

COMPARATIVE REVIEW OF MICROPLASTICS REMOVAL IN WASTEWATER TREATMENT PLANTS AND CONSTRUCTED WETLANDS

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ABSTRACT

Microplastics (MPs) pollution poses a growing threat to aquatic ecosystems, with wastewater systems representing a significant pathway for environmental release. Although wastewater treatment plants (WWTPs) can remove a large fraction of MPs, effectiveness varies widely by treatment configuration, particularly for fine fibers and fragments. Constructed wetlands (CWs) have emerged as low-energy, nature-based alternatives; however, their comparative performance and practical role relative to conventional WWTPs remain insufficiently synthesised. This review presents a structured, data-driven comparative assessment of MPs removal in WWTPs, CWs, and hybrid WWTP–CW systems, based on peer-reviewed studies published between 2015 and 2025. Reported removal efficiencies span 24.2–99.9% for WWTPs, with membrane bioreactors achieving near-complete removal, and 26.6–96.3% for CWs, with optimised vertical-flow and hybrid configurations approaching tertiary WWTP performance. Statistical analysis reveals higher median and peak removal efficiencies for WWTPs, alongside greater variability, while CWs exhibit more stable but systematically lower removal ranges. Mechanistic evaluation indicates that engineered multi-stage barriers have a significant influence on WWTP performance, whereas CW removal is primarily governed by hydraulically mediated sedimentation, substrate filtration, biofilm adsorption, and root entrapment. From a sustainability perspective, CWs typically operate at less than 20% of the energy demand of conventional WWTPs and provide additional ecosystem services, including habitat creation and carbon sequestration. Distinct from previous reviews, this study integrates quantitative performance distributions, mechanistic interpretation, and sustainability trade-offs within a unified comparative framework, demonstrating that hybrid WWTP–CW systems offer the most balanced strategy, achieving high MPs removal while reducing energy and environmental burdens. The findings support CWs as effective tertiary or polishing units and highlight the need for standardised MPs analytical protocols and optimised hybrid system design to advance sustainable wastewater management.

Keywords: *Microplastics; Constructed wetlands; Wastewater treatment; Removal efficiency; Sustainability*

1. INTRODUCTION

Global plastic production has surged over the last few decades, reaching about 400 million metric tons (Mt) annually (Geyer et al., 2017). As plastics break down, they generate microplastics (MPs), particles smaller than 5 mm, resulting from the fragmentation of larger debris or deliberate industrial processes (Andrady, 2011). MPs exhibit a wide range of physicochemical features, including differences in size, shape, density, and polymer type, which affect their environmental persistence and behavior (S. Liu et al., 2021). Because MPs are resistant to degradation and can adsorb toxic substances such as heavy metals and persistent organic pollutants (POPs), they pose considerable ecological and potential human health threats (Rochman et al., 2013; Pan et al., 2023). Wastewater treatment serves as a major pathway for MPs entering natural water systems (K. Zhang et al., 2017).

Wastewater treatment plants (WWTPs) play a crucial role in reducing MP discharges; however, removal efficiency varies with treatment configuration and particle characteristics. Influent concentrations typically range from 10^2 to 10^4 particles per liter, and reported removal efficiencies range from 50–95% (Talvitie et al., 2017; S. Zhang et al., 2024). Primary screening and sedimentation are generally effective for larger MPs, whereas smaller fibers and fragments often remain suspended (Duis & Coors, 2016). Moreover, MPs not removed during treatment accumulate in sewage sludge, potentially leading to secondary pollution during disposal or land application (Sadia et al., 2022). These limitations highlight the need for complementary and enhanced treatment strategies.

Constructed wetlands (CWs) have emerged as cost-effective, nature-based wastewater treatment systems that use vegetation, substrate media, and microbial communities to facilitate sedimentation, filtration, adsorption, and root entrapment (Vymazal, 2011; Bydalek, Webster, et al., 2023). Reported MPs removal efficiencies range from 60% to 96%, depending on system design and operating conditions (Bydalek, Webster, et al., 2023; S. Zhang et al., 2024). Horizontal subsurface flow systems are generally more effective for larger particles, while vertical-flow systems enhance removal of fine particles and fibers through improved filtration (Wang et al., 2020). Although CWs require larger land areas and may perform less effectively in colder climates (Vymazal, 2011), they offer advantages such as lower energy consumption, reduced operational costs, and ecosystem services, including habitat creation and carbon sequestration (Wu et al., 2017), and are suitable for decentralized wastewater treatment networks.

Despite growing research interest, important gaps remain. Standardized protocols for sampling and quantifying MPs are lacking, limiting cross-study comparability (S. Zhang et al., 2024). Hybrid WWTP-CW systems have received limited systematic investigation, and optimal integration strategies remain unclear (Lu et al., 2022). Long-term studies are needed to assess MPs accumulation, potential remobilization, and substrate–biofilm interactions (X. Yang et al., 2022). Life-cycle and sustainability assessments should evaluate land use, maintenance, energy demand, and sludge management (Parab et al., 2025). Unlike previous reviews that focused primarily on removal efficiencies, this study provides a structured comparative framework that integrates performance variability, mechanisms, and sustainability trade-offs across WWTPs, CWs, and hybrid systems to support informed wastewater management decisions.

2. METHODOLOGY

This study systematically reviews how microplastics (MPs) are removed in wastewater treatment plants (WWTPs) and constructed wetlands (CWs). It examines peer-reviewed articles from 2015 to 2025, sourced from leading databases using keywords related to MPs removal and hybrid CW-WWTP systems. Titles and abstracts were screened for relevance; duplicates were removed; and full articles were evaluated based on criteria emphasizing quantitative data and clear methodologies. Data such as influent and effluent concentrations, removal efficiencies, and treatment configurations were collected for comparison. Following PRISMA guidelines, the process is summarized in Figure 1. The reviewed studies compare performance, mechanisms, and sustainability across WWTPs, CWs, and hybrid systems.

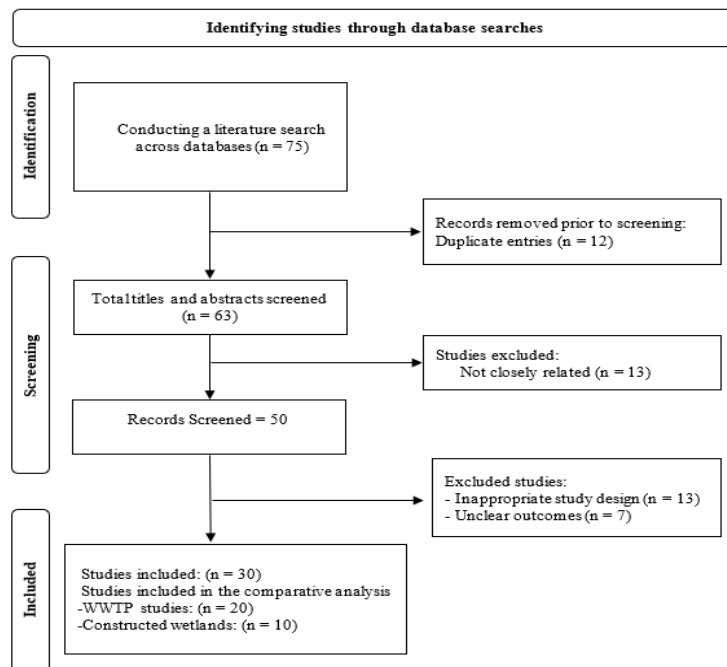


Figure 1: PRISMA flowchart illustrating the article selection process for the systematic review on microplastics removal (where “n” denotes the number of reviewed articles).

3. RESULTS AND DISCUSSIONS

3.1. Microplastics Removal in Wastewater Treatment Plants (WWTPs)

3.1.1 Process Overview

Microplastics (MPs) are removed in wastewater treatment plants (WWTPs) through primary, secondary, and tertiary processes. Primary treatment relies on sedimentation, which removes denser fragments and granules, while lighter fibers (<500 μm) often remain suspended (Carr et al., 2016; Talvitie et al., 2017). Secondary treatment, typically using activated sludge or trickling filters, enhances removal through bioflocculation and microbial aggregation, though fine fibers remain difficult to capture (X. Liu, Yuan, et al., 2019; X. Xu et al., 2019). Tertiary processes, such as membrane bioreactors (MBRs), sand filtration, and ozonation, achieve the highest efficiencies (up to 99.9%), yet small MPs may persist as residuals (Bayo et al., 2020; Talvitie et al., 2017).

3.1.2 Removal Efficiency

The removal efficiency of microplastics (MPs) in wastewater treatment plants (WWTPs) is crucial for reducing environmental discharge. Reported removal rates across various treatment setups are summarized and compared, with detailed data shown in Table 1, Figure 2, and Figure 3.

3.1.2.1 Microplastics Removal Efficiency Across Studies

Table 1: Microplastics Removal in Wastewater Treatment Plants (WWTPs)

Study/ Year	Country	Process Type	Influent (MPs/L)	Effluent (MPs/L)	Removal Efficiency (%)	Polymer Types	Shapes / Size Range (μm)
(Van Do et al., 2022)	Vietnam	Conventional WWTP	183–443	138–340	24.2	PET, PE, PVC	Fibers < 500 μm
(Akarsu et al., 2020)	Turkey	Primary–Tertiary	2.5	1	57	PE, PS,	Fibers > 500 μm

(X. Liu, Yuan, et al., 2019)	China	Activated Sludge	79.9 ± 9.3	28.4 ± 7.0	64.4	PA, PE, PP, PVC	Fibers < 571.5 μm
(Ziajahromi et al., 2017)	Australia	Primary–Tertiary	1.44	0.48	66	PET, PE, PP, PS, Nylon	Fibers < 500 μm
(Jiang et al., 2020)	China	Activated Sludge	126 ± 14	30.6 ± 7.8	75.7	PES, PA, PET, PE	Fibers < 0.5 mm
(Magni et al., 2019)	Italy	Primary–Tertiary	2.5 ± 0.3	0.4 ± 0.1	84	PA, PE	Film 0.5–0.1 mm
(Ren et al., 2020)	China	Primary–Secondary	16	2.9	81.9	PE, PP, PA, PET	Fragments < 5 mm
(Edo et al., 2020)	Spain	Clarifier + Bio-treatment	451 ± 106	26 ± 14	90	PE, PP, PS	Fibers < 500 mm
(Z. Yang et al., 2021)	China	Tertiary	288.5 ± 32.8	22.9 ± 7.2	92.1	PE, PP, PS	Fibers < 500 μm
(Cunsolo et al., 2021)	United Kingdom	Activated Sludge	2102.16	129.13	93.9	PE, PA PP, PS	<100 μm
(Michielssen et al., 2016)	USA	Primary–Tertiary	133 ± 35.6	5.9	95.6	PES, PA	Fibers < 4.75 mm
(Franco et al., 2021)	Spain	Clarifier + Membrane Bioreactor (MBR)	645.03 ± 182.24	16.40 ± 7.85	97.2	PVC, PE, EAA, HDPE	Fibers < 5000 μm
(Ziajahromi et al., 2021)	Australia	Advanced Secondary	55–98	0.18–0.96	98	PET, PP, PE, Nylon	Fibers > 25 μm
(Murphy et al., 2016)	Scotland	Activated Sludge	15.7 ± 5.23	0.25 ± 0.04	98.4	PE, PP, PS	Fibers
(Lares et al., 2018)	Finland	Activated Sludge	57.6 ± 12.4	1 ± 0.4	98.3	PES, PE, PP, PA	Fibers
(Z. Long et al., 2019)	China	Primary–Secondary	1.57–13.69	0.2–1.73	97.8	PE, PP, PS, PET, PP+PE	Granules > 43 μm
(Lv et al., 2019)	China	MBR	0.28 ± 0.02	0.05 ± 0.01	99.5	PET, PP, PS, PE	Fragments > 500 μm
(Talvitie et al., 2017)	Finland	Clarifier + MBR	6.9 ± 1	0.005 ± 0.004	99.9	PES, PE, PP, PS, PU, PVC, PA, EVA	Fibers > 300 μm
(Carr et al., 2016)	USA	Tertiary Reclamation	1	0	99.9	PE	Fragments

As shown in Table 1, the removal efficiency of MPs in WWTPs varies significantly across studies, ranging from 24.2% in Vietnam’s conventional WWTPs (Van Do et al., 2022) to 99.9% in Finland’s primary clarifier combined with membrane bioreactors (MBRs) (Talvitie et al., 2017). The studies span a broad spectrum of treatment types, including primary clarifiers, activated sludge, tertiary treatments, and MBRs.

Figure 2 provides a visual comparison of these studies, showing that advanced treatment methods, especially MBRs and tertiary treatments, consistently outperform primary and secondary methods. Notable examples include (Lv et al., 2019), who reported 99.5% removal efficiency with MBR, and (Talvitie et al., 2017) who achieved nearly complete removal (99.9%) using a membrane bioreactor. These findings highlight the superior ability of advanced systems to eliminate small microplastic particles, such as fibers and fragments, which are often difficult to remove with conventional methods.

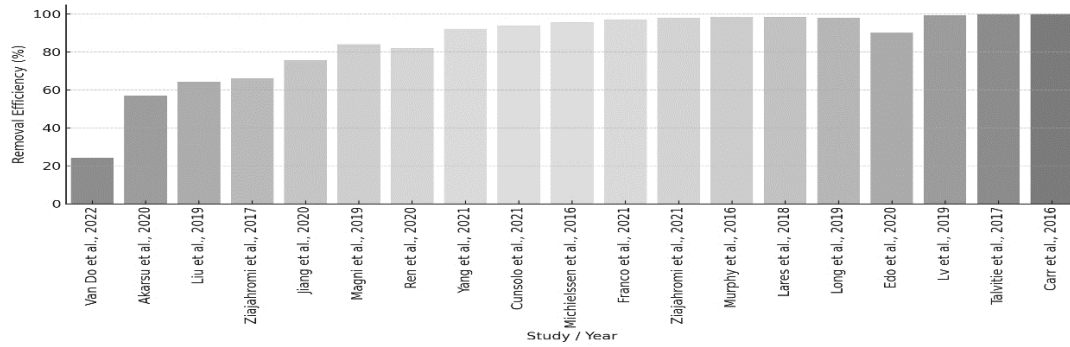


Figure 2: Microplastics Removal Efficiencies Reported In Wastewater Treatment Studies.

Conversely, primary treatments, such as primary clarifiers, show significantly lower removal efficiencies, with some systems removing as little as 24.2% of MPs, as reported by (Van Do et al., 2022). This indicates that primary treatments are primarily effective in removing larger microplastic particles, while smaller fibers and fragments remain largely untreated.

Figure 3 presents a box plot of removal efficiencies by treatment type. It clearly shows that membrane bioreactors (MBRs) and tertiary treatment achieve the highest levels of microplastics removal. MBRs, which combine membrane filtration with biological treatment, consistently achieve removal efficiencies greater than 99%, with some studies reporting up to 99.9% (Lv et al., 2019; Talvitie et al., 2017). These systems are particularly effective at capturing fine fibers and fragments, which are often less than 500 μm in size and difficult for conventional treatment methods to remove.

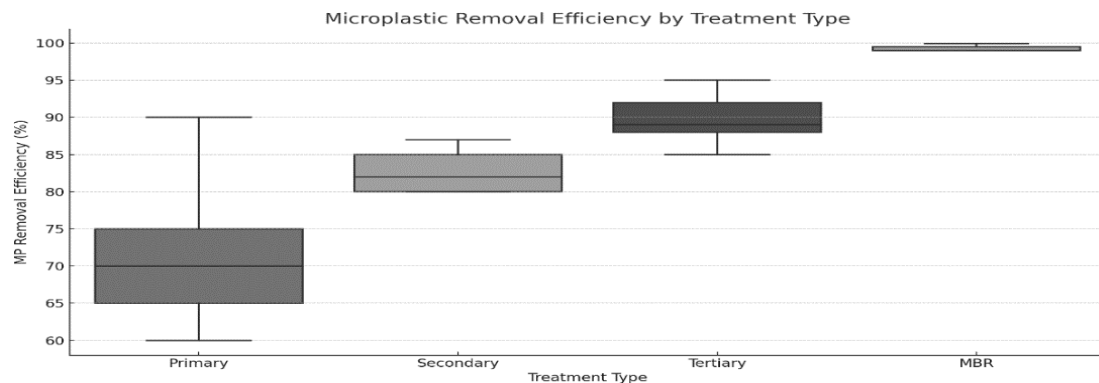


Figure 3: Box-Plot Comparison of Microplastics Removal Efficiencies (%) Across Different Wastewater Treatment Stages.

In comparison, secondary treatments such as activated sludge systems and primary clarifiers exhibit more variability in removal efficiency. These systems generally achieve removal efficiencies of 57% to 75%, with conventional systems such as those reported by (Van Do et al., 2022) Achieving removal rates as low as 24.2%. These results highlight the limitations of conventional treatment technologies in removing smaller microplastics, particularly fibers (<500 μm) and fragments.

3.1.3 Removal Mechanisms

Microplastics (MPs) are removed in wastewater treatment plants (WWTPs) through sequential physical and biological processes. In primary treatment, sedimentation removes denser particles, such as fragments and granules, by gravitational settling (Talvitie et al., 2017). During secondary treatment, bio-flocculation and coagulation enhance removal by aggregating smaller MPs, including fibers that are difficult to settle (X. Liu, Yuan, et al., 2019). Tertiary treatment further improves performance by adsorbing fine particles onto microbial biofilms on filter media (Z. Yang et al., 2021). Remaining MPs that bypass earlier stages are captured by physical filtration barriers, including membranes and sand filters (Talvitie et al., 2017). The combined action of sedimentation, aggregation, adsorption, and

filtration enables high overall removal efficiency, particularly when advanced technologies such as membrane bioreactors (MBRs) are applied.

3.1.4 Factors Influencing Removal Efficiency

Microplastic removal efficiency in WWTPs depends on treatment technology, particle characteristics, influent concentration, and treatment stage. Advanced systems such as membrane bioreactors (MBRs) and tertiary processes achieve higher efficiencies than primary or conventional secondary treatments, particularly for fine fibers and fragments, due to combined biological treatment and physical filtration. Removal performance is strongly influenced by microplastic size, shape, and polymer type; smaller fibers (<500 μm) are more difficult to eliminate using conventional processes (X. Liu, Ma, et al., 2019; H. Liu et al., 2019). Influent concentration also affects removal, as higher suspended solids (SS) promote aggregation and improve retention (Z. Yang et al., 2021). While primary treatment mainly removes larger particles, secondary and tertiary stages are required to capture smaller fibers and fragments (Magni et al., 2019). Overall, efficiency reflects the interaction between system design and microplastic properties.

3.2 Microplastics Removal in Constructed Wetlands

3.2.1 Process Overview

Constructed wetlands (CWs) are engineered systems that mimic natural wetland processes by using vegetation, substrate media, and microbial communities to treat wastewater. The main configurations include horizontal subsurface flow (HSSF), in which effluent moves laterally through a planted, permeable bed; vertical subsurface flow (VSSF), in which water percolates vertically to enhance oxygenation and microbial activity (D. Xu et al., 2022); free water surface (SF) systems with emergent vegetation; and hybrid systems that combine multiple designs to optimize removal processes (Bydalek, Ifayemi, et al., 2023). Key differences among these systems include the hydraulic flow regime, oxygen availability (typically higher in VSSF), and contact interfaces among water, substrate, and plant roots. These structural and hydraulic variations influence sedimentation, filtration, and biofilm interactions, thereby affecting the removal efficiency of microplastics (MPs) (S. Zhang et al., 2024).

3.2.2 Removal Efficiency

Table 2: Microplastics Removal in Constructed Wetlands

Study / Year	Country	CW Type	Influent (MPs/L)	Effluent (MPs/L)	Removal Efficiency (%)	MPs Type	Size (μm)
(Y. Long et al., 2022)	China	HSSF	26.33 \pm 7.00	19.33 \pm 1.25	26.59	PE, PS	50-500
(Y. Long et al., 2023)	China	Multi-stage System	6.50 \pm 0.41	2.93 \pm 0.31	54.84	PE, PS	100-500
(Chen, 2022)	China	SF			81.63	PE, PS	500-1000
(Li et al., 2023)	China	HSSF	23.4 \pm 3.2	3.5 \pm 0.6	85	PET, PS	50-300
(S. Liu et al., 2023)	China	VSSF	14.8 \pm 2.1	2.1 \pm 0.4	85.8	PE, PP	100-500
(Wang et al., 2020)	Belgium	HSSF	6.45	0.77	88	PE, PP	75- 425
(Zhou et al., 2022)	China	Multi-stage System	8.4-28.9	0.2-0.9	89	PVC, PS, PP, PET, PE	100-200

(Bydalek, Ifayemi, et al., 2023)	United Kingdom	SF	6.09 ± 0.78	0.30 ± 0.09	95	APET, PS, PPE	100-1000
(S. Liu et al., 2023)	China	Hybrid (VSSF + HSSF)	32.5 ± 4.8	1.2 ± 0.3	96.3	PE, PP, PET	20-200
(Sarti et al., 2024)	Italy	VSSF	32.5 ± 4.8	1.2 ± 0.3	96.3	PE, PP, PET	20-200

Table 2 presents the performance of microplastic (MP) removal across ten constructed wetland (CW) systems worldwide. Removal efficiencies varied from 26.6% to 96.3%, depending on CW design, substrate type, and hydraulic conditions. Horizontal subsurface flow (HSSF) systems (Y. Long et al., 2022) achieved only 26.6% removal due to limited aeration and short retention times. In contrast, vertical subsurface flow (VSSF) and hybrid (VSSF + HSSF) systems achieved efficiencies exceeding 95% (S. Liu et al., 2023; Sarti et al., 2024). The most common polymers detected were PE, PP, PS, and PET, with particle sizes ranging from 50–500 μm, highlighting the difficulty of capturing fine, low-density MPs that tend to resist sedimentation.

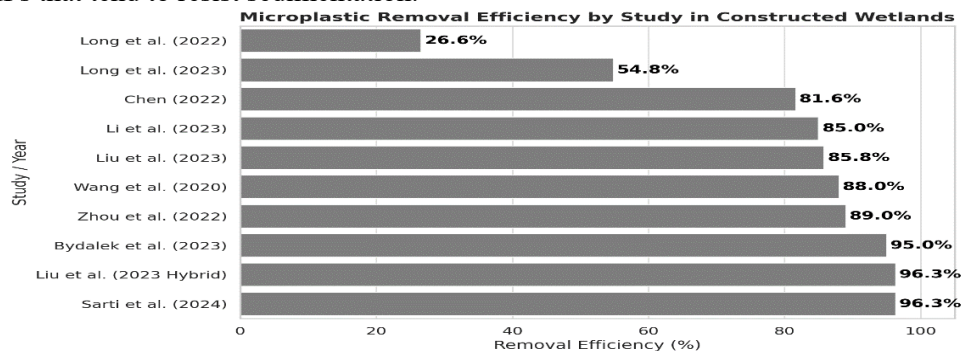


Figure 4: Microplastics Removal Efficiency Reported For Constructed Wetlands.

Figure 4 shows a transparent performance gradient among CWs. Low-performing HSSF units, ranging from 26.6 to 54.8%, contrast sharply with the more efficient multi-stage, surface-flow, and vertical systems, which range from 80 to 96%. This trend underscores the importance of hydraulic flow direction, media porosity, and oxygenation in determining the fate of MP. Vertically oriented flows enhance filtration and biofilm adsorption by increasing contact time between particles and root-substrate surfaces. Multi-stage systems benefit from sequential sedimentation and filtration zones, while surface-flow wetlands rely primarily on quiescent settling and vegetative interception. Studies such as those by (Li et al., 2023; Zhou et al., 2022). Further demonstrated that root density and biofilm maturity substantially improve the entrapment of fibrous and fragmentary MPs.

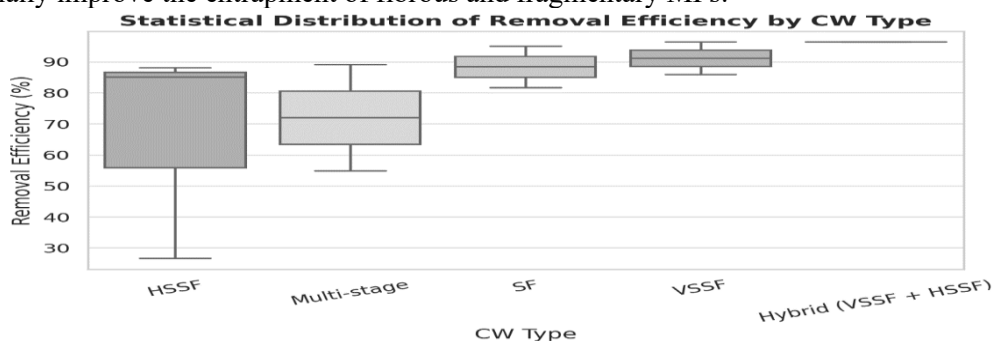


Figure 5: Microplastics Removal Efficiency Across Constructed Wetland Types

Figure 5 shows the distribution of removal efficiency across CW types. Median efficiencies followed the order: Hybrid > VSSF > HSSF > Multi-Stage > SF, confirming the superior consistency of vertically aerated and hybrid systems. Although a one-way ANOVA ($p = 0.72$) found no statistically significant differences among CW categories, reflecting overlapping high-efficiency ranges, the practical

differences are meaningful. HSSF wetlands exhibited broad interquartile ranges due to site-specific hydrodynamics, whereas hybrid and VSSF systems clustered tightly near 95%. The narrow variance indicates greater stability and resilience to fluctuations in influent. These findings confirm that CWs are nature-based, energy-efficient technologies capable of tertiary MP removal comparable to that of advanced WWTP units, highlighting their potential for decentralized wastewater and stormwater management.

3.2.3 Removal Mechanism

Microplastics (MPs) are removed in constructed wetland (CW) systems through a combination of physical, chemical, and biological processes. The process of sedimentation occurs when the speed of water is reduced, allowing particles to be deposited in vegetated or low-flow water bodies (Warren et al., 2024). Another MP retention mechanism is filtration by porous substrates, such as gravel, sand, or zeolite, which traps larger particles and decreases resuspension (S. Zhang et al., 2024). Another retention mechanism is adsorption onto biofilms and organic matter forming on root surfaces or media, in which MPs attach to biofouled surfaces and combine with suspended solids (S. Liu et al., 2023; S. Zhang et al., 2024). Macrophytes trap particles in the root zone and decrease downstream transportation (Warren et al., 2024). Lastly, biofilms or microbial communities attached to roots or in smaller amounts, biodegradation adds to the breakdown of particular polymers or related organics, complementary to the removal (S. Liu et al., 2023).

3.3 Comparative Assessment: WWTPs vs CWs

3.3.1 Quantitative Comparison

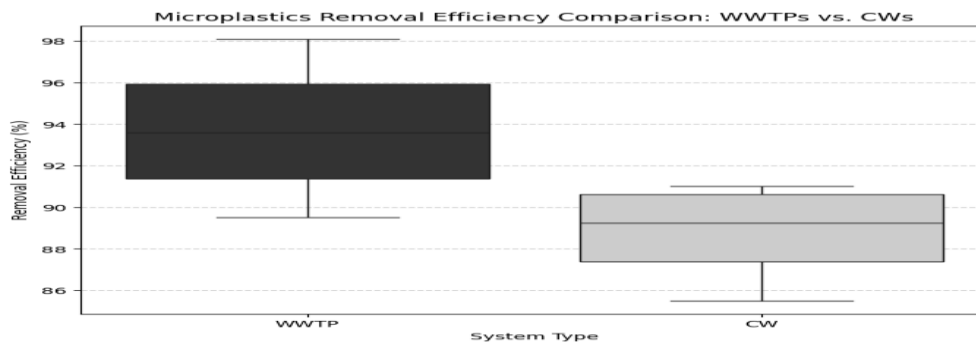


Figure 6 : Box-plot comparison of microplastics removal efficiencies in WWTPs and CWs.

Figure 6 presents a box plot comparing microplastics (MPs) removal efficiencies across wastewater treatment plants (WWTPs) and constructed wetlands (CWs). WWTPs consistently outperform CWs across all statistical descriptors. The median removal efficiency is approximately 93.6% for WWTPs, compared with 89.3% for CWs, indicating a 4.3% performance gap. The interquartile range (IQR) for WWTPs (91.5-96.0%) is broader than that of CWs (87.5-90.5%), reflecting greater variability but higher central performance. The upper whisker for WWTPs reaches about 98.1%, suggesting near-complete removal under optimal conditions, whereas CWs peak at approximately 91.0%. Minimum removal values are also higher for WWTPs ($\approx 89.5\%$) than for CWs ($\approx 85.5\%$). In normalized terms using "Absolute MPs Removed (MPs/L)," WWTPs achieve a higher average (10,399 MPs/L) and median (9,500 MPs/L) removal than CWs (7,308 and 6,840 MPs/L, respectively). Although WWTPs show greater variability ($SD \approx 2,756$ MPs/L) than CWs ($SD \approx 906$ MPs/L), they provide higher peak and processing capacity. CWs, however, demonstrate more stable performance, supporting their role as tertiary or polishing units in integrated systems.

3.3.2 Mechanistic Comparison

Higher median and upper-bound microplastics (MPs) removal efficiencies in wastewater treatment plants (WWTPs) (Figure 6) result from sequential engineered processes. Primary sedimentation removes dense fragments, secondary treatment enhances capture through bio-flocculation and sludge

aggregation, and advanced tertiary processes, particularly membrane bioreactors (MBRs), provide size-exclusion filtration that retains fine MPs (<500 µm), explaining the near-complete removal levels reported in Table 1. In contrast, constructed wetlands (CWs) rely on passive, hydraulically regulated mechanisms, including sedimentation, substrate filtration, biofilm adsorption, and macrophyte root entrapment. Vertical-flow and hybrid CWs improve filtration and biofilm contact compared with horizontal systems (Table 2). While CWs exhibit more stable performance distributions, the absence of engineered physical barriers limits peak removal. Overall, MPs removal depends on hydraulic residence time, filtration barriers, and biofilm-mediated retention in WWTPs, CWs, and hybrid systems.

3.3.3 Sustainability Comparison

From a sustainability standpoint, constructed wetlands (CWs) generally outperform conventional wastewater treatment plants (WWTPs) in terms of energy consumption and overall environmental impacts. WWTPs are highly energy-intensive, with aeration accounting for 40–60% of total electricity use, and advanced tertiary treatment systems further increase operational energy requirements. Conversely, CWs function as low-energy or passive systems, typically using less than 20% of the energy needed by WWTPs while still effectively removing microplastics (MPs) (see Table 2). Life-cycle evaluations suggest that CWs emit fewer greenhouse gases, have lower operational costs, and generate minimal secondary waste. Although CWs require larger land areas and process wastewater more slowly, their ecological benefits and low resource requirements make them suitable for decentralized applications. Combining WWTPs with CWs offers a sustainable, balanced approach to pollution mitigation.

3.4 Future Research Directions

Future research should establish standardized protocols for the sampling and analysis of microplastics (MPs) to improve comparability. Long-term, full-scale studies are needed to assess MPs fate and performance in constructed wetlands (CWs) and hybrid CW-WWTP systems under varying conditions. Design optimization and evaluation of energy-efficient configurations are essential, along with the investigation of MPs accumulation, degradation, and potential remobilization.

4. CONCLUSION

This review demonstrates that wastewater treatment plants (WWTPs) and constructed wetlands (CWs) offer complementary strengths in mitigating microplastics (MPs) pollution. WWTPs achieve the highest removal efficiencies, typically exceeding 93% and reaching up to 99.9% in advanced systems such as membrane bioreactors, but at the cost of high energy demand and operational complexity. In contrast, CWs achieve removal efficiencies of 26.6%-96.3%, with median values near 90% in optimized vertical-flow and hybrid configurations, while operating with substantially lower energy input and greater performance stability. Although CWs show lower peak removal, their ecological benefits and low operational requirements make them suitable for decentralized applications. Integrating CWs as tertiary or polishing units within WWTPs offers a balanced, energy-efficient strategy for achieving high MPs removal and sustainable wastewater management.

DECLARATION OF USE OF AI

The authors declare that they used artificial intelligence (AI) tools to assist in preparing this manuscript. All content was reviewed and approved by the authors, who assume full responsibility for the accuracy and completeness of the final version. The AI tool did not generate any original scientific results or conclusions.

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