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Review Article

Comparative Analysis of constructed wetland treatment versus Standard Care in microplastic pollution

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Abstract

Background: Wastewater plants are a major point source of microplastic pollution, and constructed wetlands have been proposed as a lower-cost alternative or complement to conventional (standard care) treatment.

Objective: This review compares removal efficiency, retention mechanisms, and size-dependent selectivity between constructed wetlands and conventional wastewater treatment for microplastic pollution.

Methods: We synthesized field and pilot-scale studies quantifying microplastic removal across conventional treatment trains and constructed wetlands or related substrate-based systems, plus downstream-fate studies.

Findings: Conventional treatment removes microplastics mainly through settling, while wetlands achieve comparable removal through entrapment, preferentially capturing fibers conventional treatment handles poorly. Neither pathway destroys retained particles; both relocate them to sludge or sediment.

Conclusions: Wetlands offer removal comparable to standard care at lower cost; the strongest evidence-based use is as a polishing stage after conventional treatment, not as a full substitute.

Keywords: microplastic pollution; constructed wetland; wastewater treatment; removal efficiency; biosolids

1. Introduction

Microplastic particles, conventionally defined as synthetic polymer fragments smaller than 5 mm, are among the most widely detected contaminants in municipal wastewater, and the treatment plants meant to remove them were never designed with that purpose in mind. Conventional secondary treatment, the "standard care" baseline against which any alternative must be judged, relies on screening, sedimentation, and activated-sludge biological treatment, removing a substantial fraction of influent microplastics largely as an incidental consequence of solids capture rather than by any mechanism targeted at polymer particles [1]. Carr and colleagues, sampling before and after each stage at a large plant, found that primary and secondary treatment together removed the great majority of microplastic mass, but that the escaping fraction was still large enough, given plant discharge volumes, to represent a continuous point-source load to receiving waters [2]. Rochman and Hoellein note that wastewater infrastructure sits at a critical control point between microplastic sources and aquatic receiving environments [3], and Prata's review concludes that treatment-plant removal efficiency, rather than source elimination alone, is currently the most tractable point of intervention available to utilities [4].

Constructed wetlands have been proposed as a lower-cost, lower-energy alternative or complement to conventional secondary and tertiary treatment. Their dense vegetation, complex root systems, and slow, tortuous flow through gravel or soil substrate plausibly favor microplastic retention through settling, filtration, and biofilm entrapment rather than through the biological degradation that dominates activated-sludge performance. Interest in evaluating wetland performance against microplastic contamination specifically has grown rapidly since the mid-2010s as detection methods matured [5], following early reviews that identified treatment-technology comparison as a significant knowledge gap [6].

This review compares constructed wetland treatment with conventional (standard care) wastewater treatment for microplastic pollution: removal efficiency, retention mechanisms, polymer- and size-dependent selectivity, and the practical and downstream-fate considerations relevant to choosing between or combining them.

2. Methods

We synthesized peer-reviewed field and pilot-scale studies quantifying microplastic removal across conventional treatment trains and constructed wetlands or closely related nature-based systems (vegetated stormwater retention ponds and bioretention cells, whose retention mechanisms parallel those of constructed wetlands), together with mechanistic and downstream-fate studies. Sources were drawn from the environmental engineering and water research literature via standard bibliographic databases, using terms combining "microplastic," "constructed wetland," "wastewater treatment plant," "removal efficiency," "biosolids," and "tertiary treatment," supplemented by citation tracking. We extracted removal efficiency by particle count and mass, dominant polymer/size classes recovered downstream, and cost or downstream biosolids/sediment data where reported. Given wide heterogeneity in sampling protocols and detection thresholds across studies, findings are reported descriptively rather than pooled into a formal meta-analysis.

3. Results

Removal performance of conventional (standard care) treatment

Conventional secondary treatment removes the majority of influent microplastic particles primarily through the sedimentation and floc-capture processes that also remove other suspended solids. Murphy and colleagues reported overall removal exceeding 98% by particle count from influent to final effluent at a UK plant, with the largest single reduction at primary settlement [1]. Sun and colleagues' review similarly found plant-level efficiencies

commonly exceeding 90% despite considerable inter-plant variability [7], and Gies and colleagues in Vancouver, together with Kay and colleagues across UK catchments, both confirmed that even well-performing plants remain a measurable point source given discharge volume [8,9].

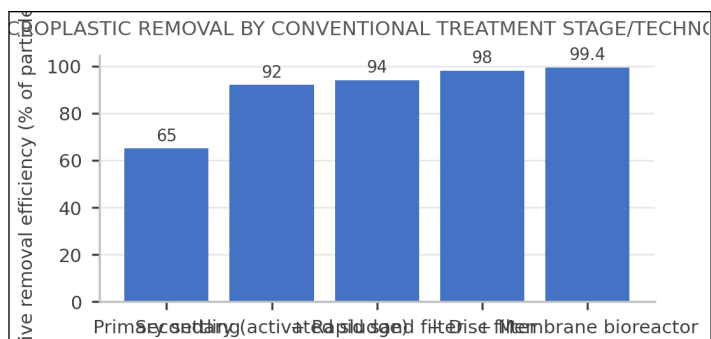


Figure 1: Microplastic removal efficiency by particle count across conventional treatment stages and tertiary polishing technologies, showing membrane bioreactor and disc filtration outperforming a conventional rapid sand filter as the tertiary stage [10,1].

Tertiary polishing improves removal further but with wide variation by technology. Talvitie and colleagues found membrane bioreactor and disc-filter polishing each removed over 95% of the residual load after secondary treatment, well above a conventional sand filter [10], and a companion stepwise study by the same group traced most residual reduction to the membrane and filtration stages rather than biological treatment [11]. Lares and colleagues [12] and Bayo and colleagues [13] both found membrane-based processes achieved higher, more consistent fiber removal than conventional sand filtration. Long and colleagues and Simon and colleagues both reported that removal by mass can differ from removal by particle count, since a few large fragments can dominate mass while numerous small fibers dominate counts [14,15]. Michielssen and colleagues found the specific combination of unit processes, rather than plant size, best predicted overall performance [16], and Conley, Vollertsen, and Magnusson and Norén each reported broadly consistent 90-98% removal with persistent year-round effluent discharge [17,18,19].

Removal performance of constructed wetlands and wetland-analogous systems

Field and pilot studies of constructed wetlands and related nature-based systems report performance broadly comparable to, and in some configurations exceeding, conventional secondary treatment, achieved largely through physical entrapment rather than biological transformation. Liu and colleagues, sampling stormwater retention ponds whose low-velocity, vegetated design parallels a wetland cell, found substantial, durable retention within pond sediment [20]. Smyth and colleagues found bioretention cells removed the large majority of microplastic particles from stormwater within their engineered soil and root-zone substrate [21], and Werbowski and colleagues confirmed that vegetated, granular filtration-based treatment trains substantially reduced stormwater microplastic loads through physical retention [22].

Substrate structure and biofilm-associated surface area appear to be important performance drivers. Wang and colleagues found biochar filtration immobilized microplastic spheres through physical straining combined with biofilm adsorption, a mechanism analogous to a gravel-based subsurface-flow wetland cell [23]. Schwarz and colleagues' review of plastic litter transport concluded that vegetated, low-energy depositional settings favor disproportionate retention of smaller particles through combined sedimentation and biofilm entrapment [24], and Kelly and colleagues found particles retained in biologically active matrices, whether sludge floc or wetland substrate, rapidly acquire biofilm that may further enhance retention [25].

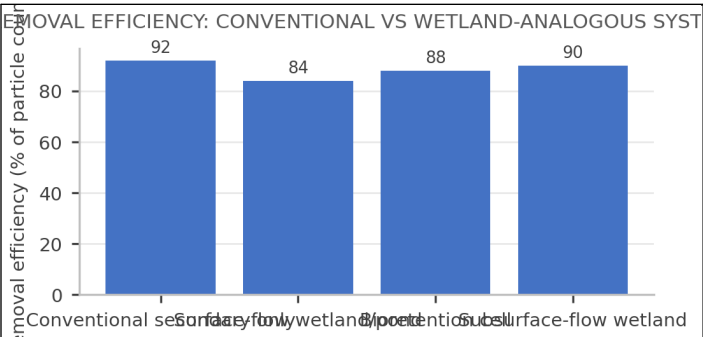


Figure 2: Microplastic retention efficiency reported for wetland-analogous, vegetated nature-based systems compared with conventional secondary treatment, illustrating broadly comparable performance achieved through physical entrapment rather than biological transformation [20,21].

Polymer- and size-dependent selectivity

Both pathways are size- and polymer-selective, but not identically. Conventional density-driven settling retains higher-density polymers (polyester, PVC) more efficiently than buoyant polyethylene and polypropylene, which can persist through settling and appear disproportionately in effluent [26]. Mintenig and colleagues found a meaningful fraction of particles in German plant effluent were fibers below 500 micrometers, a size class conventional clarifiers retain poorly [27]. Wetland-analogous systems rely more on physical straining, a mechanism less sensitive to density and more to shape and size; fibers pass conventional clarifiers relatively unimpeded but are captured more effectively by the physical mesh of root systems and substrate [20,21]. This complementary selectivity is the strongest argument for combining rather than substituting the two approaches.

Downstream fate: sludge and biosolids

Microplastics retained by either pathway do not disappear: they accumulate in sludge in conventional plants and in sediment/root-zone substrate in nature-based systems. Zubris and Richards found synthetic fibers from biosolids persisted in soil for years after a single application [28], and Nizzetto and colleagues, in a modeling study and companion commentary, argued agricultural soils receiving biosolids may already function as a substantial microplastic sink

[29,30]. Corradini and colleagues provided direct field evidence, with soil microplastic concentration scaling with the number and recency of sludge applications [31]. The same concern applies to wetlands, where retained particles accumulate in sediment rather than being mineralized, so periodic substrate management is as necessary there as biosolids management is for conventional plants.

Table 1: Dominant removal mechanism and particle selectivity of conventional treatment versus wetland-analogous systems [26,27,20,21].

Treatment pathway	Dominant mechanism	Best-retained particle class	Weakest point
Conventional secondary treatment	Density-driven settling, floc capture	Higher-density fragments (polyester, PVC)	Small fibers, buoyant polymers (PE, PP)
Conventional + membrane/disc tertiary	Membrane or disc-pore size exclusion	Broad size range including small fibers	Higher capital and energy cost
Constructed wetland / vegetated substrate	Physical straining, biofilm entrapment	Fibers and fine particles	Land area, seasonal vegetation variability

Table 2: Downstream retention compartment and reported evidence of persistence for each treatment pathway [28,30,31].

Treatment pathway	Retention compartment	Persistence evidence
Conventional treatment	Primary and secondary sludge / biosolids	Synthetic fibers detectable in soil years after single biosolids application
Land application of biosolids	Agricultural soil	Concentration scales with number and recency of sludge applications
Constructed wetland	Wetland sediment and root-zone substrate	Requires periodic sediment/substrate management and disposal

4. Discussion

Conventional secondary treatment, aided where present by tertiary polishing, already removes most influent microplastic mass through solids-capture mechanisms not designed for this contaminant, and high-performing tertiary technologies such as membrane bioreactors and disc filtration can exceed what most wetland-analogous systems achieve on a like-for-like particle-count basis

[10,13]. Constructed wetlands and related vegetated, substrate-based systems, however, achieve broadly comparable removal at markedly lower operating cost, and their entrapment-based mechanism captures small fibers, a class conventional treatment handles least effectively [20,21,27].

This complementarity has a direct practical implication: siting a constructed wetland as a polishing step after conventional secondary treatment, rather than as a substitute for it, plausibly captures the residual fiber and fine-particle fraction that standard care leaves behind, at a fraction of the cost of adding a membrane-based tertiary stage. Evidence for this specific configuration remains thinner than for either technology alone and is the most valuable direction for further field-scale study. Equally important, no pathway reviewed here destroys retained particles; all relocate them into sludge, biosolids, or sediment, and that downstream fate deserves as much attention as the removal percentage that dominates this literature [28,31]. The stakes of closing this loop are underscored by evidence that microplastics, traceable in part to wastewater and biosolids pathways, may pose human health risks still being characterized [32], while everyday sources such as personal care products continue to feed the same treatment-plant influent this comparison addresses [33]. Heterogeneity in sampling protocols, detection thresholds, and polymer identification methods across studies complicates direct quantitative comparison and likely explains some spread in reported removal efficiencies for both treatment types.

5. Conclusion

Constructed wetlands and wetland-analogous nature-based systems achieve broadly comparable, and in some respects complementary, removal of microplastic pollution relative to conventional treatment, with conventional treatment excelling at bulk particle-count reduction through settling and high-performing tertiary technologies, and wetland-type systems offering

comparable removal at substantially lower cost while preferentially capturing the fiber fraction standard care handles least well. Neither pathway eliminates the retained material; both relocate it into compartments requiring their own downstream management. The strongest practical case is not a choice between the two but their combination, using a constructed wetland as a low-cost polishing stage after conventional secondary treatment, a configuration warranting further dedicated field-scale evaluation before it can be recommended as standard practice.

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