to its cost-effectiveness and multitude of ecosystem services benefits, various types of NbS technologies are applied to treat wastewater [26] and even in removing microplastics [29]. Among these NbS technologies are constructed wetlands, green infrastructures, macrophytes, and microphytes, as shown in Table 2.

Table 2. Comparison of NbS technologies for wastewater treatment of microplastics.

Nature-based Solution	Microplastics Removal Rate
Constructed wetlands	< 100%
Green infrastructures	50-99%
Macrophytes	> 94%
Microphytes	> 82%

3.1. Constructed Wetlands

Constructed wetlands (CWs) are man-made systems to treat different types of wastewaters such as domestic, agricultural, commercial, and industrial effluents [73]. As an NBS, they mimic the features and functions of natural wetland by utilizing natural materials such as gravel, sand, and their associated microbial assemblages, along with natural biogeochemical and physical processes to treat wastewater [74,75]. The treated water can then be utilized for several uses, including gardening, cleaning, firetrucks, irrigation, or releasing to other bodies of water [27]. Various configurations of CWs exhibit different efficiencies in microplastic removal from wastewater, which are affected by several factors, including the flow type, vegetation, and additional ecological components.

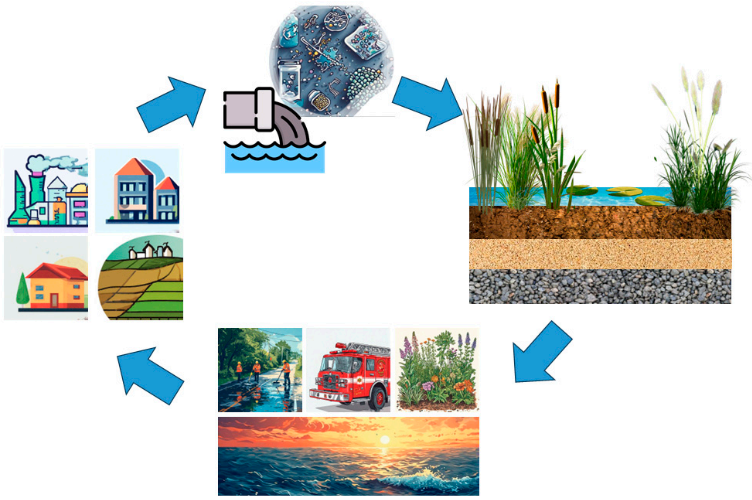

Figure 2. Sources and utilization of treated wastewater with microplastics using constructed wetlands.

The horizontal subsurface flow CWs is among technologies with the highest microplastic removal efficiencies, often reaching 100% [76]. These secondary or tertiary wastewater treatment technologies consist of a basin filled with a media composed of gravel and sand, and vegetation, where water flows horizontally through the filter media, allowing for filtration and the degradation of microplastics and other organic pollutants by microorganisms. Macroinvertebrates also play a role in the CWs as they can ingest a non-negligible quantity of microplastics and distribute them in the CWs [77]. While horizontal subsurface flow CWs offer a good filter for microplastics, the high accumulation can impair the nutrient cycling, which may significantly impact the water quality, particularly concerning eutrophication of terrestrial and aquatic ecosystems [78].

The vertical flow CWs also demonstrate high removal efficiencies up to 100% of microplastics. These technologies rely on both physical and biological degradation to treat wastewater by passing it vertically through a bed of porous media, typically sand and gravel, and vegetation. In a sand-filled vertical flow CWs, microplastics can be retained at 100% removal efficiency; 96% with gravel as filling material; and up to 99.8% when earthworms are added [79]. For laundry wastewater, this technology can also remove > 95% of microfibers from the influent in addition to 93% removal efficiency for chemical oxygen demand and 94% for turbidity [80].

Surface flow CWs involve water flowing above the surface of a constructed basin, with vegetation rooted in the sediment (gravel and soil) below, where physical, chemical, and biological processes remove pollutants, including microplastics. Compared to other types of CWs, this technology has a lower removal rate at around 81.63% [76]. This is due to microplastics often being retained near the inlet area, with the physical characteristics of microplastics (size, type of polymer) and the substrate affecting the removal performance. In some cases, microplastic concentrations may increase due to atmospheric deposition, highlighting the complexity of microplastic dynamics in these systems [31].

Constructed wetland microbial fuel cells are an innovative technology that integrates the wastewater treatment capabilities of CWs into the clean energy-generating potential of microbial fuel cells. This system utilizes the natural processes of a CWs, specifically the redox gradient between aerobic and anaerobic zones, and the electron transfer capabilities of microorganisms within a microbial fuel cell [81]. In this system, exoelectrogenic bacteria in the anaerobic zone oxidize organic matter, releasing electrons that pass through an external circuit to a cathode, where they are combined with protons and oxygen to produce water and generate electricity. Hence, this approach enhances sustainability while fostering a circular economy by utilizing cleaner energy from biofuels created as byproducts from plants and microbes [82]. Meanwhile, the presence of vegetation, such as *Denitratisoma, Sulfuritalea, and Endomicrobium*, demonstrated the highest efficiency at 96.7 % with a power density of 14.90 mW m−2, outperforming both unplanted systems and conventional CWs [83]. This offers a double solution addressing the challenges of insufficient electricity and wastewater management through the integration of indigenous plant species.

Multi-stage CWs are systems that treat domestic sewage, agricultural wastewater, and industrial effluents by combining different types of CWs in series to enhance pollutant removal and improve water quality. With the integration of different CWs, the removal process is optimized through sequential treatment stages, which can have removal efficiencies greater than 89% of microplastics [84]. The results of another study showed that these systems can achieve an efficiency up to 94.7% for microplastics, with 2.2 particles/L microplastics and fluoro-rubber particles are not removed in the effluent [85].

3.2. Green Infrastructures

Green infrastructures are another NbS technology to mitigate microplastic pollution by capturing, filtering, and retaining these tiny plastic particles from stormwater runoff, wastewater, and even atmospheric deposition. Besides CWs, green infrastructures include bioretention systems, green walls, permeable pavements, and retention ponds.

Bioretention systems or rain gardens are NbS that can remove microplastics from stormwater runoff by combining physical filtration and adsorption. As illustrated in Figure 3, these systems utilize a multi-layered structure composed of the ponding zone, soil layer (plant uptake, substrate sorption, nitrification zone), internal water storage (denitrification zone), and underdrain [86,87]. The engineered media and plants have properties that attract and bind to microplastics, effectively removing them from the water [88]. To increase their efficiency, some bioretention systems incorporate various locally available and low-cost inorganic/organic materials like biochar, vermiculite, zeolite, fly ash, perlite, biosorbents, and other sorbents [86]. Bioretention systems have shown a microplastic removal rate ranging from 80% to over 99%, which is particularly effective for particles with sizes 20 µm or above [34].

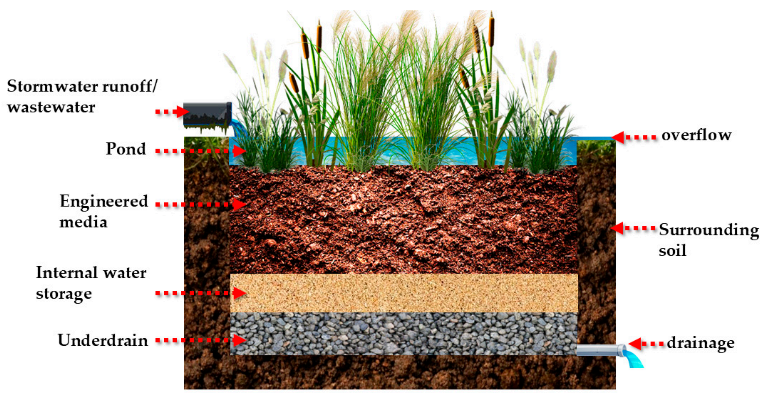

Figure 3. Retention System with internal water storage and underdrain.

Living green walls are NbS, which are also known as vertical gardens, green walls, living walls, or eco walls. Like CWs, green walls are composed of vegetation, substrates, and irrigation, making them a miniature vertically installed CWs on infrastructure walls, They have the advantages of treating wastewater in various infrastructures requiring no space, making them an ideal NbS for wastewater in urban environments [89]. Among their benefits are improvement in air quality, temperature regulation, building energy efficiency, noise reduction, aesthetic value, and enhancement of overall well-being [31]. When used for wastewater treatment, they can effectively remove microplastics (100-500 µm size range) at a 50-60% removal rate [31]. As illustrated in Figure 4, they can be classified into modular types composed of different plants in containers in the form of trays, vessels, planter tiles, or flexible bags, and carrying the substrate materials, such as soil or mineral granules; and continuous types of living walls that uses permeable screens such as foam or felt layers without soil substrates, both requiring specific supporting structures [89].

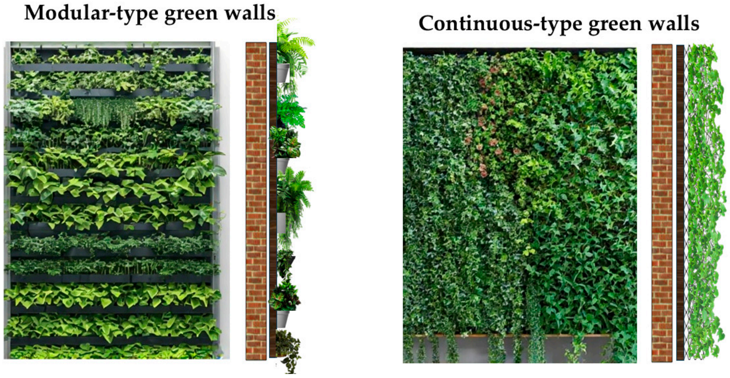

Figure 4. Modular and continuous types of green walls.

Permeable pavements are another NbS designed to store stormwater and then drain it into pipeline networks. They have an added advantage of retaining particular pollutants in urban stormwater [90]. As shown in Figure 5, they consist of a permeable surface layer and an underlying stone reservoir base. The surface layer can be made of various materials like porous asphalt, pervious concrete, or permeable pavers. The subsurface layer, or reservoir, is typically composed of open-graded aggregate, which stores stormwater and allows it to infiltrate into the soil or flow into an underdrain for further reuse. This filtration process can effectively capture microplastics, acting as a sink for microplastics and other particulate pollutants in stormwater runoff. Specifically, the surface layers and geotextiles within the pavement structure can retain microplastics and tire wear particles [91]. Studies show that permeable pavements demonstrate removal efficiencies between 89–96.6%, especially for particles less than 100 μm [34]. This makes permeable pavements a promising tool for mitigating microplastic pollution in urban environments. Moreover, they also offer several benefits as an NbS, like reducing the urban heat, improving air quality, reducing salt usage, enhancing safety through better traction, aesthetics, and increasing property values.

Figure 5. Illustration of permeable pavements.

Stormwater retention ponds, or simply retention ponds, act as sinks for microplastics, trapping them within their sediments and preventing them from being transported further downstream. This occurs through a combination of physical processes like settling and sedimentation, as well as biological processes within the pond ecosystem. The ponds also receive higher hydraulic loads than natural water bodies, which can lead to increased microplastic accumulation in the sediments [92]. Retention ponds consist of several key components that work together to collect, store, and filter

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water. As shown in Figure 6, these ponds include the basin itself (composed of bioretention soil and gravel bed), inlet and outlet structures, an emergency spillway, and surrounding vegetation. Bioretention soil is an engineered soil mix that consists of sand, compost, and topsoil, designed to effectively filter and treat stormwater runoff and wastewater. Retention ponds can store 55–98% of microplastics and up to 85% other sediments [34]. In another study, the average retention was 88% for small microplastics (<500 μm) and 95% for large microplastics (>500 μm), including tire wear materials [93]. Moreover, microplastic characteristics such as weight and size decrease from surface to subsurface soil, while larger sizes are retained mostly near inlets than outlets [94].

Figure 6. Illustration of retention ponds.

3.3. Microphytes and Macrophytes

Microphytes and macrophytes can act as NbS for microplastic pollution by accumulating and potentially removing these particles from aquatic environments. These organisms can trap, absorb, and potentially even degrade microplastics, offering a sustainable approach to wastewater treatment.

Microphytes are microscopic, single-celled, photosynthetic organisms, essentially microscopic algae. They are found in both freshwater and marine environments and play a vital role in aquatic ecosystems. Some microalgae species have shown the ability to capture microplastics through heteroaggregation, where microplastic particles attach to the algal cells, and then can be removed from the water [95]. Once microplastics enter the bodies of water, they are colonized by biofilms through the excretion of extracellular polymeric substances (EPS) from microalgae. The accumulated biofilm increases the density of the microplastics, which are transported to the sediments [96]. As shown in Table 3, *Spirulina sp.* accumulated the highest amount of EPS (4.59 g), followed by *Tetraselmis chuii* (3.27 g), *Chlorella vulgaris* (3.03 g), and *Dunaliella salina* (2.86 g) [97]. Moreover, *Spirulina sp.* had the highest efficiency with flocculating 1.397 g of microplastics among other strains, suggesting that *Spirulina sp.* and *Tetraselmis chuii* are particularly effective in producing EPS that can be utilized to remove microplastics from the aquatic environment [97]. Meanwhile, another study found that an EPS releasing freshwater blue-green microalgae, *Chroococcidiopsis cubana*, has 91% microplastics removal efficiency under optimal conditions with a concentration of 89,352 numbers/mL microplastics and a microalgal cell concentration of 2,539,705 cells/mL [98].

Table 3. Comparison of different microphytes as NbS for wastewater treatment of microplastics.

Microphytes	**Microplastics Removal/ Flocculation**
Spirulina sp.	Most effective
Tetraselmis chuii	Effective
Chlorella vulgaris	> 94%
Dunaliella salina	Less effective
Chroococcidiopsis cubana	> 91%

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Macrophytes, on the other hand, are large aquatic plants that play a crucial role in freshwater ecosystems, serving as habitats, food sources, and influencing water quality. They can be used for wastewater treatment as they can trap microplastics through physical adhesion to their surfaces, facilitated by their morphology and biofilms. They can also adsorb microplastics onto their surfaces and even internalize them, particularly if the particles are small enough or the plant surface is hydrophobic [99]. Table 4 summarizes the efficiency of different macrophytes for microplastic removal. *Hydrilla verticillata* showed higher retention of polyethylene terephthalate (PET) microplastics (800-1000 μm) in both still and dynamic water conditions, while *Mayaca fluviatilis* was more effective for smaller PET particles (600-800 μm) due to its higher perimeter-to-area ratio and surface cellulose [100]. In another study, *Myriophyllum aquaticum* demonstrated a high retention efficiency of 93.38% for microplastics larger than 100 μm under optimized conditions such as flow rate, aeration, and plant density [29]. In floating treatment wetlands, *Cyperus papyrus* and *Pontederia sagittate* achieved removal rates of 82.4% and 81.1% in water columns and sediments, respectively, primarily through root retention [101]. Meanwhile, *Eichhornia crassipes*, commonly known as water hyacinth, is a fast-growing, floating aquatic plant, that can achieve a removal efficiency between 55.3% to 69.1% for polystyrene particles (0.5 to 2 μm) within 48 hours, with root adsorption being the primary mechanism [102]. Moreover, *Iris pseudacorus* and *Lythrum anceps* were found to reduce microplastic numbers in water at up to 81.5% and 77.3% respectively, regardless of the size of the pollutants or the type of plants, with roots playing a crucial role in adsorption [103].

Table 4. Comparison of different macrophytes as NbS for wastewater treatment of microplastics.

Macrophytes	Microplastic size	Removal Efficiency	Mechanism
Hydrilla verticillata	800-1000 μm	High	Leaf surface area
Mayaca fluviatilis	600-800 μm	Moderate	Surface cellulose
Myriophyllum aquaticum	>100 μm	93.38%	Optimized conditions
Cyperus papyrus, Pontederia sagittata	Various sizes	82.4%-81.1%	Root retention
Eichhornia crassipes	0.5-2 μm	55.3%-69.1%	Root adsorption
Iris pseudacorus	Various sizes	81.5%	Root adsorption
Lythrum anceps	Various sizes	77.3%	Root adsorption

Both microalgae and macrophytes show promising potential for microplastic removal in aquatic environments. *Spirulina sp.* and *Tetraselmis chuii* are microphytes with highly effective microplastic removal due to their EPS production. On the other hand, *Hydrilla verticillata* and *Iris pseudacorus* are the most effective macrophytes through physical retention and adsorption mechanisms. Beyond nutrient removal, these NbS offer numerous benefits in wastewater treatment, including the ability to reduce sunlight penetration, suppress algal blooms, filter pollutants, and support microbial activity. They also provide habitats for beneficial organisms and can contribute to the overall health of the treated water body [104]. These approaches offer a potentially more sustainable solution compared to other traditional wastewater treatment technologies, which may have limitations in terms of cost, energy efficiency, or secondary pollution.

4. Prospects, Challenges, and Policy Recommendations

Nature-based solutions present a promising approach to address microplastic pollution in wastewater. By harnessing natural processes, these solutions offer sustainable, cost-effective, and multifunctional benefits, making them a viable alternative to conventional treatment methods. In terms of environmental sustainability, NbS reduces reliance on energy-intensive and chemical-based methods, promoting ecosystem restoration and biodiversity enhancement [74]. These solutions are cost-efficient as they are particularly advantageous in decentralized and rural contexts where traditional infrastructure and financing mechanisms are limited [27]. In addition to wastewater

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treatment, NbS technologies provide several co-benefits, such as carbon sequestration, mitigation of the urban heat, improved water security, and other ecosystem services [72].

Despite their benefits, adopting NbS for the treatment of microplastics in wastewater presents several challenges. First, achieving consistently high removal levels across different microplastic sizes, shapes, and polymer types remains a challenge. Once microplastics enter CWs, they accumulate within the ecosystem, affecting the vegetation and microorganisms as well as the cycling of elements such as carbon, nitrogen, and phosphorus [33]. While adsorption-based techniques are promising, conventional adsorbents may not be effective for nanoplastics and can face limitations in capacity, reusability, and adsorption time [105]. Moreover, microplastics removed from wastewater are often transferred to sludge, and the potential for microplastics to be released back into the environment from sludge needs careful consideration [106].

Standardization of methods to detect and quantify microplastics in wastewater and sewage sludge is needed for comparing results across studies and evaluating the effectiveness of different technologies. These remain challenging due to their small size and diverse nature, which complicates the assessment of NbS performance and the development of effective treatment strategies [107].

One of the non-technical challenges is the large land requirement for CWs, particularly in densely populated or land-scarce areas [74]. This is a significant limitation, especially when compared to other wastewater treatment technologies that may require less space. Additionally, NbS, like other wastewater treatment systems, require proper maintenance and operation to ensure their effectiveness. Factors like clogging, fouling, and inadequate biomass density can hinder performance [24]. While studies show that NbS are cost-effective, these systems are usually not income-generating, making them less attractive to investors who are profit-driven. In such cases, the local government usually subsidizes the cost of maintaining the facilities to make them operate continuously and sustainably on a longer-term basis [73].

Climate-related uncertainties, such as the increasing frequency and magnitude of typhoons, flooding, and droughts, can affect the performance of NbS technologies, especially those relying on natural processes [24]. These are particularly relevant to countries with high vulnerability to natural hazards. Another challenge is public perception and acceptance of NbS technologies [108]. When communities perceive NbS as having any negative environmental or societal impact, the implementation of adoption of NbS projects are opposed, especially when they are proposed near one's residence. Finally, widespread adoption and scaling up of NbS initiatives are hampered by the lack of policy support [26]. This includes insufficient regulations, inadequate enforcement, and a lack of clear guidelines for industries and local governments to reduce microplastic pollution.

Given the prospects and challenges mentioned above, several policy recommendations can be made to effectively adopt NbS for microplastic wastewater treatment. These recommendations aim to facilitate the integration of NbS into existing frameworks for wastewater management, promote research and innovation, and ensure sustainable practices.

- *Development of Supporting Policies and Framework.* Comprehensive guidelines should be established for the design, planning, implementation, and maintenance of NbS technologies, including the definition of performance metrics for microplastic removal and environmental impact assessments. NbS should be incorporated into existing water quality regulations and standards to ensure they are recognized as viable alternative treatment options alongside conventional methods.
- *Promoting Research and Innovation*. R&D initiatives focusing on the effectiveness of NbS in microplastic removal must be funded. Pilot projects must be supported, particularly those that demonstrate the feasibility and effectiveness of NbS, providing valuable data for scaling successful models.
- *Partnerships and Information and Education Campaign (IEC).* Collaboration among government agencies, academic institutions, non-governmental organizations, civil society, and the private sector must be promoted to exchange knowledge, best practices, and resources related to NbS.

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Citizen science should be conducted to raise awareness about the benefits of NbS for wastewater treatment and the risks of microplastic pollution, engaging various stakeholders in the process.

- *Sustainable Financing Mechanisms*. Financial incentives, such as grants, subsidies, or tax breaks, must be provided for municipalities and industries that adopt NbS for wastewater treatment. Green financing options must be explored to support the development and maintenance of NbS, ensuring the accessibility of funding for NbS projects.
- *Integration of NbS into Urban Planning*. Development and urban planners must be encouraged to integrate NbS into land-use planning and infrastructure development.
- *Accessibility and Capacity Building*. NbS initiatives must ensure to be accessible, particularly for marginalized and underserved populations. Training and capacity-building programs must be provided for local stakeholders, including community members and wastewater treatment operators, to enhance their understanding and skills related to NbS.

5. Conclusions and Future Research Directions

Nature-based solutions are technologies that utilize nature to address societal and environmental problems. Due to cost-efficiency and a human ecological approach, their utilization has been continuously growing, including the application to wastewater treatment containing microplastics. This study extended the academic discourse by presenting an overview of microplastic pollution and its impacts, the role of NbS technologies in microplastic removal, and the prospects and challenges for NbS adoption.

The study found that the primary sources of microplastics are cosmetics and personal care products, plastic manufacturing, fishing and aquaculture, vehicle tire wear, clothing and textiles, and paints and coatings. Secondary sources include the degradation of larger plastics from MSW, improper waste disposal, wastewater, and surface runoff. Microplastic pollution impacts human health, terrestrial and aquatic ecosystems, societies, and economies. Several NbS technologies are utilized to remove microplastics from wastewater. These include the CWs (horizontal subsurface flow, vertical flow, surface flow, microbial fuel cells, multistage) with up to 100% efficiency and green infrastructures (bioretention systems, green walls, permeable pavements, retention ponds) with up to 99% efficiency. Among the microphytes, *Spirulina sp.* seems to be the most effective in microplastic removal and flocculation, followed by *Tetraselmis chuii, Chlorella vulgaris, Dunaliella salina,* and *Chroococcidiopsis cubana,* with efficiency of up to 94%. Moreover, the commonly used macrophytes are *Hydrilla verticillata, Mayaca fluviatile, Myriophyllum aquaticum, Cyperus papyrus, Pontederia sagittata, Eichhornia crassipes, Iris pseudacorus,* and *Lythrum anceps,* which can remove up to 93.38% microplastics.

Besides wastewater treatment and microplastic removal, NbS are cost-efficient and provide various ecosystem services. Yet, their widespread adoption is confronted by a number of barriers, such as the decrease in efficiency in removing other wastewater contaminants, standard detection of microplastics, evaluation of NbS performance, and non-technical (operations and maintenance, public acceptance, climate risks, financing) challenges. Hence, several strategies are recommended, including the development of supporting policies and frameworks, promoting research and development, building partnerships, IEC, providing sustainable financing mechanisms, integration of NbS into urban planning, and capacity building.

This paper identified several gaps in the NbS literature for wastewater treatment of microplastics, which serve as a basis for further research. Most of the reviewed studies analyzed the impacts of microplastic pollution and the effectiveness of NbS technologies in the short term. Future studies may look at the long-term impacts of microplastics on humans, the environment, and the sustainability of NbS systems. There are limited studies in other NbS technologies that can be further analyzed, such as riparian buffer strips, aquifer recharge, and urban forest. To increase the value of NbS, the vegetation can be evaluated for further utilization, such as creating biochar, biomass, and other products. Microplastics act as vectors facilitating the development and transfer of antimicrobial-resistant bacteria, which potentially exacerbates the global threat of antimicrobial

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resistance (AMR). Future studies may consider analyzing the efficiency of different NbS technologies in removing microplastics with antimicrobial resistance in wastewaters. With the compounding risks to human health, the analyses could be extended to evaluate the socioeconomic acceptability of NbS to wastewater treatment of microplastics with AMR. Finally, a real options valuation of NbS can be conducted considering the compounding impacts of technology, social acceptability, and climate risk uncertainties for a more robust decision-making for the adoption of a more human ecological solution to wastewater treatment towards the achievement of SDGs.

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Abbreviations

The following abbreviations are used in this manuscript:

AMR	Antimicrobial resistance
CW	Constructed wetland
EPS	Extracellular polymeric substances
IEC	Information and education campaign
MSW	Municipal solid waste
NbS	Nature-based solution
PET	Polyethylene terephthalate

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