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Nanocellulose nano zero valent iron composite membranes for synergistic microplastic remediation and sustainable water purification a review

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Abstract

Microplastic (MP) pollution in aquatic ecosystems has emerged as a critical environmental and public health crisis, necessitating advanced remediation technologies that surpass the limitations of conventional water treatment. This review provides a comprehensive analysis of MP sources, transport pathways, and ecological impacts, while critically evaluating the efficacy of conventional versus nanotechnology-based remediation strategies. Particular emphasis is placed on the synergistic potential of composite membranes combining nanocellulose (NC) with nano zero-valent iron (nZVI).. Nanocellulose, distinguished by its high surface area, biodegradability, and hygroscopic nature, provides a porous matrix for the adsorption and physical retention of microplastic particles. Immobilized nZVI may provide additional reactive and adsorptive sites for the removal of co-occurring dissolved

contaminants. However, the available evidence does not directly demonstrate polymer-chain degradation or mineralization of microplastics by NC- nZVI membranes. Therefore, microplastic remediation by these composites is interpreted primarily as particle capture rather than chemical degradation. Following the PRISMA 2020 guidelines, a systematic review of literature from 2010 to 2025 was conducted, screening 1,327 publications and synthesizing data from 142 selected studies. The analysis reveals that NC-nZVI composites leverage synergistic physicochemical effects to significantly enhance removal efficiency compared to standalone materials. Using the PICO framework, this review contrasts these advanced composites with conventional methods (e.g., coagulation, sand filtration), which often lack efficacy against nano-scale plastics. Unlike previous reviews that considered nanocellulose, nZVI or nano-enabled microplastic remediation technologies separately, the present review examines the intersection of these three research areas and distinguishes direct evidence from NC- nZVI systems tested against microplastics from indirect evidence from NC only materials, nZVI applications to other contaminants and related nanocomposites. Key contributions include a synthesis of recent experimental removal efficiencies and a discussion on the alignment of these technologies with Sustainable Development Goal 6 (Clean Water and Sanitation). Furthermore, the review identifies critical knowledge gaps, including the paucity of real-world field trials, potential ecotoxicological implications of nanomaterial release, and scalability challenges. By highlighting these deficiencies, this study outlines a strategic roadmap for developing engineered, bio-based water treatment solutions capable of mitigating the pervasive threat of microplastics.

Keywords

Microplastic; Nanocellulose; Nano Zero-Valent Iron; Composite Membrane; Water Purification; Sustainability.

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1.0 Introduction

Plastic pollution has escalated globally over recent decades, resulting in the accumulation of millions of tons of waste that fragment into microplastics (MPs) and disperse throughout aquatic environments. These MPs—defined as fragments, fibers, microbeads, and foams measuring 5 mm or less—are now ubiquitous in oceans, rivers, lakes, and even drinking water supplies (Arbabi et al., 2023). Persisting for decades to centuries, these particles continually fragment into nanoplastics that can penetrate biological membranes. The exposure risks are multifaceted: MPs physically abrade aquatic life, leach toxic additives, and function as vectors for adsorbed pollutants, a phenomenon often described as the “Trojan Horse” effect. Both laboratory and field investigations have documented MP-induced oxidative stress and reproductive toxicity in diverse aquatic taxa, with trace MPs increasingly detected in human consumables (Sunny et al., 2025). As noted by Koelmans et al. (2019), while safe drinking water is a mandated global objective, the persistence of MPs constitutes a significant barrier to its realization. Consequently, the development of technologies to ensure microplastic-free water is integral to achieving the United Nations Sustainable Development Goal 6 (Clean Water and Sanitation).

Conventional remediation methodologies, including coagulation, sand filtration, and activated carbon adsorption, demonstrate limited efficacy against the smallest plastic fractions. Traditional filtration generally requires energy-intensive fine-pore structures that are prone to fouling, while coagulation and flocculation processes often fail to settle nano-scale plastics effectively and generate hazardous chemical sludge. Similarly, adsorption onto non-renewable media poses secondary waste challenges and difficulties with regeneration. Critically, conventional wastewater treatment plants (WWTPs) rarely eliminate the full spectrum of MP sizes, with tertiary effluents frequently discharging significant particle loads (Sayam et al.,

2025). Thus, innovative, sustainable processes capable of sequestering nano-scale fractions are urgently required to overcome these limitations and deliver more efficient solutions.

Recent research on microplastic remediation has expanded beyond passive filtration and conventional adsorption to include actively propelled micro and nanorobotic systems. These platforms are being investigated because controlled motion may increase contact between the remediation material and dispersed plastic particles. Recent reviews have summarized their synthesis, propulsion mechanisms, operational factors and potential applications while also identifying material recovery, process control, cost and scale-up as important barriers to practical implementation ((Ali et al., 2025b; Ali et al., 2025c).

Biopolymer based adsorbents and membranes offer a complementary strategy because they can combine renewable feedstocks with tunable surface chemistry and porous structures. A recent review identified cellulose, alginate, chitosan and other related biopolymers as important platforms for microplastic and nanoplastic capture while emphasizing the influence of surface functionality, solution chemistry, material regeneration and practical operating conditions (Ali et al., 2025a) Most studies have developed alginate polyopamine membrane capsules, montmorillonite reinforced polyethyleneimine functionalized alginate capsules and hydroxyethylene diphosphonic acid modified alginate capsules for nanoplastic removal (Ali et al., 2026; Y. Wang et al., 2026). These studies demonstrate the current emphasis on the three-dimensional biopolymer matrices, surface functionalization, mechanical reinforcement and mechanistic evaluation. However, they involve alginate based systems rather than NC- nZVI composites and are therefore considered related technological evidence, not direct evidence of NC- nZVI performance.

Within this broader group of sustainable materials, nanocellulose is particularly relevant because its high specific area, interconnected fibrillar structure and abundant hydroxyl groups facilitate physical entrapment and

surface interactions with plastic particles. Nanocellulose can also be obtained from renewable biomass and modified chemically to alter its surface charge and affinity for contaminants (Sanjeev et al., 2025; Sayam et al., 2025). Hygroscopic nanocellulose networks have demonstrated the capacity to capture colloidal microplastics and nanoplastics, supporting their use as scaffolds in water treatment materials (Leppanen et al., 2022). The incorporation of nZVI into such a scaffold may improve nanoparticle dispersion and introduce additional reactive and adsorptive sites hence providing the rationale for examining NC- nZVI composites as a distinct class of microplastic remediation materials.

Concurrently, nZVI consists of nano-scale Fe(0) particles with a strong reducing core capable of donating electrons, which facilitates the precipitation of metals and the degradation of organic compounds (Tarekegn et al., 2021). While nZVI offers a metallic core for reduction and an iron-oxide shell for chemisorption, its practical application is hindered by rapid oxidation and aggregation, which diminish reactive surface area (Tarekegn et al., 2021; Toli et al., 2024). Embedding nZVI within a support matrix, such as NC, addresses these stability issues. The high aspect-ratio fibrils of NC provide anchoring sites and physical spacing, preventing nZVI aggregation while retaining its reductive reactivity (Toli et al., 2024). Additionally, carboxymethylated NC has been used to stabilize nZVI, creating composites that successfully remove toxic heavy metals, such as hexavalent chromium, suggesting parallel efficacy for MP remediation (Nitodas et al., 2023).

Previous reviews have examined individual components of the present topic but have differed substantially in scope. Broad reviews of nano enabled microplastic remediation have evaluated nanoadsorbents, photocatalysts, magnetic materials and membrane processes without focusing specifically on NC- nZVI composites ((Ouda et al., 2023; Sanjeev et al., 2025) Nanocellulose focused reviews have discussed its synthesis, surface functionalization, membrane applications, antifouling properties and capacity to capture microplastics or other water pollutants (Abdelhamid, 2024; Sayam et al.,

2025) Conversely, reviews of nZVI and supported nZVI nanocomposites have concentrated mainly on the reduction, adsorption or degradation of dissolved contaminants such as metals, dyes and organic compounds rather than on microplastic removal (Toli et al., 2024).

Among the reviews identified in the literature search, none specifically evaluated the intersection of nanocellulose, nZVI and microplastic remediation while distinguishing direct NC- nZVI evidence from evidence derived from related but compositionally different systems. The distinctive contribution of the present review is therefore not a general overview of nanocellulose or nanotechnology, but a critical evidence assessment of the proposed NC- nZVI platform. Direct evidence is defined as the studies in which material containing both NC and nZVI was experimentally tested for microplastic or nanoplastic removal. Indirect evidence includes NC based materials tested against microplastics, NC supported nZVI tested against non plastic contaminants and other iron or metal oxide containing NC composites. Using the PRISMA and PICO frameworks, this review evaluates the extent to which the proposed functions of NC and nZVI are supported when the two components are integrated, compares the available evidence with conventional and other nano enabled remediation approaches, and identifies the experiments required before NC- nZVI can be regarded as a validated microplastic treatment technology. In particular, the review examines removal mechanisms, performance reporting, evidence quality, environmental safety and barriers to practical implementation.

Table 1: Comparison of present review with representative reviews on nanocellulose, nZVI and microplastic remediation.

Review	Principal focus	Treatment of nanocellulose	Treatment of nZVI	Treatment of Microplastic
(Ouda et al., 2023)	Broad nano enabled remediation of	Included among wider	Not the central focus	Yes

	microplastics and nanoplastics	nanomaterial strategies			
Burhani et al. (2024)	Potential of nanocellulose for micropastic removal	Central focus	Not evaluated as an NC component	Yes	
(Abdelhamid, 2024)	Nanocellulose materials for water pollutant removal	Central focus	Not a central focus	Not the exclusive target	
(Toli et al., 2024)	Supported nZVI nanocomposites for sustainable water treatment	Cellulosic supports may be included among multiple support materials	Central focus	Not the principal contaminant	
(Sanjeev et al., 2025)	Nanotechnology based microplastic removal from wastewater	Included within broad nano-enabled treatment materials	Not specifically integrated with NC	Yes	
(Sayam et al., 2025)	Biopolymer and nanocellulose based microplastic removal technologies	Central focus	Not a central focus	Yes	
Present review	Critical assessment of the proposed NC-nZVI platform for microplastic remediation	Evaluated as the supporting and particle capture matrix	Evaluated as the immobilized reactive component	Yes	

2.0 Methodology

2.1 Literature search and eligibility

This systematic review was conducted following the PRISMA 2020 guidelines (Page et al., 2021) to guarantee transparency and reproducibility.. Literature searches were performed in Scopus, Web of Science, PubMed and Google Scholar, supplemented by grey literature screening. The search covered publications from January 2010 to December 2025, and the final search was completed on 20 January 2026. The search strategy was designed to capture studies on microplastics or nanoplastics, conventional and nanotechnology based removal methods, nanocellulose, nZVI and composite membranes.

The core search string used for Scopus and Web of Science was: *("microplastic OR nanoplastic") AND ("conventional methods OR nanotechnology") AND ("nanocellulose" OR "nanomaterial" OR "cellulose nanofiber" OR "cellulose nanocrystal" OR "bacterial nanocellulose") AND ("nZVI" OR "zero-valent iron") AND ("composite membrane" OR "membrane" OR "adsorbent")*.

The search terms were adapted for PubMed and Google Scholar according to each databases search format. The number of records identified from each source were as follows: Scopus 581, Web of Science 461, PubMed 276, Google Scholar 363 and grey literature 84. This gave a total of 1765 records before duplicate removal. Only English language publications were considered. Peer reviewed journal articles were prioritized for the final synthesis, while relevant grey literature was used only for background or contextual information when appropriate. During manuscript revision, the reviewer recommended an update of publications in the background context. The studies published in 2026 appeared after the formal search period and they are therefore cited as post search developments in the introduction. They were not incorporated into PRISMA record counts or used to calculate the performance outcomes presented in the results section.

2.2 Inclusion and exclusion criteria

Studies were selected using predefined inclusion and exclusion criteria. Articles were included if they met at least one of the following criteria: first, examined microplastic or nanoplastic removal from water or wastewater. Second, evaluated nanocellulose, nZVI, NC- nZVI or related nanocomposite materials for pollutant removal relevant to water treatment. Third, compared conventional, advanced or nanotechnology based microplastic removal methods. Fourth, reported ecological, toxicological or human health implications relevant to microplastic remediation. For studies included in the performance synthesis, quantitative outcomes such as removal efficiency, rejection percentage, adsorption capacity, flux or fouling behaviour were required.

Studies were included if they were conference abstracts without full data, editorials, commentaries, theoretical models without experimental or review evidence, non-English publications, duplicate publications of the same dataset or studies unrelated to microplastic remediation or water treatment. Studies focusing only on heavy metals, dyes or organic pollutants were excluded from the microplastic performance synthesis unless they were directly relevant to NC-supported nZVI stabilization, membrane design, leaching, reactivity or safety. Studies using membranes or adsorbents without NC, nZVI or a clearly related nanocomposite component were excluded from the NC- nZVI focused evidence synthesis.

2.3 Selection process

After duplicate removal, 1327 records were screened by title by title and abstract. During this stage, 1155 records were excluded because they were outside the scope of the review, did not address microplastic or nanoplastic remediation, did not involve water treatment applications, or did not concern NC, nZVI, membrane based systems or related nanotechnology based approaches. A total of 172 reports were then sought for full text retrieval and assessed for eligibility. At full stage, 30 reports were excluded. The reasons for exclusion were as follows: not relevant to microplastic remediation (n=21),

insufficient methodological detail for extraction or comparison (n=6). Any duplicate publication of the same dataset (n=3). Therefore, 142 studies were included in the final review. The selection process and exclusion reasons are summarized in the PRISMA flow diagram (Figure 1).

Two reviewers independently screened titles and abstracts and then assessed potentially eligible full texts. Disagreements were resolved through discussion, and a third reviewer was consulted where consensus could not be reached. Inter-reviewer agreement was high, with Cohen's kappa greater than 0.8.

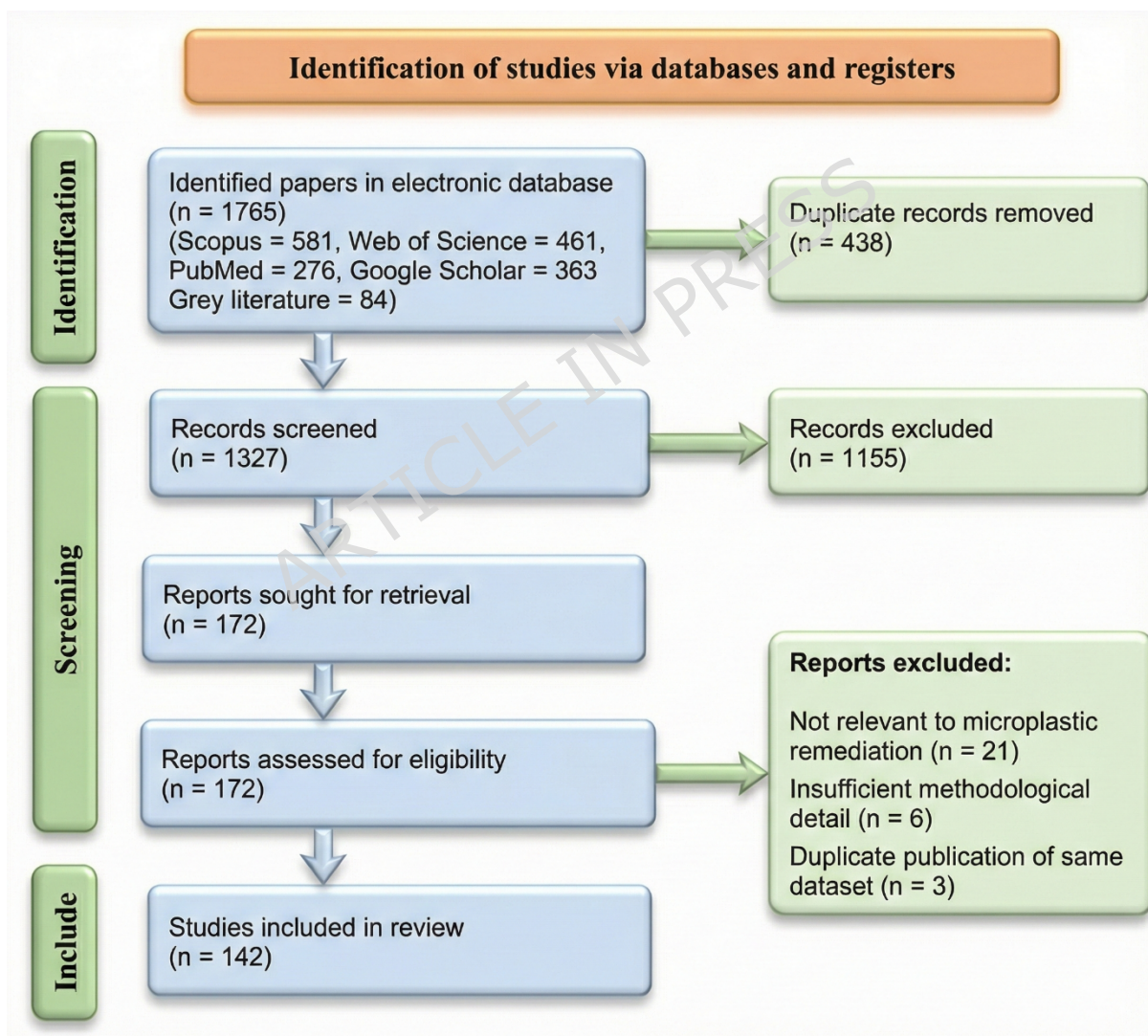


Figure 1: PRISMA flowchart outlining the literature selection and screening process.

2.4 Data extraction

Data were extracted using a standardized protocol capturing: author/year, membrane composition, preparation method, target MP polymer type, experimental parameters (initial concentration, pH), and performance metrics (removal efficiency, adsorption capacity, flux). To avoid overinterpretation of related material systems, each study was additionally classified according to the directness of evidence. Direct evidence was defined as a primary experimental study in which a material containing both nanocellulose and nZVI was tested for microplastic or nanoplastic removal from water. Indirect evidence included nanocellulose based materials tested for microplastic removal without nZVI, NC-supported nZVI tested against non-plastic contaminants, nZVI based systems tested for microplastic removal without nanocellulose and review papers or mechanistic studies that supported the rationale but did not provide primary NC- nZVI microplastic removal data.

2.5 Quality assessment

Methodological quality and risk of bias were evaluated using criteria adapted from the CRED (Criteria for Reporting and Evaluation of Ecotoxicity Data) framework. Each included study was evaluated using the following criteria. First, clear description of material composition and synthesis method. Second, adequate characterization of microplastic or nanoplastic particles including polymer type and particle size. Third, used of appropriate controls such as blank, NC only or nZVI only systems where applicable. Fourth, reporting of experimental conditions including pH, initial concentration, contact time or filtration conditions. Fifth, reporting of replicates, variance or statistical analysis. Sixth, reporting of membrane performance indicators such as flux, rejection, fouling or reusability where relevant and lastly, directness of evidence for NC- nZVI microplastic removal.

Each criterion was rated as adequate, partial or not reported. Studies were then classified as high, moderate or low reporting quality. High quality studies reported most methodological details, appropriate controls and

quantitative outcomes. Moderate quality studies reported the main experimental outcomes but lacked some controls, statistical information or operational details. Low quality studies lacked key methodological details required for reproducibility or comparison.

The quality assessment showed that reporting varied substantially across the included literature. In particular, many studies did not report appropriate control experiments, replicate measurements, variance, fouling behaviour, flux recovery or reusability. These limitations reduced the comparability of the evidence and contributed to the decision not to conduct a formal meta-analysis.

2.6 Data synthesis

Eligible studies were grouped according to material type, microplastic polymer category and directness of the evidence for NC- nZVI microplastic removal. Because the included studies differed substantially in membrane composition, microplastic type, particle size, water matrix, initial concentration, contact time, filtration configuration and reporting format, a formal meta-analysis was not appropriate. Instead, a descriptive quantitative synthesis was conducted for studies reporting removal efficiency or rejection percentage. Removal efficiency values were summarized as reported ranges, minimum and maximum values and study level medians where appropriate. For studies reporting a range, the range was retained in the table while the midpoint was used only for calculating the descriptive study level median. Review articles, studies reporting only adsorption capacity without removal percentage and studies without primary experimental removal data were excluded from the numerical summary. The resulting statistics were interpreted as descriptive indicators rather than pooled effect estimates.

3.0 Background

3.1 Microplastic pollution

3.1.1 Definition and classification

Microplastics (MPs) are defined as plastic particles smaller than 5 mm, a classification standard adopted by the European Maritime Strategic Framework Directive (MSFD) (Rist et al., 2018). They are categorized by size into small MPs (0.001–1 mm) and large MPs (1–5 mm), with particles smaller than 0.1 μm typically classified as nanoplastics (NPs) (Pan et al., 2019). While the International Union of Pure and Applied Chemistry (IUPAC) sets the lower MP limit at 0.1 μm , technical detection limits often limit practical analysis to particles $>1 \mu\text{m}$. Morphologically, MPs appear as fragments, fibers, microbeads, foams, and granules (**Figure 2**), with fragments and fibers dominating wastewater streams (Conesa & Ortuño, 2022; Cristaldi et al., 2020). MPs are further classified by origin: *Primary MPs* are intentionally manufactured particulates, such as cosmetic microbeads and virgin resin pellets, while *Secondary MPs* result from the degradation of larger plastic debris via mechanical, photolytic, and biological weathering (S. He et al., 2022; Bayo et al., 2020).

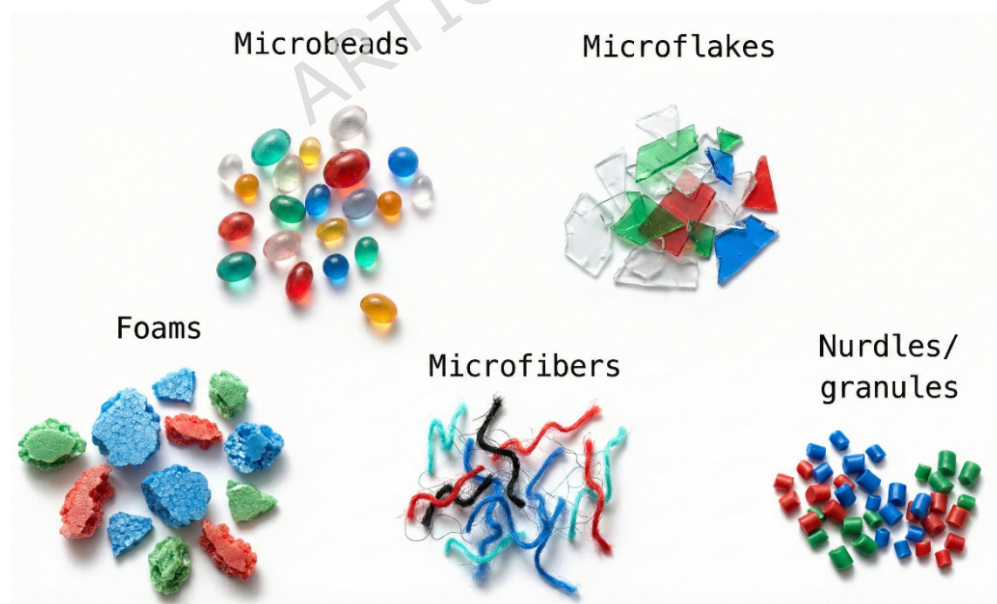


Figure 2: Morphological classifications of microplastics observed in aquatic environments. Adapted with permission from Conesa & Ortuño (2022).

3.1.2 Production and formation

Global plastic production continues to rise, with only 9% of waste recycled, leaving the remainder to accumulate in landfills or the environment (Geyer et al., 2017). The durability of thermoplastics means environmental degradation occurs over centuries. Solar UV radiation is a primary driver of photo-oxidative fragmentation of macroplastics into MPs (Zhao et al., 2018). Similarly, while mechanical abrasion and biodegradation further reduce particle size to the nanoplastic range.

3.1.3 Environmental sources

The origins of microplastics are broadly bifurcated into land-based and ocean-based sources (**Figure 3**). Land-based activities are responsible for the vast majority, accounting for approximately 80–90% of aquatic MP pollution (Duis & Coors, 2016). These sources include mismanaged landfills, industrial effluent, and urban runoff, with significant contributions from synthetic textile fibers released during washing, tire wear particles, and personal care products containing microbeads (Mondal et al., 2024; Guerranti et al., 2019). The proliferation of single-use plastics, such as bottles, straws, and cutlery, further exacerbates this load, as does the recent surge in single-use polypropylene face masks driven by the COVID-19 pandemic (Fadare & Okoffo, 2020).

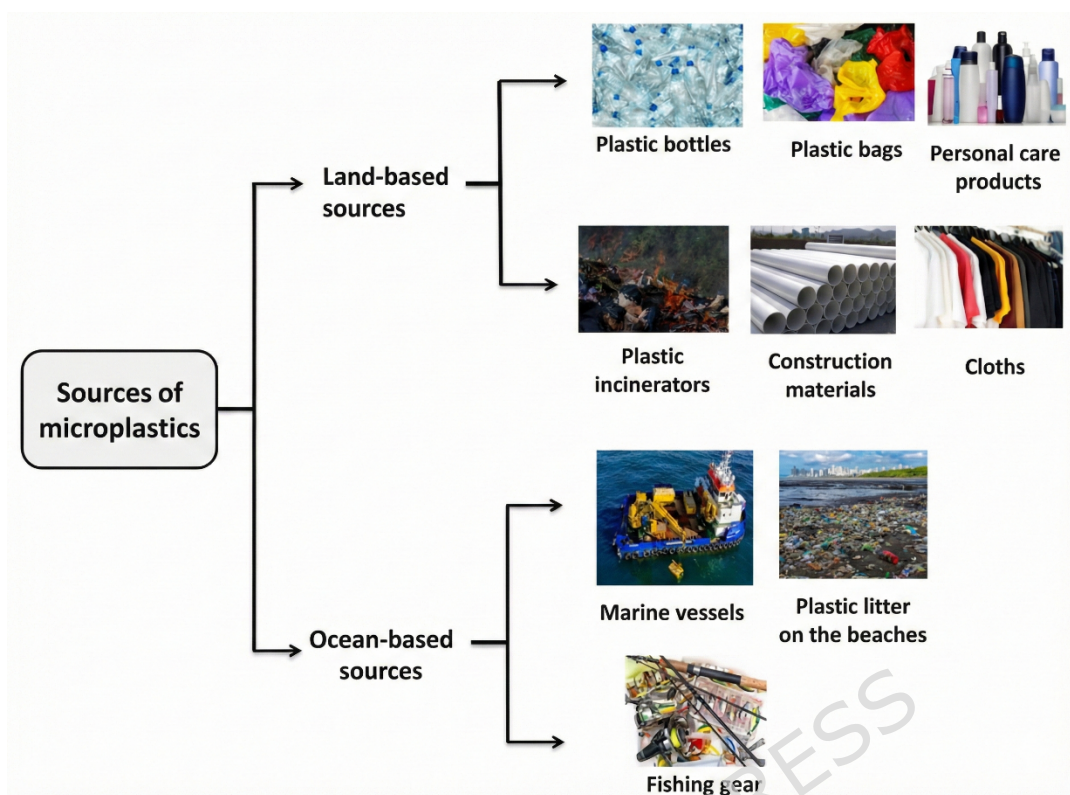


Figure 3: Classification of microplastic pollution sources: Land-based versus ocean-based pathways. Adapted with permission from Osman et al., (2023). Conversely, ocean-based sources contribute approximately 10–20% of aquatic MPs (W. C. Li, 2018). These originate primarily from marine activities such as commercial fishing, where discarded gear and “ghost nets” degrade into secondary microplastics, alongside waste from shipping vessels and offshore industries (Karbalaee et al., 2018; Naji et al., 2017).

3.1.4 Identification methodologies

Identifying microplastics involves a combination of visual sorting and advanced spectroscopic analysis. Visual identification is often the first step for larger particles ($> 500 \mu\text{m}$) but is prone to significant error rates ranging from 20 to 70%, particularly for smaller fractions where distinguishing plastics from organic debris is challenging (Iyare et al., 2020). To achieve reliable polymer identification, spectroscopic methods are essential. Fourier Transform Infrared (FTIR) spectroscopy is the standard technique for analyzing polar functional groups, with recent advances in μ -FTIR allowing

detection down to 5–10 μm . Alternatively, Raman spectroscopy offers higher resolution, capable of analyzing particles down to 1 μm non-destructively, although it remains susceptible to fluorescence interference from organic matter and often requires rigorous sample pretreatment (Xu et al., 2020; Nene et al., 2025).

3.1.5 Ecological and human health impacts

Microplastics permeate aquatic food webs through ingestion and subsequent bioaccumulation, posing severe threats to ecological and human health. Organisms ranging from zooplankton to cetaceans suffer physical blockages, oxidative stress, and reproductive failure upon MP ingestion (Osman et al., 2023). **Figure 4** illustrates the life cycle of microplastics, while **Figure 5** details their specific pathways and health impacts. Beyond physical harm, MPs act as vectors for adsorbed contaminants, including heavy metals and antibiotics, amplifying the toxicological burden (J. Li et al., 2018). Human exposure is becoming increasingly evident, occurring through the consumption of contaminated seafood, water, and salt. MPs have now been detected in critical biological samples, including human blood, placenta, sputum, and lung tissue (Schymanski et al., 2018). The potential for MPs to induce cytotoxicity and inflammatory responses in human cells, including brain cells, underscores the urgency of developing effective remediation strategies (Schirinzi et al., 2017).

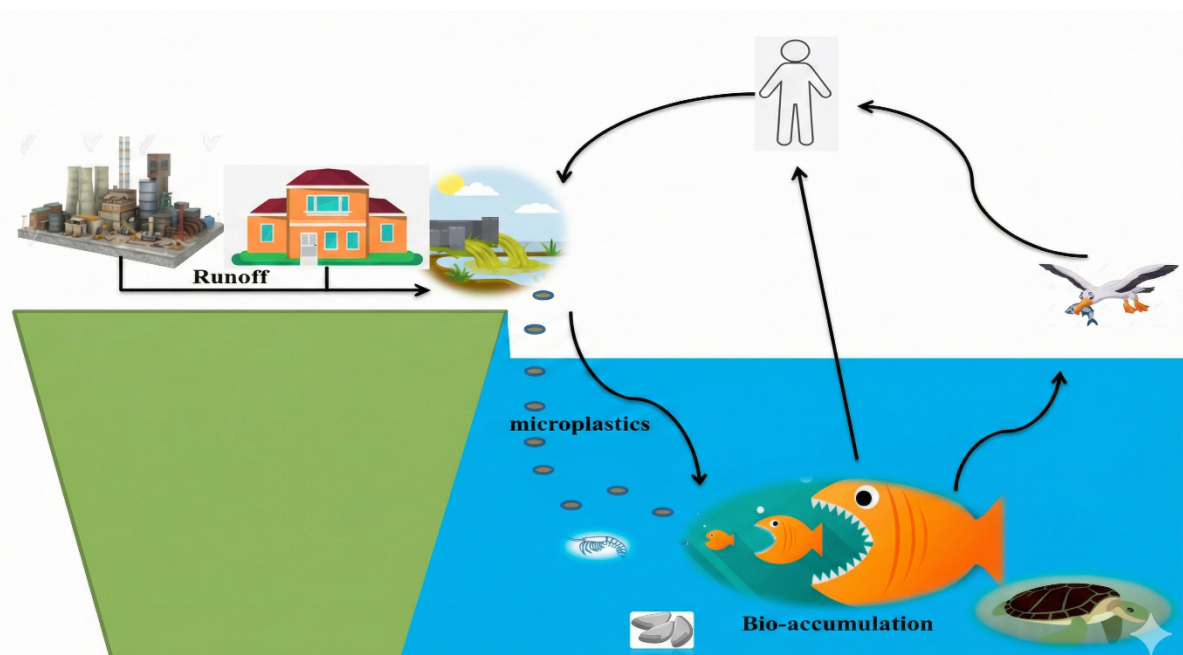


Figure 4: Life cycle of microplastics in the environment. Adapted with permission from Osman et al., (2023).

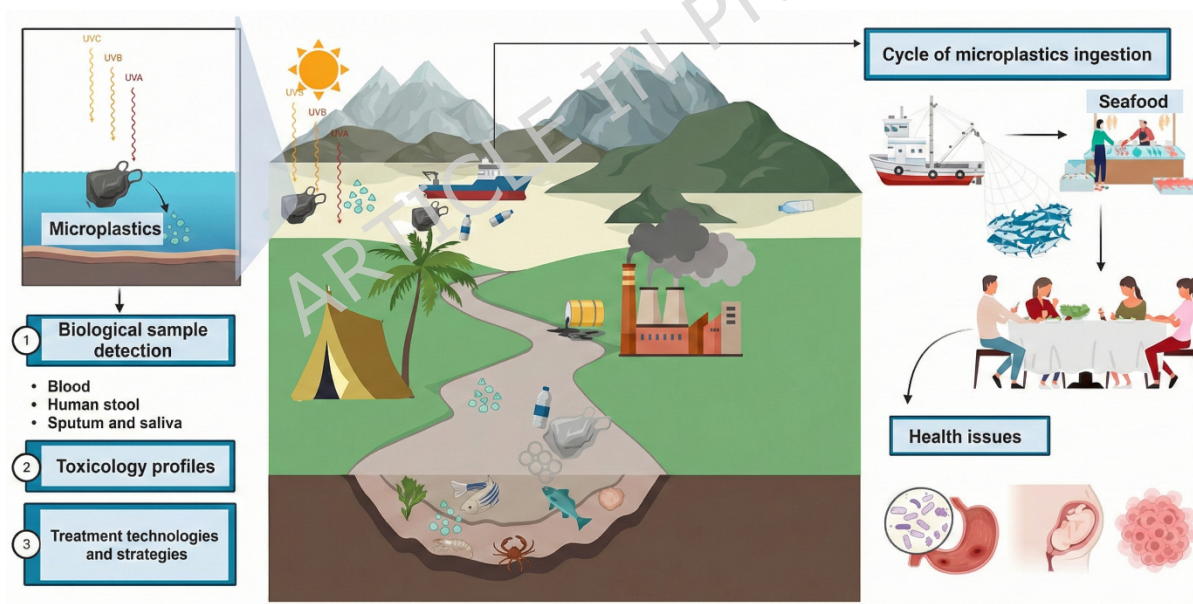


Figure 5: Microplastic effects and pathways on the environment and human health. Adapted with permission from Osman et al., (2023).

3.2 Remediation methodologies

3.2.1 Conventional methods

Conventional remediation techniques rely on established physical and chemical processes, but often struggle with the unique properties of microplastics. Adsorption using materials, such as chitin and graphene oxide, demonstrates high removal efficacy but often lacks selectivity, thereby limiting overall performance (Sun et al., 2020). Coagulation, a staple of wastewater treatment utilizing aluminum or iron-based agents, destabilizes suspended particles to facilitate sedimentation. However, this process generates significant volumes of chemical sludge and is less effective for neutral or low-density plastics that do not settle easily (Padmaja et al., 2020). Membrane filtration, ranging from microfiltration to reverse osmosis, provides a physical barrier to contaminants but is energy-intensive and susceptible to membrane fouling, which compromises long-term efficiency (Pizzichetti et al., 2021).

3.2.2 Advanced methods

To address the limitations of conventional methods, advanced techniques have been developed. Magnetic separation utilizes magnetic seeds, such as iron nanoparticles, to retrieve plastics, though its efficacy can be reduced in complex matrices with competing pollutants (Zhang et al., 2021; Abdel Maksoud et al., 2020). Advanced Oxidation Processes (AOPs), including ozonation and Fenton processes, generate highly reactive hydroxyl radicals to degrade polymers. While effective at breaking down organic pollutants, AOPs are energy-intensive and may generate toxic by-products (Ebrahimbabaie et al., 2022). Biological approaches, such as microbial degradation, utilize the “plastisphere” microbiome—including bacteria, fungi, and algae—to enzymatically hydrolyze polymers. While sustainable, degradation rates are inherently slow and difficult to control in open environmental systems (Krueger et al., 2015)(Hou et al., 2022). Recent studies have also highlighted integrated photothermal and photocatalytic approaches as emerging strategies for microplastic and nanoplastic

degradation, particularly because they may enhance light utilization and polymer transformation under controlled conditions (Xiao et al., 2024). However, these approaches remain distinct from NC-nZVI membrane capture system and should be considered complementary rather than direct evidence for NC-nZVI performance.

3.3 Challenges in current remediation

Conventional methods generally lack the precision to remove nanoplastics and the scalability to treat high-volume effluents sustainably. Physical filtration is prone to clogging, while chemical methods generate secondary pollutants. The “gap” in treating the smallest plastic fraction drives the need for engineered nanomaterials.

3.4 Nanotechnology-based approaches

3.4.1 Overview of nanomaterials

Nanomaterials offer high surface-area-to-volume ratios and tunable reactivity, enhancing adsorption and catalysis (Ouda et al., 2023). **Table 2** outlines the unique properties of these materials and their specific applications in water purification. Synthesis methods vary widely, allowing researchers to tailor structure and functionality. Techniques such as the sol-gel process transform colloidal solutions into homogeneous gels, while hydrothermal synthesis uses high-temperature, high-pressure environments to yield well-crystallized particles (Bokov et al., 2021)(Altammar, 2023). Electrospinning is particularly useful for generating nanofibers, and “green synthesis” utilizes biological entities like plant extracts as reducing agents to minimize hazardous chemicals (Baig et al., 2021)(Sanjeev et al., 2025). **Figure 6** depicts these various synthesis techniques. These materials can be engineered to possess specific optical, antimicrobial, and mechanical properties, enabling the development of highly specialized water treatment solutions that reduce operational costs at scale (Elhenawy et al., 2024).

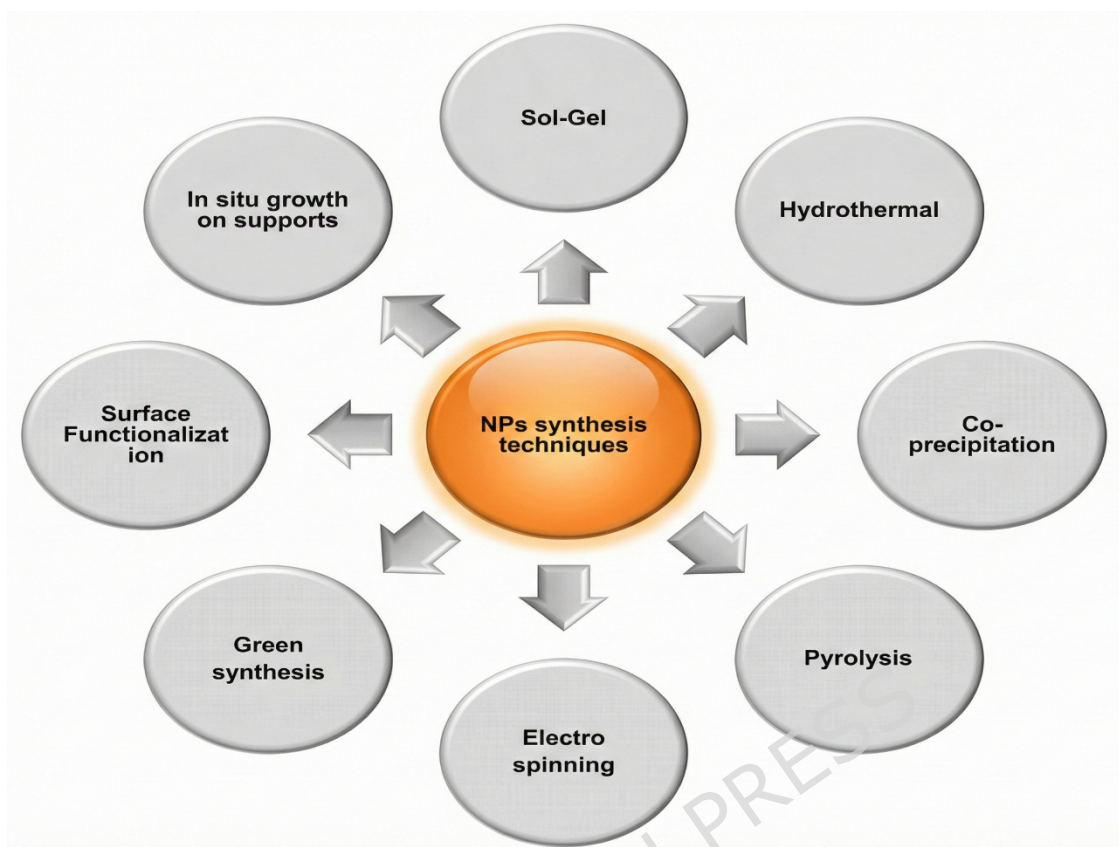


Figure 6: Schematic of standard synthesis techniques for nanoparticle fabrication. Adapted with permission from Sanjeev et al., (2025).

Table 2: Nanomaterial properties and their specific applications in water purification.

Properties of nanomaterials	Application in the water purification process
Large surface area	Nanomaterials are characterized by having a substantial surface area-to-volume ratio owing to their nano-scale dimensions. This unique property enables nanomaterials to interact more closely with pollutants in drinking water, making them efficient adsorbents and catalysts.
High reactivity	The high chemical and physical reactivity of nanomaterials is particularly beneficial in the catalytic processes, where the contaminants in drinking water are broken down.

Selective adsorption	The surfaces of nanomaterials can be engineered to adsorb specific types of pollutants in drinking water selectively. Their surface chemistry can be easily modified to target specific contaminants, making them a versatile material capable of removing a wide range of pollutants.
High mechanical strength	Certain types of nanomaterials, such as nanocomposites, exhibit high mechanical strength and durability. This unique property is advantageous in the production of reinforced water infrastructure components that prevent corrosion and leakage.
Improved optical properties	Specific types of nanomaterials, such as quantum dots, exhibit distinct optical properties that can be used for sensing and monitoring water quality. They can change their fluorescence or absorbance in the presence of certain contaminants.
Size-dependent properties	The nanomaterial's properties depend mainly on its size, and changing its size completely alters its properties. Therefore, by controlling nanomaterial size, their properties can be modified to suit different water treatment applications.
Stability and regeneration	Certain nanomaterials are highly stable and can be regenerated. It reduces the overall cost of the drinking water purification process.
Photocatalytic activity	Some nanomaterials, including titanium dioxide and zinc oxide nanoparticles, exhibit high photocatalytic activity, meaning they can break down organic pollutants and inactivate microorganisms in the presence of ultraviolet (UV) light.
Antimicrobial properties	Some nanomaterials, such as silver nanoparticles, have antimicrobial properties that help to disinfect drinking water by preventing the growth of harmful microorganisms.

3.4.2 Nanocellulose: A sustainable scaffold

Nanocellulose (NC) represents a premier sustainable material derived primarily from plants, though bacterial and tunicate sources also exist. It exists in several derivatives, including Cellulose Nanofibrils (CNFs),

Cellulose Nanocrystals (CNCs), Bacterial Nanocellulose (BNC), Enzymatic Nanocellulose (ENC), and TEMPO-oxidized cellulose nanofibrils (TOCNFs) (Abdelhamid, 2024). These derivatives vary in size and aspect ratio as detailed in **Table 3**. For instance, CNFs typically have diameters of 2–20 nm and lengths of several microns, while CNCs are shorter and highly crystalline. Fabrication techniques include mechanical methods like grinding and homogenization, physical techniques such as electrospinning, chemical treatments like acid hydrolysis, and biological enzymatic hydrolysis (S. Zhang et al., 2019)(R. Li et al., 2015)(Hassan et al., 2018).

Table 3: Dimensions and aspect ratios of common NC derivatives.

Name	Diameter (nm)	Length (μm)	Aspect Ratio (L/D)
Cellulose nanofibrils (CNFs)	2–20	100–1000	50–500
Cellulose nanocrystals (CNCs)	5–20	100–500	20–50
Bacterial nanocellulose (BNC)	10–100	1–100	10–100
Enzymatic nanocellulose (ENC)	5–50	100–500	20–100
TEMPO-oxidized cellulose nanofibrils (TOCNFs)	2–10	100–1000	50–500

NC possesses a high aspect ratio, mechanical stiffness, and abundant surface hydroxyl groups, which facilitate the formation of dense, porous networks ideal for physical sieving and electrostatic adsorption of pollutants (Ahankari et al., 2020). Its physicochemical features, including high crystallinity and susceptibility to surface functionalization (e.g., oxidation and esterification), enable it to be tailored for specific contaminants, making it a versatile

platform for water purification (Xu et al., 2020). **Table 4** illustrates the relationship between these features and adsorption capacity.

Table 4: Impact of physicochemical features of NCs on pollutant adsorption capacity.

NC Features	Effect on Adsorption	Reference
High surface area	Increases the specific surface area from micro- to nano-size, thus enhancing the NC adsorption capacity. The mixed aerogel (ratio of 1:3 CNC/CNF) can exhibit a higher specific surface area than either pure CNC or pure CNF.	(Xu et al., 2020)
High aspect ratio	The aspect ratio of CNC (10–80) is generally lower than that of CNF (80–500), depending on NC sources and treatment processes. Favors the set-up of percolated CNCs and entangled CNF networks held by strong hydrogen bonding, thus enhancing the adsorbent mechanical strength.	(Xu et al., 2020)
High mechanical stiffness	CNC and CNF have high mechanical stiffness (modulus) of ~130 and ~70 GPa, respectively, which increases the adsorbent material's stiffness and cohesion. High crystalline forms (CNCs and CNFs) are transparent and gas-impermeable with a very high tensile strength up to 8 times that of steel.	(Trache et al., 2020)
High crystalline degree	NC high crystallinity degree (60–80%) enhances the adsorbent chemical resistance and reduces cellulose solubility even in high polar solvents.	(Tanpichai et al., 2012)

NC Features	Effect on Adsorption	Reference
Susceptible to surface functionalization	Hydroxyl group functionalization (oxidation, esterification, etherification, radical grafting, and silylation) increases the NC adsorption capacity.	(Eyley & Thielemans, 2014)
Stability in water	Reduces biofouling of NC-based adsorbents. The surface of cellulose-based water treatment materials is negatively charged due to the high concentration of hydroxyl and carboxylate groups, leading to stronger electrostatic repulsion between the surface and most model foulants.	(Nguyen et al., 2012)
High surface tension	The high surface tension (NC surface energy is $\sim 60 \text{ mJ m}^{-2}$) of NC-based adsorbents by water improves wetting characteristics and reduces biofouling.	(Abdelmouleh et al., 2004)

3.4.3 Nano Zero-Valent Iron (nZVI)

Nano zero-valent iron (nZVI) is a potent reductant widely used for dechlorinating organics and sequestering heavy metals due to its high reactivity (P. Li et al., 2020). However, its tendency to oxidize and agglomerate limits its standalone utility. **Figure 7** highlights the properties of nZVI relevant to environmental remediation. To mitigate these issues, green synthesis of nZVI using plant polyphenols, such as those from green tea, eucalyptus, or mint extracts, has emerged as a strategy to stabilize the particles (Namakka et al., 2024). This bio-based approach utilizes the antioxidant properties of the extracts—specifically polyphenols and reducing sugars—to efficiently reduce Fe(II) and Fe(III) ions while preventing agglomeration (Simo et al., 2025). This method may enhance particle stability and reduce toxicity risks by limiting agglomeration and uncontrolled particle release. However, green synthesis alone does not establish environmental

safety. The ecotoxicological behaviour of nZVI depends on particle size, surface coating, oxidation state, dosage, exposure duration, water chemistry and extent of $\text{Fe}^{2+}/\text{Fe}^{3+}$ ion release. Therefore, any nZVI based water treatment material should be evaluated for nanoparticle detachment, iron leaching and biological effects before practical application.

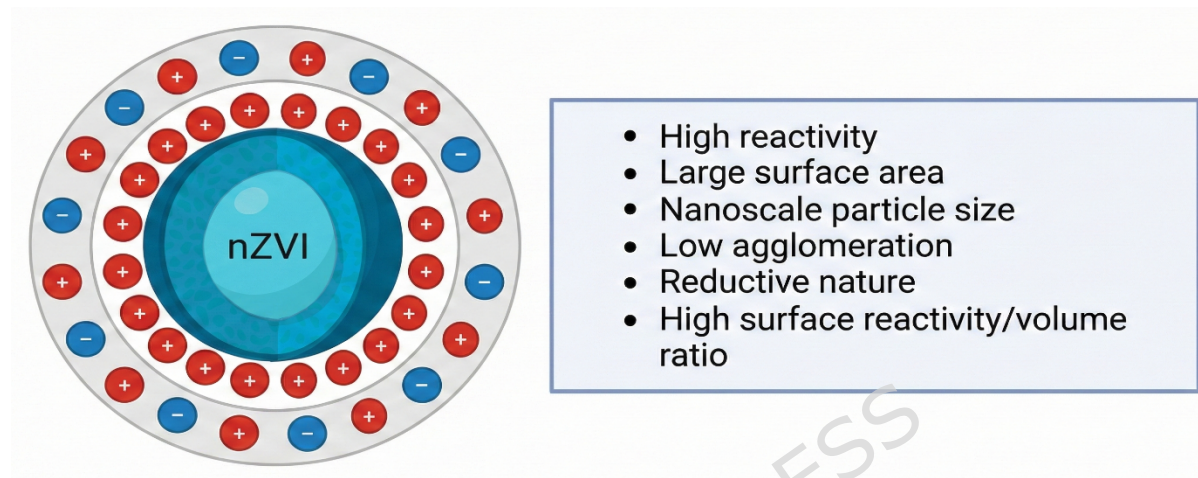


Figure 7: *Physicochemical properties of nano zero-valent iron (nZVI) relevant to environmental remediation.*

Source: Developed by the author

3.4.4 Nanocomposite membranes (NC-nZVI)

Integrating nZVI into an NC matrix can improve the dispersion and stabilization of nZVI by limiting nanoparticles aggregation and preserving accessible surface sites. However, the NC- nZVI studies identified in this review mainly concern the removal of dissolved contaminants rather than the degradation of microplastic polymers. Consequently, the presence of nZVI in the NC matrix should not be interpreted as evidence of microplastic degradation. For microplastic remediation, the currently supported mechanisms are primarily adsorption, physical entrapment and membrane retention. Fabrication techniques for these composites include phase inversion (often used for flat-sheet membranes) and interfacial polymerization (commonly used for hollow fibers), which allow precise control over membrane structure (Ahankari et al., 2020). This hybridization enhances hydraulic permeability and pollutant binding compared to

unmodified membranes, utilizing the high aspect ratio of NC to anchor nZVI particles effectively (Song et al., 2022). Such composites represent a circular-economy approach, often using agricultural waste for fabrication, thereby offering a sustainable solution for environmental remediation (Nasrollahzadeh et al., 2021). **Table 5** provides a comparative analysis of these advanced approaches against conventional methods.

Table 5: Comparative analysis of conventional, advanced, and nanotechnology-based remediation methods.

Removal Technique	Advantage	Limitation	Reference
<i>Conventional methods</i>			
Adsorption	Easy to use and design; Various adsorbents available; Relatively cheap process; Fair separation efficiency; No sludge waste formation.	Poor sustainability (recycling/reuse); Possibility of adsorbent leakage; Risk of reincorporation of pollutants.	(Mondal et al., 2024; Jaafarzadeh Haghighi Fard et al., 2023)
Coagulation	Fast and straightforward; Different coagulants available; Removes various pollutants; Relatively low cost; High removal of small-sized MPs.	pH-dependent; Increased sludge production; Increased chemical costs; Low removal percentage for large-size MPs.	(Osman et al., 2023)
Membrane-based filtration	Highly reliable; More efficient than coagulation/adsorption; Wide applicability;	Membrane fouling; Membrane abrasion.	(Mondal et al., 2024)

Removal Technique	Advantage	Limitation	Reference
	High separation efficiency.		
<i>Advanced methods</i>			
Magnetic separation	High removal efficiency; Removes from sediment, freshwater, and seawater.	Non-selective pollutant removal.	(Osman et al., 2023)
AOP's	Highly safe (no reintroduction of toxins); Satisfactory conversion efficiency.	Intermediate applicability; Average sustainability; Lower efficiency than membranes; Higher costs.	(Fazli et al., 2025)
Microbial degradation	Environmentally friendly; Low cost; Simple/safe for large scale; Minimal chemicals/sludge.	Slow; Environmental conditions hard to control; Lack of reproducibility; Difficulty finding suitable microbial communities.	(Padervand et al., 2020; Arossa et al., 2019)
<i>Nanotechnology</i>			
Nanocellulose	Large surface area; Biodegradable; High removal efficiency;	High production costs; Integration issues; Frequent	(Sayam et al., 2025)

Removal Technique	Advantage	Limitation	Reference
	High capacities; Reusability.	membrane fouling.	
Nano zero valent iron (nZVI)	High reactivity; Cost effectiveness; Aggregates microplastics.	Poor reusability; Passivation.	(Zhou et al., 2023)

3.5 Performance evaluation metrics

Key metrics for evaluating these technologies include Pure Water Flux (PWF), Rejection (R%), and Fouling Resistance. PWF measures the volume of pure water permeating the membrane per unit area and time, where declines typically indicate fouling or pore blockage (Samani et al., 2024). Microplastic rejection (R%) quantifies the percentage of MPs retained by the membrane, a critical indicator of separation efficiency that is influenced by factors such as pore size distribution and surface charge. Finally, Fouling Resistance assesses the membrane's ability to maintain flux over time despite high contaminant loads, ensuring long-term operational stability and reducing energy requirements (Enfrin et al., 2019).

4.0 Results

The database search yielded 1,765 records. Following deduplication and screening, 142 full-text articles met the inclusion criteria (**Figure 1**). **Table 6** summarizes the characteristics of key studies relevant to NC based and NC-nZVI inspired microplastic removal systems. Since direct experimental studies on NC- nZVI membranes for microplastic removal remain limited, the table distinguishes primary NC- nZVI evidence from indirect evidence derived from NC only materials, NC combined with other nanoparticles, nZVI used for non-plastic contaminants and related review based evidence. **Table 6** was expanded to include fabrication method, particle characteristics,

experimental conditions and reusability data. Unavailable information is marked NR to avoid unsupported assumptions.

Table 6: Performance metrics of NC-based composite membranes for MP removal.

Study (Author, Year)	Mem- brane composition	Fabrication Method	Target MP/Particle Characteristics	Experimental Conditions	Reusability data	Removal efficiency (%)	Adsorption capacity (mg/g)	Water Flux (Lm ⁻² h ⁻¹)	Evidence category for NC-nZVI microplastic removal
(Yadav et al., 2025)	NC-aerogel with Fe ₃ O ₄ -TiO ₂ NPs	NR	Polystyrene (PS) - (aminated PS-NH ₂)	NR	NR	98	-	-	Microplastic study, but the active nanoparticles were Fe ₃ O ₄ -TiO ₂ , not nZVI; therefore, this is related NC-based

									evidence not direct NC-nZVI evidence
(Sayam et al., 2025)	CNC , CNF	NR	PS-NH ₂	NR	NR	88.8-98	586.95	-	Secondary evidence/review based evidence
(Faria et al., 2022)	BNC	NR	Spherical Polystyrene (10µm)	NR	NR	93-96	-	-	Microplastic removal study using bacterial nanocellulose but without nZVI
(Sharma et al., 2025)	CNF - nZVI	NR	Polystyrene	NR	NR	75-98	-	-	Secondary evidence

(M. Liu et al., 2023)	CNF aerogel with cellulose acetate & CNT	NR	Polystyrene (PS-NH ₂)	NR	NR	88.8	586.95	1146 L m ⁻² h ⁻¹	Primary or related microplastic removalal evidence, but the composite contains CNT rather than nZVI
(Zhuan et al., 2022)	TEM PO-oxidized CNF aerogel	NR	Polystyrene	NR	NR	-	146.4	-	Primary microplastic removalal evidence using modified CNF, but without nZVI

(Kim et al., 2022)	Cellulose benz oate + CNT/MC NT composite filter	NR	Generic MPs	NR	NR	97	-	-	Relevant cellulose based filtration evidence, but not NC-nZVI
(J. H. Wang et al., 2022)	Attapulgitte-NC	NR	Generic MPs;	NR	NR	99	-	-	Relevant NC-composite evidence, but not NC-nZVI
(Zhuan g et al., 2022)	Cellulose nano fiber (CNF)	NR	Fluorescent polystyrene	NR	NR	-	146.38	-	Primary CNF microp lastic adsorption evidence, but without nZVI

Direct evidence refers only to primary experimental studies in which an NC-nZVI material was tested against microplastics or nanoplastics. Indirect evidence was retained because it informs material design, adsorption behaviour, nZVI immobilization or membrane performance, but it was not used as proof that NC-nZVI membranes have been experimentally validated for microplastic removal.

4.1 Descriptive quantitative synthesis of removal efficiencies

A descriptive quantitative synthesis was performed using only primary experimental studies in Table 6 that reported microplastic removal efficiency or rejection percentage. Studies that reported adsorption capacity only, review level evidence or unverified secondary values were not included in this calculation. Based on the available percentage removal data, five related NC/cellulose based or nanocomposite studies provided usable removal efficiency values: (Yadav et al., 2025; Faria et al., 2022; Liu et al., 2023; Kim et al., 2022; J. H. Wang et al., 2022).

Across these studies, reported removal efficiencies ranged from 88.8% to 99%. Four of the five studies reported point values or upper range values of at least 96%, indicating generally high removal under controlled experimental conditions. Using one study level value per study, with the midpoint used for the Faria et al., (2022) range of 93-96%, the descriptive median removal efficiency was 97%. This median should not be interpreted as pooled effect size because the studies differed in material composition, plastic type, particle size, water chemistry and experimental design.

Importantly, this quantitative summary represents related NC/cellulose based and nanocomposite systems rather than confirmed direct NC- nZVI membrane performance. The available evidence was therefore sufficient for a descriptive quantitative synthesis of related systems, but not for a separate quantitative synthesis of direct NC- nZVI microplastic removal studies.

Table 7: Descriptive quantitative synthesis of reported microplastic removal efficiencies from primary related NC/cellulose based studies.

Evidence group	Studies included in numerical summary	Removal in efficiency values used	Descriptive result
Related NC/cellulose based nd nanocomposite microplastic removal studies	Yadav et al. (2025), Faria et al. (2022), Liu et al. (2023), Kim et al. (2022) and Wang et al. (2022)	98%, 93-96%, 88.8%, 97%, 99%	Range (88.8-99%), median (97%)
Direct NC- nZVI microplastic removal studies	Insufficient verified primary data in the current evidence table	Not calculated	Separate quantitative synthesis not possible
Adsorption capacity only studies	Zhuang et al. (2022) and other studies reporting without percentage removal	Not included in removal efficiency calculation	Reported separately as adsorption capacity
Review or secondary evidence	Sayam et al. and review derived values unless traced to primary studies	Not included	Used for background only, not numerical synthesis

Removal efficiency ranges were retained as reported. For calculating the descriptive study level median, one value was used per study. The midpoint was used only for studies reporting a range. The summary is descriptive and unweighted. It should not be interpreted as a meta analytic pooled estimate or as direct evidence of NC- nZVI membrane performance.

5.0 Discussion

5.1 *Efficacy and distinction between microplastic capture and degradation*

The systematic review confirms that NC-based composite membranes possess significant potential for MP remediation. The high removal rates (>90%) observed across multiple studies are driven by the nanofibrillar network's high surface area. The addition of nZVI or carbon nanotubes (CNTs) introduces active sites that facilitate adsorption via electrostatic attraction and, in some cases, catalytic degradation. The functionalization of NC (e.g., with cationic groups) further enhances the binding of anionic plastic particles (A. K. Sharma et al., 2025 & Sayam et al., 2025). The evidence synthesized in this review indicates that removal of microplastics by NC-based materials occurs predominantly through adsorption and physical retention within the nanofibrillar network. The large surface area, interconnected pore structure and surface functional groups of NC facilitate particle entrapment and interactions such as electrostatic attraction, hydrogen bonding and hydrophobic association depending on the properties of the membrane and surface of microplastic. A reduction in the concentration of microplastics in the aqueous phase therefore demonstrates removal from water but does not, by itself, demonstrate chemical degradation of the polymer.

The direct experimental evidence that NC- nZVI membranes mineralize microplastic polymer chains was not identified among the studies included in this review. The available NC- nZVI studies primarily demonstrate the stabilization of nZVI on nanocellulose and the removal of dissolved contaminants including metal ions and phosphorous. These findings support the structural and reactive potential of the composite but cannot be extrapolated directly to microplastic degradation. Although (Yadav et al., 2025) reported both adsorption and photodegradation of polystyrene using a nanocellulose sponge containing $\text{Fe}_3\text{O}_4\text{-TiO}_2$ nanoparticles, the

photodegradation occurred under UV irradiation and was attributed to TiO_2 rather than nZVI.

Accordingly, NC- nZVI should presently be described as a prospective microplastic capture rather than a demonstrated polymer degradation system. Future studies should distinguish adsorption from degradation by combining aqueous-phase particle measurements with analyses changes in polymer chemical structure and molecular weight, identification of transformation products and where mineralization is claimed, measurements of total organic carbon or carbondioxide evolution. Appropriate NC-only and NC- nZVI controls are also required to determine the specific contribution of each component.

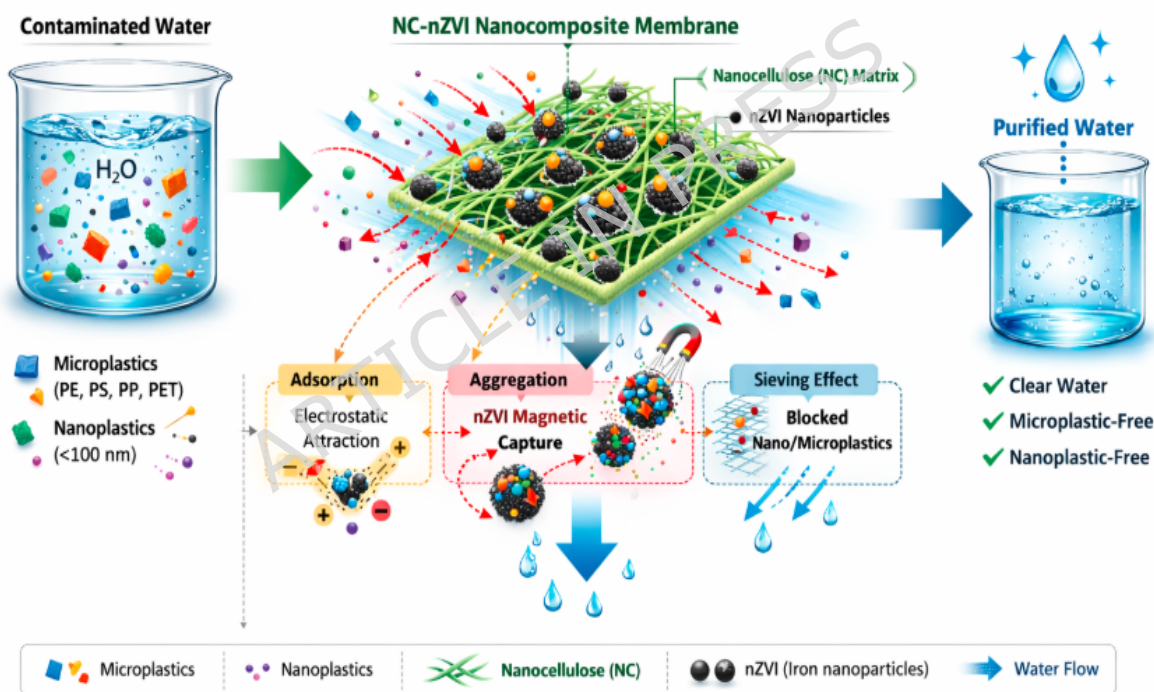


Figure 8: Removal of microplastics and nanoplastics using NC-nZVI nanocomposite membrane

5.2 Direct versus indirect evidence for NC-nZVI membranes

The evidence base for NC-nZVI membranes in microplastic remediation remains at an early stage. Most studies summarized in this review provide indirect support rather than direct validation of NC-nZVI membranes for

microplastic removal. Direct validation would require a primary experimental study in which a material containing both nanocellulose and nZVI is tested against defined microplastic or nanoplastic particles under reported water treatment conditions. Such studies should include appropriate controls including NC only, nZVI only and blank membrane systems to determine whether nZVI provides a measurable improvement beyond the nanocellulose matrix.

Several included studies are important but should not be interpreted as direct NC-nZVI evidence. Nanocellulose only and bacterial nanocellulose systems demonstrate the ability of cellulose networks to absorb or retain microplastics but they do not establish the role of nZVI. NC materials containing Fe_3O_4 - TiO_2 or CNTs provide relevant evidence for nanocomposite design, adsorption and in some cases photocatalytic behaviour, but their mechanisms cannot be transferred directly to nZVI containing membranes. Similarly, NC supported nZVI studies involving metal ions or other dissolved contaminants demonstrate that nanocellulose can stabilize nZVI and reduce aggregation but they do not confirm microplastic capture or polymer degradation.

Therefore, the present review interprets NC- nZVI as a promising but not yet fully validated membrane platform for microplastic remediation. The available evidence supports the design rationale: NC may provide the porous adsorptive scaffold, while immobilized nZVI may contribute additional reactive and adsorptive sites supporting removal of co-occurring dissolved contaminants. However, the magnitude of any specific improvement caused by nZVI in microplastic removal remains uncertain because direct comparative experiments are scarce. Future work should prioritize side by side testing of NC only and NC- nZVI membranes using identical microplastic types, particle sizes, solution chemistry and filtration conditions.

5.3 *Patterns of variability*

While performance was generally high, variability was observed based on MP size and surface chemistry. Smaller nanoplastics (<1 μm) proved more

difficult to remove than larger microplastics via simple filtration, necessitating adsorption-dominant mechanisms. Furthermore, experimental conditions such as ionic strength played a critical role; high salinity was found to shield electrostatic interactions, potentially reducing removal efficiency in marine environments (Badawi et al., 2025). Most available studies used polystyrene, particularly spherical or functionalized polystyrene particles as the model microplastic. This limits the applicability of the findings to environmentally diverse polymers such as polyethylene, polypropylene, polyethylene terephthalate, polyvinyl chloride and weathered mixed plastic fragments. These polymers differ in density, hydrophobicity, surface charge, crystallinity, shape and ageing behaviour, all of which influence adsorption, membrane retention and fouling. Therefore, the high removal efficiencies reported for polystyrene should not be generalized to all environmental microplastics without further validation using multiple polymer types and weathered particles.

5.4 Strength of evidence

Although the findings are promising, most investigations have been limited to laboratory-scale experiments. There is a notable absence of field trials involving NC-nZVI membranes, and only a limited number of studies have utilized authentic wastewater matrices. The available evidence is primarily derived from experiments conducted under controlled laboratory conditions using model microplastic particles. Furthermore, few studies have reported on reproducibility or provided statistical measures of confidence. Many investigations lacked appropriate controls (e.g., comparisons between NC-only and NC-nZVI membranes) or did not include replicate experiments, making it challenging to assess variability in outcomes. This observation is consistent with broader evaluations in the field; for instance, only a small proportion of microplastic studies meet stringent quality criteria. For example, only 4 of 50 studies on microplastics in drinking water fully met established quality standards (Koelmans et al., 2019).

The descriptive quantitative synthesis showed high reported removal efficiencies among relate NC/cellulose based and nanocomposite systems with values ranging from 88.8% to 99% and a study level median of 97%. However, these values were obtained from heterogenous systems and should be interpreted cautiously. The summarized studies differed in material composition, microplastic type, particle size, surface chemistry, water matrix and operating conditions. In addition, the numerical summary mainly reflects indirect evidence from NC based or related nanocomposite systems rather than direct NC- nZVI membrane studies. Therefore, the high median removal efficiency should be understood as evidence of the promise of NC-based and related materials under controlled conditions not as proof of validated NC- nZVI performance.

Hydraulic performance was reported inconsistently across the reviewed studies. (Faria et al., 2022) evaluated absolute and relative water flux over repeated filtration cycles and reported progressive pore clogging, whereas (F. Liu et al., 2024) reported an area normalized flux of $1146 \text{ Lm}^{-2}\text{h}^{-1}$ for a cellulose nanofiber oated delignified wood filter. However, many of the other materials were evaluated through batch adsorption rather than continuous membrane filtration. Furthermore, most studies did not report standardized pure water flux, operating pressure, flux decline, cleaning procedures or post cleaning flux recovery. Consequently, high removal efficiency alone cannot establish whether material can maintain adequate throughout during prolonged operation. The limited availability of comparable fouling and FRR data is therefore a critical knowledge gap that currently restricts assessment of cleaning requirements, energy demand, membrane lifetime and industrial scalability. Future studies should report initial and post filtration water flux, applied pressure, effective membrane area, reversible and irreversible fouling indices, FRR after a defined cleaning procedure and performance over repeated filtration cycles in realistic water matrices.

5.5 Limitation of evidence and contradictions

This review did not identify any direct contradictions; all included studies consistently demonstrated the high efficacy of nanocomposite membranes for microplastic removal. Nevertheless, performance variations were observed. For example, a study employing a chitin-graphene oxide sponge reported removal rates ranging from approximately 72 to 92% for functionalized polystyrene microplastics, including amine-terminated PS-NH₂ (Puteri et al., 2025). By contrast, other systems have achieved near-complete removal (up to 99%) of mixed microplastics from real-world water matrices (Acarer, 2023 & Sayam et al., 2025). These discrepancies in removal efficiency may be attributed to factors such as microplastic morphology, surface charge, and experimental conditions (e.g., solution pH or ionic strength). For instance, elevated ionic strength can attenuate electrostatic interactions, thereby diminishing adsorption efficiency (Badawi et al., 2025). In environments with higher salinity or ionic content, the electrostatic attraction between charged nanomaterials and microplastics is reduced, resulting in lower capture rates. It is important to note that few studies have systematically compared multiple microplastic types under identical conditions, leaving uncertainty regarding the consistency of NC-based membrane performance across different polymer classes. Most investigations utilized a single model plastic (typically pristine spherical polystyrene), which may not adequately represent the diversity of shapes and compositions present in environmental water samples (Badawi et al., 2025).

The available literature does not yet provide enough direct evidence to conclude that NC-nZVI membranes consistently outperform NC only materials for microplastic removal. Some studies demonstrate that NC can capture microplastics, while others show that NC can stabilize nZVI for the removal of dissolved contaminants. However, these two lines of evidence should not be combined as proof that NC-nZVI has already been experimentally validated for microplastic remediation. The present evidence should therefore be interpreted as promising but incomplete. Direct

comparisons between NC only, nZVI only and NC-nZVI membranes are required before contribution of nZVI to microplastic capture, aggregation or degradation can be confirmed.

5.6 Environmental and ecotoxicological risks of nZVI leaching and nanomaterial release

Although immobilizing nZVI within NC matrix may reduce nanoparticle aggregation and improve material handling, it does not eliminate environmental risk. The main safety concern is the possible release of iron nanoparticles or dissolved iron species during filtration, cleaning, regeneration or disposal of the spent membrane. In aqueous environments, nZVI can oxidize to iron oxides and release Fe^{2+} and Fe^{3+} ions. At controlled levels, iron is an essential element, but excess dissolved iron and reactive iron surfaces may contribute to oxidative stress and biological disturbance (Zeng et al., 2023).

The toxicity of released nZVI is strongly context dependent. Important controlling factors include nZVI loading, particle size, surface coating, oxidation state, water pH, dissolved oxygen, ionic strength, natural organic matter and exposure duration. Potential biological effects reported for nZVI include membrane damage, oxidative stress, changes in microbial activity and adverse effects on aquatic organisms. These effects are particularly relevant for water treatment applications because released nanoparticles or ions could enter downstream aquatic systems if the membrane is damaged or insufficiently retained (Keller et al., 2012).

For NC- nZVI membranes, risk assessment should therefore consider both particulate release and ionic leaching. Particulate release refers to the detachment of nZVI or NC- nZVI fragments from the membrane structure. Ionic leaching refers to the release of dissolved iron species during nZVI corrosion or oxidation. These processes should be measured separately because they have different implications for membrane stability, treatment performance and ecotoxicity. A membrane that retains high microplastic

removal efficiency may still be unsuitable for application if it releases unacceptable quantities of nanoparticles or dissolved iron.

The spent membrane also represents a secondary risk pathway. During operation, the membrane may cumulate microplastics, nanoplastics, absorbed pollutants, biofilm and iron corrosion products. If the membrane is regenerated, cleaning solutions should be assessed for released microplastics, iron species and nanomaterials. If the membrane is discarded, disposal procedures should prevent the re-entry of captured plastics and embedded nanoparticles into the environment.

Future NC-nZVI studies should therefore include leaching and ecotoxicological endpoints alongside removal efficiency. At minimum, studies should report dissolved iron, Fe^{2+} and Fe^{3+} speciation where possible, nanoparticle release, membrane mass loss, changes in nZVI oxidation state after use, and biological response assays using environmentally relevant organisms or microbial communities. Control experiments using NC only, nZVI only and blank membranes are also necessary to identify whether observed toxicity originates from the nanocellulose matrix, released iron, detached nanoparticles, captured microplastics or transformation products. Without these safety data, NC- nZVI membranes should be considered promising experimental materials rather than environmentally validated treatment systems.

5.7 Scalability, membrane fouling, operational cost and long term field performance

The practical application of NC- nZVI membranes depends not only on microplastic removal efficiency but also on whether the material can be produced reproducibly, operated for long periods and regenerated without releasing secondary contaminants. At present, most studies relevant to NC-based microplastic removal are laboratory scale investigations using small membrane areas, controlled water chemistry and model plastic particles. These conditions are useful for mechanistic evaluation, but they do not fully

represent the hydraulic, chemical and biological complexity of municipal wastewater, industrial effluents or natural waters.

Scalability: Large scale production of NC- nZVI membranes requires consistent control of nanocellulose quality, nZVI particle size, nZVI loading, particle dispersion and membrane thickness. Variation in NC source, pretreatment method, fibrillation intensity and surface functionalization can affect membrane porosity, mechanical strength and adsorption behaviour. Similarly, nZVI synthesis must control aggregation, oxidation and uneven particle distribution within the NC matrix. These factors are manageable at laboratory scale but may become difficult during batch to batch production. Future studies should therefore report synthesis yield, membrane area produced per batch, nZVI loading, iron distribution, mechanical strength and reproducibility across multiple fabrication batches.

Membrane fouling: Fouling is likely to be a major operational limitation because real water contains suspended solids, natural organic matter, salts, bio-film forming microorganisms and co-contaminants in addition to microplastics. Fouling may occur through pore blockage, cake layer formation, adsorption of organic matter, biofouling and deposition of iron corrosion products. In NC- nZVI membranes, nZVI oxidation or passivation may further alter pore structure and reduce reactive surface availability. Therefore, removal efficiency alone is not sufficient to assess practical performance. Studies should report initial pure water flux, microplastic contaminated water flux, flux decline, reversible and irreversible fouling, cleaning method, flux recovery ratio and performance after repeated filtration cleaning cycles.

Operational cost: The cost of NC- nZVI membrane application will depend on the source and pretreatment of biomass, energy required for nanocellulose production, iron precursor cost, reducing and stabilizing agents, solvent and water consumption, membrane casting or drying processes, supporting materials, module fabrication, cleaning chemicals, regeneration frequency and final disposal of spent membranes. Although the use of agricultural waste

for NC production may improve sustainability, it does not automatically guarantee low cost because purification, fibrillation and drying can be energy intensive. Similarly, nZVI increases material functionality but may add costs related to synthesis, oxidation control, safety monitoring and leaching assessment. At present, the available literature does not provide enough standardized cost data to estimate treatment cost data to estimate treatment cost per unit volume of water. Future studies should include techno-economic analysis comparing NC- nZVI with NC-only with NC only membranes, conventional membranes and other nano enabled treatment systems.

Long term field performance: Long term field validation remains one of the largest evidence gaps. Laboratory studies often use pristine spherical polystyrene or other model particles, whereas environmental microplastic vary in polymer type, size, shape, surface oxidation, biofilm coverage and contaminant loading. Real wastewater also contains competing particles and dissolved constituents that may reduce adsorption, accelerate fouling or alter nZVI reactivity. Pilot-scale testing should therefore be conducted using real wastewater or natural water matrices over extended operating periods. Such studies should monitor removal efficiency, water flux, pressure requirements, fouling development, cleaning effectiveness, membrane integrity, nZVI oxidation, iron leaching, nanoparticle detachment and the fate of retained microplastics.

Overall, NC- nZVI membrane remain promising but are not yet ready to be considered industrially validated. Demonstrating laboratory removal efficiency is only the first step. For practical deployment, future research must show that these membranes can be manufactured reproducibly, operated at meaningful flow rates, cleaned and reused without major performance loss, and applied in real water matrices without unacceptable nanomaterial release or excessive cost.

6.0 Limitations of this review

The findings of this review should be interpreted in light of some limitations. First, the restriction to English-language literature and the potential

exclusion of non-digitized or unpublished works may introduce linguistic and publication biases. Second, despite the application of a systematic methodology, inconsistencies in terminology and indexing across databases may have led to the omission of relevant studies; specifically, although the search strategy targeted conventional methods, composite membranes, NC, and nZVI, pertinent research using hybrid nomenclature may have been overlooked. Third, data heterogeneity regarding microplastic type, size, membrane composition, water chemistry, operating conditions and reporting units precluded a formal meta-analysis of effect sizes. To partially address this limitation, a descriptive quantitative synthesis of reported percentage removal or rejection and was not weighted by sample size, membrane area, operating pressure or experimental uncertainty. It should therefore be interpreted as a descriptive summary rather than a pooled estimate of treatment performance. Fourth, as this study relies on secondary data rather than primary fieldwork, the conclusions reflect reported efficacy rather than empirically observed practices. Notwithstanding these constraints, this review offers a transparent synthesis of the current landscape. It confirms the consistently high removal performance of NC-based membranes (Sayam et al., 2025) while underscoring the necessity for future multilingual and field-based inquiries to advance emerging microplastic removal technologies. Finally, there's lack of direct experimental evidence distinguishing microplastic capture from polymer degradation in NC- nZVI systems. The most available removal data describe decreases in aqueous microplastic concentrations and do not establish polymer chain cleavage, transformation product formation or mineralization. In addition, there's limited availability of leaching and ecotoxicological data for NC- nZVI membranes used in microplastic remediation. Most studies emphasize removal efficiency, adsorption capacity or material synthesis while fewer studies report nanoparticle detachment, dissolve iron release, ecotoxicological endpoints or the environmental fate of spent membranes. As a result, this review cannot determine whether NC- nZVI membranes are environmentally safe under

long-term operating conditions. Future studies should integrate removal performance with leaching tests, regeneration studies, toxicity assays and end of life assessment. Consequently, the present review cannot determine whether NC- nZVI membranes chemically degrade microplastics, and this question remains a priority for future experimental degradation. Furthermore, studies included in this review examine NC only materials, NC combined with other nanoparticles, nZVI supported on NC for non-plastic contaminants or broader review level evidence. These studies are useful for developing the mechanistic rationale for NC-nZVI systems, but they do not provide direct validation of NC-nZVI membranes for microplastic removal. This limitation has been addressed by classifying the evidence as direct or indirect and by avoiding conclusions that exceed the available experimental support.

7.0 Conclusion and future perspectives

This review confirms that microplastic pollution remains a persistent challenge for aquatic systems as well as humans. Conventional treatment methods have important limitations, especially for small microplastics and nanoplastics under complex water matrix conditions. Nanocellulose based materials offer a promising bio-based platform because their high surface area, porous fibrillar networks and modifiable surface chemistry can support microplastic adsorption and physical retention.

The specific integration of nanocellulose with nZVI should be viewed as a prospective strategy rather than a fully validated microplastic treatment technology. The available literature provides useful indirect evidence: nanocellulose can capture microplastics in several experimental systems and nanocellulose can stabilize nZVI and reduce aggregation in studies targeting dissolved contaminants. However, the number of direct comparative studies testing NC- nZVI membranes against microplastics remains limited and the available data are largely derived from controlled laboratory experiments using model particles and simplified water matrices. Therefore, the current evidence does not yet permit a definitive conclusion that NC- nZVI membranes

consistently outperform NC only or nZVI only systems for microplastic removal.

On the basis of the available evidence, the main value of NC- nZVI lies in its design rationale. NC may provide the renewable, hydrophilic and porous capture matrix, while immobilized nZVI may contribute additional reactive or adsorptive sites and may support the removal of co-occurring dissolved contaminants. Nevertheless, claims regarding polymer degradation, long-term fouling resistance, reusability, nanomaterial stability and performance in real wastewater remain insufficiently resolved. Future research should therefore prioritize .. Concurrently, immobilizing nZVI within this matrix can limit nanoparticle aggregation and preserve reactive surface sites for the removal of selected dissolved contaminants. However, direct degradation of microplastic polymer chains by NC- nZVI membranes has not yet been demonstrated..Current empirical evidence supports high microplastic removal efficiencies for several NC based and related nanocomposite materials. However, direct comparative evidence for NC-nZVI membranes remains insufficient. Therefore, the superior performance of NC-nZVI over NC only or nZVI only systems should be treated as a hypothesis requiring further experimental validation rather than as an established conclusion. Furthermore, the multifunctionality of these materials—capable of sequestering MPs while degrading co-occurring organic pollutants—positions them as robust solutions for complex wastewater matrices. Utilizing agricultural waste for NC production further aligns this technology with circular economy principles and SDG 6.

Despite these promising laboratory-scale results, the transition to industrial application faces significant hurdles. Scalability remains a primary challenge, as producing high-purity NC and nZVI is energy-intensive, necessitating the development of cost-effective green synthesis methods. Moreover, current data relies heavily on short-term experiments using model particles such as spherical polystyrene, highlighting a lack of pilot-scale trials assessing fouling resistance and hydraulic stability in real-world effluents. The field is

further complicated by the absence of standardized metrics for nanoplastic removal, which prevents rigorous meta-analysis, and by unresolved concerns regarding ecotoxicological safety. Specifically, the long-term stability of nanocomposites requires rigorous life-cycle assessments to evaluate the potential leaching of iron or nanomaterials, and to ensure that remediation agents do not introduce new environmental risks.

To advance the field accordingly, NC- nZVI membranes should presently be regarded as a promising research direction rather than an industrially validated treatment technology. Their practical relevance will depend on future evidence demonstrating scalable fabrication, acceptable operational cost, long term fouling control, membrane regeneration, field stability and environmental safety under realistic water treatment conditions. Life cycle assessment, cost analysis and standardized reporting protocols will also be essential before this technology can be recommended for large scale water treatment. Future investigations should establish whether NC- nZVI membranes merely transfer microplastics from water to the membrane or can promote genuine polymer transformation under defined reaction conditions. Any claim of degradation should be supported by evidence of polymer chain modification, molecular weight reduction, transformation product formation and where applicable, mineralization. Researchers should also determine whether treatment produces smaller plastic fragments, because fragmentation without mineralization could increase the formation of nanoplastic rather than eliminate the plastic contaminant. In addition, future studies should directly test NC only, nZVI only, NC-nZVI membranes under identical conditions. Such work should report microplastic type, size, concentration, water chemistry, membrane fabrication method, flux, rejection, fouling behaviour, reusability, iron leaching, ecotoxicological endpoints and any evidence of polymer transformation. This will allow the field to determine whether NC-nZVI offers a real performance advantage over related NC based or iron-containing systems. Furthermore, future studies should test NC-nZVI and related NC based membranes using environmental

relevant polymer types including PE, PP, PET, PVC and weathered mixed microplastics rather than just relying mainly on model polystyrene particles. From a policy perspective, regulatory frameworks must evolve to establish clear discharge limits for nanoplastics and safety standards for the use of nanomaterials in water treatment. Ultimately, NC-nZVI composite membranes offer a highly effective, bio-based solution for MP remediation, and overcoming these remaining engineering and regulatory challenges will be key to deploying this technology as a cornerstone of next-generation water security.

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The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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References

- Abdel Maksoud, M. I. A., Elgarahy, A. M., Farrell, C., Al-Muhtaseb, A. H., Rooney, D. W., & Osman, A. I. (2020). Insight on water remediation application using magnetic nanomaterials and biosorbents. *Coordination Chemistry Reviews*, 403(January). <https://doi.org/10.1016/j.ccr.2019.213096>
- Abdelhamid, H. N. (2024). Nanocellulose-Based Materials for Water Pollutant Removal: A Review. *International Journal of Molecular Sciences*, 25(15). <https://doi.org/10.3390/ijms25158529>
- Abdelmouleh, M., Boufi, S., Belgacem, M. N., Duarte, A. P., Ben Salah, A., & Gandini, A. (2004). Modification of cellulosic fibres with functionalised silanes: Development of surface properties. *International Journal of Adhesion and Adhesives*, 24(1), 43-54. [https://doi.org/10.1016/S0143-7496\(03\)00099-X](https://doi.org/10.1016/S0143-7496(03)00099-X)
- Acarer, S. (2023). A review of microplastic removal from water and wastewater by membrane technologies. *Water Science and Technology*, 88(1), 199-219. <https://doi.org/10.2166/wst.2023.186>
- Ahankari, S., George, T., Subhedar, A., & Kar, K. K. (2020). Nanocellulose as a sustainable material for water purification. *SPE Polymers*, 1(2), 69-80. <https://doi.org/10.1002/pls2.10019>

- Ali, I., Wang, Y., Li, W., Han, J., Lu, H., Naz, I., & Gao, W. (2025). *International Journal of Biological Macromolecules* Recent innovations in the developments of biopolymer-based materials for the removal of micro- and nanoplastics : A review of performance , critical factors , practicability and knowledge gaps. 331(October), 2359595.
- Ali, I., Wang, Y., Li, W., Noman, M., Han, J., & Naz, I. (2026). *Highly efficient and biodegradable alginate-Polydopamine-mixed matrix three-dimensional membrane capsules for the broad-Spectrum removal of diverse Nanoplastics in complex water environments* ☆. 394(February), 137617.
- Ali, I., Wei, L., Jiangang, H., Saroj, D. P., & Naz, I. (2025). Remediation of micro- and nanoplastics by robotic technology : Performance , critical factors and marketing barriers. *Journal of Environmental Management*, 394(April), 127257. <https://doi.org/10.1016/j.jenvman.2025.127257>
- Ali, I., Wei, L., Jiangang, H., Wei, G., Yue, W., & Naz, I. (2025). Corrigendum to “ Robot-based materials for the remediation of plastic particles : Synthesis modulations , motion behaviors and influencing factors .” *Materials Today Chemistry*, 50(September), 103039. <https://doi.org/10.1016/j.mtchem.2025.103039>
- Altammar, K. A. (2023). A review on nanoparticles: characteristics, synthesis, applications, and challenges. *Frontiers in Microbiology*, 14(April), 1–20. <https://doi.org/10.3389/fmicb.2023.1155622>
- Arbabi, A., Gholami, M., Farzadkia, M., & Djalalinia, S. (2023). Microplastics removal technologies from aqueous environments: a systematic review. *Journal of Environmental Health Science and Engineering*, 21(2), 463–473. <https://doi.org/10.1007/s40201-023-00872-z>
- Arossa, S., Martin, C., Roszbach, S., & Duarte, C. M. (2019). Microplastic removal by Red Sea giant clam (*Tridacna maxima*). *Environmental Pollution*, 252, 1257–1266. <https://doi.org/10.1016/j.envpol.2019.05.149>
- Badawi, A. K., Hasan, R., & Ismail, B. (2025). Sustainable coagulative removal of microplastic from aquatic systems: recent progress and outlook. *RSC Advances*, 15(31), 25256–25273. <https://doi.org/10.1039/d5ra04074d>
- Baig, N., Kammakakam, I., Falath, W., & Kammakakam, I. (2021). Nanomaterials: A review of synthesis methods, properties, recent progress, and challenges. *Materials Advances*, 2(6), 1821–1871. <https://doi.org/10.1039/d0ma00807a>
- Bokov, D., Turki Jalil, A., Chupradit, S., Suksatan, W., Javed Ansari, M., Shewael, I. H., Valiev, G. H., & Kianfar, E. (2021). Nanomaterial by Sol-

- Gel Method: Synthesis and Application. *Advances in Materials Science and Engineering*, 2021. <https://doi.org/10.1155/2021/5102014>
- Conesa, J. A., & Ortuño, N. (2022). Reuse of Water Contaminated by Microplastics, the Effectiveness of Filtration Processes: A Review. *Energies*, 15(7), 1-16. <https://doi.org/10.3390/en15072432>
- Cristaldi, A., Fiore, M., Zuccarello, P., Conti, G. O., Grasso, A., Nicolosi, I., Copat, C., & Ferrante, M. (2020). Efficiency of wastewater treatment plants (Wwtps) for microplastic removal: A systematic review. *International Journal of Environmental Research and Public Health*, 17(21), 1-23. <https://doi.org/10.3390/ijerph17218014>
- Duis, K., & Coors, A. (2016). Microplastics in the aquatic and terrestrial environment: sources (with a specific focus on personal care products), fate and effects. *Environmental Sciences Europe*, 28(1), 1-25. <https://doi.org/10.1186/s12302-015-0069-y>
- Ebrahimbabaie, P., Yousefi, K., & Pichtel, J. (2022). Photocatalytic and biological technologies for elimination of microplastics in water: Current status. *Science of the Total Environment*, 806. <https://doi.org/10.1016/j.scitotenv.2021.150603>
- Elhenawy, S., Khraisheh, M., AlMomani, F., Al-Ghouti, M., Selvaraj, R., & Al-Muhtaseb, A. (2024). Emerging Nanomaterials for Drinking Water Purification: A New Era of Water Treatment Technology. *Nanomaterials*, 14(21). <https://doi.org/10.3390/nano14211707>
- Enfrin, M., Dumée, L. F., & Lee, J. (2019). Nano/microplastics in water and wastewater treatment processes – Origin, impact and potential solutions. *Water Research*, 161, 621-638. <https://doi.org/10.1016/j.watres.2019.06.049>
- Eyley, S., & Thielemans, W. (2014). Surface modification of cellulose nanocrystals. *Nanoscale*, 6(14), 7764-7779. <https://doi.org/10.1039/c4nr01756k>
- Fadare, O. O., & Okoffo, E. D. (2020). Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID- 19 . The COVID-19 resource centre is hosted on Elsevier Connect , the company ' s public news and information. *Science of the Total Environment*, January.
- Faria, M., Gomes, M., Mendonça, I., Kaufmann, M., Ferreira, A., & Cordeiro, N. (2022). *Bacterial cellulose biopolymers : The sustainable solution to water-polluting microplastics*. 222(August). <https://doi.org/10.1016/j.watres.2022.118952>

- Fazli, A., Athanassiou, A., & Fragouli, D. (2025). *Current Approaches and Challenges in Advanced Oxidation Processes for Nanoplastic Degradation*. 04352. <https://doi.org/10.1002/advs.202504352>
- Geyer, R., Jambeck, J. R., & Law, K. L. (2017). Production, use, and fate of all plastics ever made. *Science Advances*, 3(7), 25-29. <https://doi.org/10.1126/sciadv.1700782>
- Guerranti, C., Martellini, T., Perra, G., Scopetani, C., & Cincinelli, A. (2019). Microplastics in cosmetics: Environmental issues and needs for global bans. *Environmental Toxicology and Pharmacology*, 68(March), 75-79. <https://doi.org/10.1016/j.etap.2019.03.007>
- Hassan, M., Berglund, L., Hassan, E., Abou-Zeid, R., & Oksman, K. (2018). Effect of xylanase pretreatment of rice straw unbleached soda and neutral sulfite pulps on isolation of nanofibers and their properties. *Cellulose*, 25(5), 2939-2953. <https://doi.org/10.1007/s10570-018-1779-2>
- He, S., Jia, M., Xiang, Y., Song, B., Xiong, W., Cao, J., Peng, H., Yang, Y., Wang, W., Yang, Z., & Zeng, G. (2022). Biofilm on microplastics in aqueous environment: Physicochemical properties and environmental implications. *Journal of Hazardous Materials*, 424(PB), 127286. <https://doi.org/10.1016/j.jhazmat.2021.127286>
- Hou, L., Xi, J., Liu, J., Wang, P., Xu, T., Liu, T., Qu, W., & Lin, Y. B. (2022). Biodegradability of polyethylene mulching film by two *Pseudomonas* bacteria and their potential degradation mechanism. *Chemosphere*, 286(July 2021), 131758. <https://doi.org/10.1016/j.chemosphere.2021.131758>
- Iyare, P. U., Ouki, S. K., & Bond, T. (2020). Microplastics removal in wastewater treatment plants: A critical review. *Environmental Science: Water Research and Technology*, 6(10), 2664-2675. <https://doi.org/10.1039/d0ew00397b>
- Jaafarzadeh Haghighi Fard, N., Jahedi, F., & Dehdarirad, H. (2023). The Possibility of Microplastic Removal by Earthworms and Comparing With Conventional Chemical Removal Methods (A Global and Deeply Systematic Review). *Journal of Polymers and the Environment*, 31(12), 5050-5064. <https://doi.org/10.1007/s10924-023-02954-3>
- Karbalaei, S., Hanachi, P., Walker, T. R., & Cole, M. (2018). Occurrence, sources, human health impacts and mitigation of microplastic pollution. *Environmental Science and Pollution Research*, 25(36), 36046-36063. <https://doi.org/10.1007/s11356-018-3508-7>
- Keller, A. A., Garner, K., Miller, R. J., & Lenihan, H. S. (2012). *Toxicity of*

- Nano-Zero Valent Iron to Freshwater and Marine Organisms*. 7(8), 1–10.
<https://doi.org/10.1371/journal.pone.0043983>
- Kim, S., Sin, A., Nam, H., Park, Y., Lee, H., & Han, C. (2022). Advanced oxidation processes for microplastics degradation: A recent trend. *Chemical Engineering Journal Advances*, 9, 100213.
<https://doi.org/10.1016/J.CEJA.2021.100213>
- Koelmans, A. A., Mohamed Nor, N. H., Hermesen, E., Kooi, M., Mintenig, S. M., & De France, J. (2019). Microplastics in freshwaters and drinking water: Critical review and assessment of data quality. In *Water Research* (Vol. 155, pp. 410–422). Elsevier Ltd.
<https://doi.org/10.1016/j.watres.2019.02.054>
- Krueger, M. C., Harms, H., & Schlosser, D. (2015). Prospects for microbiological solutions to environmental pollution with plastics. *Applied Microbiology and Biotechnology*, 99(21), 8857–8874.
<https://doi.org/10.1007/s00253-015-6879-4>
- Li, J., Zhang, K., & Zhang, H. (2018). Adsorption of antibiotics on microplastics. *Environmental Pollution*, 237, 460–467.
<https://doi.org/10.1016/j.envpol.2018.02.050>
- Li, P., Yu, J., Huangfu, Z., Chang, J., Zhong, C., & Ding, P. (2020). Applying modified biochar with nZVI/nFe₃O₄ to immobilize Pb in contaminated soil. *Environmental Science and Pollution Research*, 27(19), 24495–24506. <https://doi.org/10.1007/s11356-020-08458-0>
- Li, R., Zhang, L., & Wang, P. (2015). Rational design of nanomaterials for water treatment. *Nanoscale*, 7(41), 17167–17194.
<https://doi.org/10.1039/c5nr04870b>
- Liu, F., Lu, J., Li, J., Feng, Q., Tan, S., Wang, J., Bao, Z., & Xu, Z. (2024). Efficient microplastics adsorption in aqueous environments via bidirectional ordered graphene oxide/nanocellulose aerogels. *International Journal of Biological Macromolecules*, 282, 137021.
<https://doi.org/10.1016/J.IJBIOMAC.2024.137021>
- Liu, M., Ye, Y., Xu, L., Gao, T., Zhong, A., & Song, Z. (2023). Recent Advances in Nanoscale Zero-Valent Iron (nZVI)-Based Advanced Oxidation Processes (AOPs): Applications, Mechanisms, and Future Prospects. *Nanomaterials*, 13(21). <https://doi.org/10.3390/nano13212830>
- Mondal, S., Das, P., Mondal, A., Paul, S., Pandey, J. K., & Das, T. K. (2024). Remediation of Plastic and Microplastic Waste. In *Remediation of Plastic and Microplastic Waste*. <https://doi.org/10.1201/9781003449133>

- Naji, A., Esmaili, Z., & Khan, F. R. (2017). Plastic debris and microplastics along the beaches of the Strait of Hormuz, Persian Gulf. *Marine Pollution Bulletin*, 114(2), 1057–1062. <https://doi.org/10.1016/j.marpolbul.2016.11.032>
- Namakka, M., Rahman, M. R., Bin Mohamad Said, K. A., & Muhammad, A. (2024). Insights into micro-and nano-zero valent iron materials: synthesis methods and multifaceted applications. *RSC Advances*, 14(41), 30411–30439. <https://doi.org/10.1039/d4ra03507k>
- Nasrollahzadeh, M., Sajjadi, M., Iravani, S., & Varma, R. S. (2021). Starch, cellulose, pectin, gum, alginate, chitin and chitosan derived (nano)materials for sustainable water treatment: A review. *Carbohydrate Polymers*, 251(May 2020), 116986. <https://doi.org/10.1016/j.carbpol.2020.116986>
- Nene, A., Sadeghzade, S., Viaroli, S., Yang, W., Uchenna, U. P., Kandwal, A., Liu, X., Somani, P., & Galluzzi, M. (2025). Recent advances and future technologies in nano-microplastics detection. *Environmental Sciences Europe*, 37(1). <https://doi.org/10.1186/s12302-024-01044-y>
- Nguyen, T., Roddick, F. A., & Fan, L. (2012). Biofouling of water treatment membranes: A review of the underlying causes, monitoring techniques and control measures. *Membranes*, 2(4), 804–840. <https://doi.org/10.3390/membranes2040804>
- Nitodas, S., Skehan, M., Liu, H., & Shah, R. (2023). Current and Potential Applications of Green Membranes with Nanocellulose. *Membranes*, 13(8). <https://doi.org/10.3390/membranes13080694>
- Osman, A. I., Hosny, M., Eltaweil, A. S., Omar, S., Elgarahy, A. M., Farghali, M., Yap, P. S., Wu, Y. S., Nagandran, S., Batumalaie, K., Gopinath, S. C. B., John, O. D., Sekar, M., Saikia, T., Karunanithi, P., Hatta, M. H. M., & Akinyede, K. A. (2023). Microplastic sources, formation, toxicity and remediation: a review. In *Environmental Chemistry Letters* (Vol. 21, Issue 4). Springer International Publishing. <https://doi.org/10.1007/s10311-023-01593-3>
- Ouda, M., Banat, F., Hasan, S. W., & Karanikolos, G. N. (2023). Recent advances on nanotechnology-driven strategies for remediation of microplastics and nanoplastics from aqueous environments. *Journal of Water Process Engineering*, 52(February), 103543. <https://doi.org/10.1016/j.jwpe.2023.103543>
- Padervand, M., Lichtfouse, E., Robert, D., & Wang, C. (2020). Removal of microplastics from the environment. A review. In *Environmental Chemistry Letters* (Vol. 18, Issue 3, pp. 807–828).

<https://doi.org/10.1007/s10311-020-00983-1>

- Padmaja, K., Cherukuri, J., & Anji Reddy, M. (2020). A comparative study of the efficiency of chemical coagulation and electrocoagulation methods in the treatment of pharmaceutical effluent. *Journal of Water Process Engineering*, 34(February), 101153. <https://doi.org/10.1016/j.jwpe.2020.101153>
- Page, M. J., Mckenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-wilson, E., Mcdonald, S., ... Moher, D. (2021). *The PRISMA 2020 statement : an updated guideline for reporting systematic reviews Systematic reviews and Meta-Analyses*. <https://doi.org/10.1136/bmj.n71>
- Pan, Z., Guo, H., Chen, H., Wang, S., Sun, X., Zou, Q., Zhang, Y., Lin, H., Cai, S., & Huang, J. (2019). Microplastics in the Northwestern Pacific: Abundance, distribution, and characteristics. *Science of the Total Environment*, 650, 1913–1922. <https://doi.org/10.1016/j.scitotenv.2018.09.244>
- Pizzichetti, A. R. P., Pablos, C., Álvarez-Fernández, C., Reynolds, K., Stanley, S., & Marugán, J. (2021). Evaluation of membranes performance for microplastic removal in a simple and low-cost filtration system. *Case Studies in Chemical and Environmental Engineering*, 3(October 2020), 0–4. <https://doi.org/10.1016/j.cscee.2020.100075>
- Puteri, M. N., Gew, L. T., Ong, H. C., & Ming, L. C. (2025). Technologies to eliminate microplastic from water: Current approaches and future prospects. *Environment International*, 199(5), 109397. <https://doi.org/10.1016/j.envint.2025.109397>
- Rist, S., Carney Almroth, B., Hartmann, N. B., & Karlsson, T. M. (2018). A critical perspective on early communications concerning human health aspects of microplastics. *Science of the Total Environment*, 626, 720–726. <https://doi.org/10.1016/j.scitotenv.2018.01.092>
- Samari, M., Heydari, R., & Gholami, F. (2024). Nanofiltration membrane functionalized with CuxP nanoparticles: A promising approach for enhanced pesticide removal and long-term stability. *Journal of Cleaner Production*, 445(October 2023), 141352. <https://doi.org/10.1016/j.jclepro.2024.141352>
- Sanjeev, N. O., Vallabha, M. S., & Rabi, R. R. L. (2025). Nanotechnology-based approaches for the removal of microplastics from wastewater: a comprehensive review. *Beilstein Journal of Nanotechnology*, 16, 1607–1632. <https://doi.org/10.3762/bjnano.16.114>

- Sayam, S., Islam, T., Tusti, T. H., & Ghosh, J. (2025). Microplastic removal from wastewater through biopolymer and nanocellulose-based green technologies. *RSC Sustainability*. <https://doi.org/10.1039/d5su00634a>
- Schirinzì, G. F., Pérez-Pomeda, I., Sanchís, J., Rossini, C., Farré, M., & Barceló, D. (2017). Cytotoxic effects of commonly used nanomaterials and microplastics on cerebral and epithelial human cells. *Environmental Research*, 159(September), 579–587. <https://doi.org/10.1016/j.envres.2017.08.043>
- Schymanski, D., Goldbeck, C., Humpf, H. U., & Fürst, P. (2018). Analysis of microplastics in water by micro-Raman spectroscopy: Release of plastic particles from different packaging into mineral water. *Water Research*, 129, 154–162. <https://doi.org/10.1016/j.watres.2017.11.011>
- Sharma, A. K., Choudhary, H., Chauhan, P., & Chaliha, J. (2025). Nanomaterials for the remediation of microplastics in wastewater. *Nano Trends*, 12(September). <https://doi.org/10.1016/j.nwnano.2025.100152>
- Simo, C. A. N., Dika, J. M., & Kede, C. M. (2025). *Materials Advances morinda bark extracts using response surface analysis*. 184–195. <https://doi.org/10.1039/d4ma00714j>
- Song, M., Hu, X., Gu, T., Zhang, W. xian, & Deng, Z. (2022). Nanocelluloses affixed nanoscale Zero-Valent Iron (nZVI) for nickel removal: Synthesis, characterization and mechanisms. *Journal of Environmental Chemical Engineering*, 10(3), 107466. <https://doi.org/10.1016/J.JECE.2022.107466>
- Sun, C., Wang, Z., Chen, L., & Li, F. (2020). Fabrication of robust and compressive chitin and graphene oxide sponges for removal of microplastics with different functional groups. *Chemical Engineering Journal*, 393(February), 124796. <https://doi.org/10.1016/j.cej.2020.124796>
- Sunny, A. R., Sazzad, S. A., Islam, M. A., Mithun, M. H., Hussain, M., Raposo, A., & Bhuiyan, M. K. A. (2025). Microplastics in Aquatic Ecosystems: A Global Review of Distribution, Ecotoxicological Impacts, and Human Health Risks. *Water (Switzerland)*, 17(12), 1–21. <https://doi.org/10.3390/w17121741>
- Tanpichai, S., Quero, F., Nogi, M., Yano, H., Young, R. J., Lindstro, T., Sampson, W. W., & Eichhorn, S. J. (2012). *Effective Young 's Modulus of Bacterial and Microfibrillated Cellulose Fibrils in Fibrous Networks*.
- Tarekegn, M. M., Hiruy, A. M., & Dekebo, A. H. (2021). Nano zero valent iron (nZVI) particles for the removal of heavy metals (Cd²⁺, Cu²⁺ and Pb²⁺) from aqueous solutions. In *RSC Advances* (Vol. 11, Issue 30, pp. 18539–

- 18551). Royal Society of Chemistry. <https://doi.org/10.1039/d1ra01427g>
- Toli, A., Mystrioti, C., & Papassiopi, N. (2024). From Nano Zero-Valent Iron to Nanocomposite Materials for Sustainable Water Treatment. *Sustainability (Switzerland)*, 16(7). <https://doi.org/10.3390/su16072728>
- Trache, D., Tarchoun, A. F., Derradji, M., Hamidon, T. S., Masruchin, N., Brosse, N., & Hussin, M. H. (2020). Nanocellulose: From Fundamentals to Advanced Applications. In *Frontiers in Chemistry* (Vol. 8, Issue May). <https://doi.org/10.3389/fchem.2020.00392>
- Wang, J. H., Mahmoud, M. S., & Mahmoud, A. S. (2022). Integrated Efficiency of Using Nanocellulose-Nano Zero Valent Iron Composite in Water Treatment. In *BioResources* (Vol. 17, Issue 1, pp. 975-992). <https://doi.org/10.15376/biores.17.1.975-992>
- Wang, Y., Ali, I., Li, W., Noman, M., Han, J., Naz, I., Wan, P., Han, X., & Ren, S. (2026). *International Journal of Biological Macromolecules Unveiling the removal mechanism of nanoplastics by hydroxyethylene diphosphonic acid modified sodium alginate three-dimensional membrane capsules : A combined experimental and DFT study*. 362(October 2025), 152096.
- Xiao, Y., Tian, Y., Xu, W., & Zhu, J. (2024). *Photodegradation of Microplastics through Nanomaterials : Insights into Photocatalysts Modification and Detailed Mechanisms*.
- Xu, Q., Poggi, G., Resta, C., Baglioni, M., & Baglioni, P. (2020). Grafted nanocellulose and alkaline nanoparticles for the strengthening and deacidification of cellulosic artworks. *Journal of Colloid and Interface Science*, 576(January 2026), 147-157. <https://doi.org/10.1016/j.jcis.2020.05.018>
- Yadav, C., Chu, K. H., Hassan, Z., Lee, J. H., & Jang, W. D. (2025). Nanocellulose sponges embedding metal oxide nanoparticles for adsorption and photodegradation of microplastics. *Chemosphere*, 386(April), 144614. <https://doi.org/10.1016/j.chemosphere.2025.144614>
- Zeng, G., He, Y., Wang, F., Luo, H., Liang, D., Wang, J., Huang, J., & Yu, C. (2023). *Toxicity of Nanoscale Zero-Valent Iron to Soil Microorganisms and Related Defense Mechanisms : A Review*. 1-17.
- Zhang, N., Li, Y. Bin, He, H. R., Zhang, J. F., & Ma, G. S. (2021). You are what you eat: Microplastics in the feces of young men living in Beijing. *Science of the Total Environment*, 767, 144345. <https://doi.org/10.1016/j.scitotenv.2020.144345>
- Zhang, S., Zhang, F., Jin, L., Liu, B., Mao, Y., & Liu, Y. (2019). Preparation of

spherical nanocellulose from waste paper by aqueous NaOH / thiourea. *Cellulose*, 26(8), 5177-5185. <https://doi.org/10.1007/s10570-019-02434-9>

Zhao, J., Ran, W., Teng, J., Liu, Y., Liu, H., Yin, X., Cao, R., & Wang, Q. (2018). Microplastic pollution in sediments from the Bohai Sea and the Yellow Sea, China. *Science of the Total Environment*, 640-641, 637-645. <https://doi.org/10.1016/j.scitotenv.2018.05.346>

Zhou, W., Huang, D., Chen, S., Du, L., Wang, G., Li, R., & Xu, W. (2023). Modified nano zero-valent iron reduce toxicity of polystyrene microplastics to ryegrass (*Lolium Perenne* L.). *Chemosphere*, 337(March). <https://doi.org/10.1016/j.chemosphere.2023.139152>

Zhuang, J., Rong, N., Wang, X., Chen, C., & Xu, Z. (2022). Adsorption of small size microplastics based on cellulose nanofiber aerogel modified by quaternary ammonium salt in water. *Separation and Purification Technology*, 293, 121133. <https://doi.org/10.1016/J.SEPPUR.2022.121133>