Nature Environment and Pollution Technology
An International Quarterly Scientific Journal
p-ISSN: 0972-6268
(Print copies up to 2016)
e-ISSN: 2395-3454
Vol. 25 | No. 3 | Article ID D1886 | 2026
Original Research Paper
https://doi.org/10.46488/NEPT.2026.v25i03.D1886
Open Access Journal

Nanotechnology in Automotive Wastewater Remediation: Functional Roles, Drawbacks, and Future Prospects

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Abbreviation: Nat. Env. & Poll. Technol.
Website: www.neptjournal.com

Received: 02-10-2025
Revised: 30-12-2025
Accepted: 13-01-2026

Key Words:

Pollutants
Nanomaterials
Wastewater treatment
Nano-enhanced bioremediation
Nano-adsorbents
Nanomembranes
Nano-catalysts
Lifecycle assessment

Citation for the Paper:

Ajuka, L.O., Petinrin, M.O., Idusuyi, N., Oluwasegun, K.M. and Fayomi, O.S., 2026. Nanotechnology in automotive wastewater remediation: Functional roles, drawbacks and future prospect. *Nature Environment and Pollution Technology*, 25(3), D1886. https://doi.org/10.46488/NEPT.2026.v25i03.D1886

Note: From 2025, the journal has adopted the use of Article IDs in citations instead of traditional consecutive page numbers. Each article is now given individual page ranges starting from page 1.

ABSTRACT

An estimated 2.73×10^{12} gallons of water are generated annually in the automotive sector, resulting in complex wastewater streams. Pollutant-free water from this sector is essential for a safe environmental footprint for various applications, as wastewater causes corrosion, equipment blockages, and increased chemical costs via vehicle wash bays, paint/coating shops, plating lines, and coolant handling, mapping nanomaterial functions to automotive-typical contaminants (oils/greases, surfactants, dyes, heavy metals: Pb, Cu, Zn, and Cr). Average water-contaminant loads, including grease and oil (1100 mg.L^{-1}), COD (4500 mg.L^{-1}), and overall suspended solids (3500 mg.L^{-1}), create some level of health risk, and treatment methods have shifted from the physical techniques of gravity separation, dissolved air flotation, and demulsification, which involve nanotechnology, to hybridization. With a per-wash prediction of globally used vehicles in 2015, 218 billion liters of wastewater run off to potential water streams, initiating water-nanoparticle mobility before it can be treated for re-use. Based on their high surface-to-volume ratio, nanoscale size, ordered structure, and filtration competence resulting from their inherent mechanical, thermal, antifouling, and antibacterial properties, nano-engineered materials, including nano-adsorbents, nanomembranes, and nano-catalysts, are specifically used to overcome the limitations of conventional wastewater treatment methods. Oil-based wastewater treated with magnetic sorbent nanoparticles acts as an emulsifier, thereby containing microbes and causing microorganism-infested wastewater. Therefore, an effective means of treating wastewater with a variety of compositions is nanoenhanced bioremediation. Hence, a nanotechnology technique that fuses bioremediation and nano-remediation to achieve nano-enhanced bioremediation for completely enhanced wastewater remediation is proposed to abate environmental pollution. However, long-term risks and lifecycle assessments of nanomaterial deployment in wastewater treatment will further validate the degree of trade-off between its specific automotive service applications and safety, with regulatory frameworks to meet long-term sustainability goals.

1. INTRODUCTION

Automotive manufacturing and service operations generate complex wastewater streams dominated by COD/BOD-rich organics, oils/greases, surfactants, dyes, and heavy metals, profiles that challenge single-stage treatment and motivate the assessment of nanotechnology-enabled options (photocatalysis, nanoadsorbents, nano-membranes) alongside hybrid trains (Fall et al. 2007, Pottekkatt et al. 2025). Automotive industry activities, including component manufacturing, vehicle assembly, drivability, and maintenance, consume and contaminate significant volumes of water, thereby contributing to the global decline in freshwater resources (Babakura et al. 2023, Ali et al. 2019). Based on an Automotive

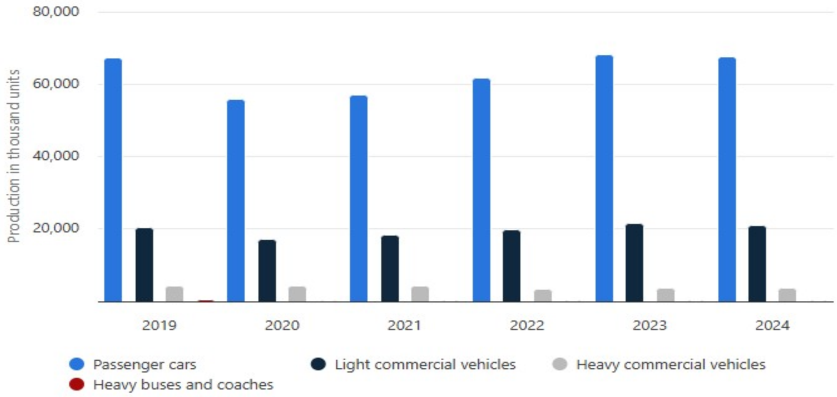

Fig. 1: Global motor vehicle production estimate, 2019-2024, by type (in 1,000 units, Statista 2025).

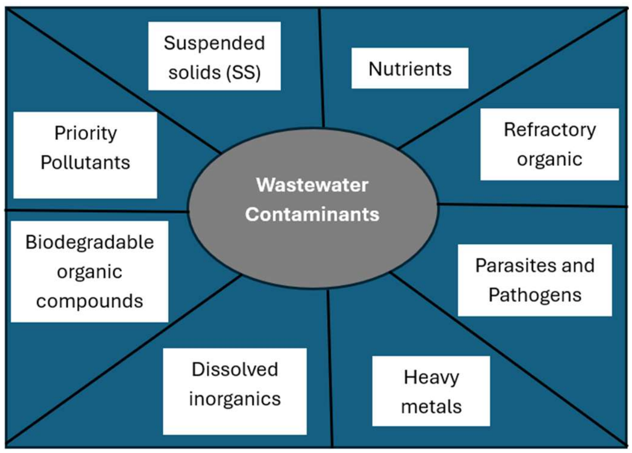

Fig. 2: Categorical wastewater contaminants. (Adapted from Gavrilescu 2010).

World report, producing a single car requires over 39,000 gallons of water, and the inclusion of tire production in the process may lead to variation in the estimate, with total annual consumption exceeding 2.73×10^{12} gallons due to the production of approximately 70 million cars worldwide (Membracon 2025, Karchiyappan 2022). In addition to direct vehicle production, ancillary processes such as electroplating, leather tanning, and textile finishing substantially add to the industry's environmental footprint. Recent statistics confirm that global car production surpassed 90 million units annually, including passenger cars and commercial vehicles (Fig. 1, Statista 2023). Moreover, the global car wash industry alone consumes approximately 218 billion liters of water per month, based on 170 liters used per wash and an estimated 1.3 billion vehicles worldwide (Monney et al. 2020).

The extensive use of water in automotive processes introduces numerous pollutants into wastewater streams. Activities such as painting, surface treatment, coating, rinsing, machining, and cooling generate oily effluents containing heavy metals, hydrocarbons, surfactants, detergents, dyestuff, phosphates, and other hazardous contaminants (Landrigan et al. 2018, Tian et al. 2020). When untreated wastewater is discharged, a common practice in developing countries (Zhongming et al. 2020), it eventually infiltrates rivers, lakes and dams. This not only reduces the availability of clean water but also degrades ecosystems and impacts food chains (Meyer et al. 2019, Chigare et al. 2019). For example, untreated radiator coolants, often replaced with plain water in underdeveloped regions, accelerate scaling and corrosion in vehicle systems while simultaneously releasing toxic byproducts into the surrounding environment (Fig. 2). The cumulative global impact is profound, and services that depend on freshwater consume over 64 billion cubic meters annually, further straining water security under conditions of rapid population growth (UNESCO-WWAP 2014). Beyond conventional pollutants, nanomaterials and nanosized particles released from industrial and automotive sources raise additional concerns.

When dispersed into aquatic environments, nanoparticles can aggregate, alter water pH, and affect temperature, with subsequent ecological consequences (Su et al. 2020, Hanif et al. 2020, Rehman et al. 2019). The instability of highly reactive nanometal oxides under environmental conditions further complicates their long-term behavior and safety (Matlochova et al. 2014). These challenges underscore the dual role of nanotechnology, while potentially hazardous in unmanaged forms, engineered nanomaterials also offer unique advantages for wastewater remediation.

In recent years, nanotechnology has been increasingly explored for its ability to address complex industrial effluents, including those generated by the automotive sector (Fig. 2). Engineered nanomaterials such as MXenes, graphene derivatives, metal organic frameworks (MOFs), and TiO_2-based photocatalysts demonstrate enhanced adsorption capacities, catalytic activity, and antimicrobial effects, enabling efficient removal of oils, heavy metals, dyes, and microbial contaminants from wastewater (Abdulkareem et al. 2023, Zhang et al. 2022, Gnanamoorthy et al. 2022, Abdelfatah et al. 2022, Bagyalakshmi et al. 2025, Zhao et al. 2022, Zhou et al. 2024, Moatmed et al. 2019). These findings position nanotechnology as a critical enabler of advanced water treatment systems, aligning with global calls for sustainable and circular economic solutions (UNESCO-WWAP 2024, Olawade et al. 2013).

Fig. 3 illustrates the increasing research attention devoted to nanotechnology-enhanced wastewater remediation in the automotive sector, as reflected in the increasing number of annual publications indexed in Fig. 3. It underscores the growing recognition of both the severity of automotive wastewater challenges and the promise of advanced nanotechnology-based solutions, but a not yet ready industry-wide adoption, because the technology readiness lags behind scientific activity due to limitations in Pilot-scale validation, standardized performance metrics, insufficient assessment of long-term risks and lifecycle impacts, minimal cost and scalability analysis, and weak regulatory frameworks supporting nanotechnology deployment.

2. AUTOMOTIVE WASTEWATER COMPOSITION

Car-wash and service-station effluents frequently exhibit emulsified oils/greases (~1100 $mg \cdot L^{-1}$), COD (~4500 $mg \cdot L^{-1}$), and TSS (~3500 $mg \cdot L^{-1}$), along with surfactants/detergents, metals, and dyes from paint/coating and plating lines. Gravity separators reduce loads but seldom meet reuse/discharge requirements without additional treatment. To avoid repeating constituent summaries, we provide a single consolidated composition figure/table and reference it later in the text (Fall et al. 2007, Fayed et al. 2023). The consolidated composition showing the constituent details is presented in Fig. 4 and Table 2, respectively.

The automotive industry is among the most water-intensive industrial sectors, relying heavily on water for manufacturing, painting, surface coating, cooling, washing, and cleaning. Each of these processes generates complex wastewater streams containing diverse organic, inorganic, and sometimes toxic contaminants that pose serious risks to the environment if discharged untreated. The documented impacts of these pollutants include aquatic toxicity, oxygen depletion, eutrophication, and bioaccumulation of heavy metals in aquatic organisms, thereby threatening both ecosystems and human health (Bhat et al. 2021, Koul et al. 2022). Although automotive wastewater is predominantly

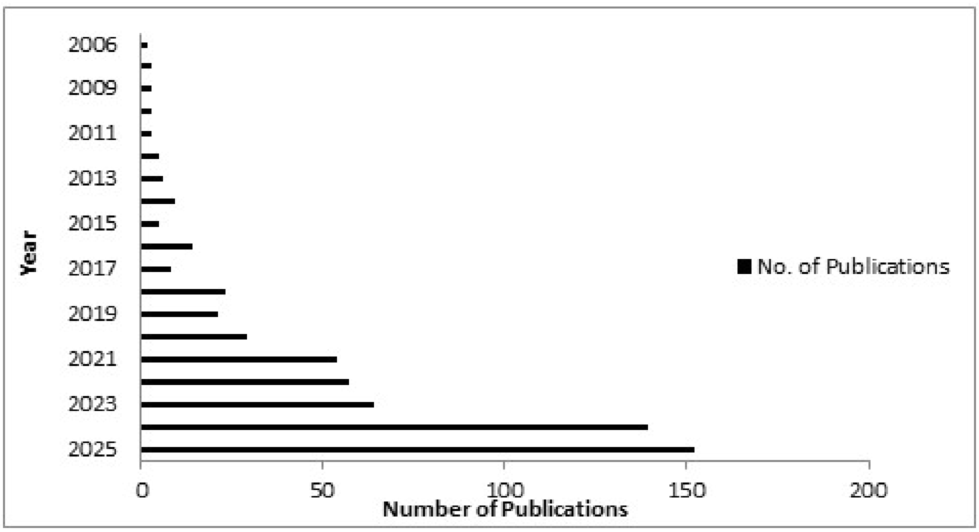

Fig. 3: Number of yearly publications on automotive nano-remediated wastewater [Sciencedirect.com].

water (≈99.9%), the remaining 0.1% comprises a broad array of pollutants with high variability, depending on the process inputs and wastewater sources. These include suspended solids (350–1200 $mg.L^{-1}$), biodegradable organics such as proteins, carbohydrates, and lipids, inorganic solids including sediment, soil particles, and salts, and trace levels of micro-pollutants (Owhonka et al. 2021, Ahmadi et al. 2020). Particulate matter contributes to chemical oxygen demand (COD) values ranging from 250–1000 $mg.L^{-1}$, reflecting a high organic load. In addition, automotive effluents contain toxic compounds, such as hydrocarbons, surfactants, phosphates, and phenolic derivatives, which hinder microbial degradation in conventional treatment systems (Deshpande et al. 2020, Bhat et al. 2021). Notably, approximately 63% of phosphate compounds occur in soluble forms, complicating their removal and exacerbating eutrophication risks when discharged into receiving water bodies (Michael et al. 2023, Deshpande et al. 2020).

The sources of wastewater contributing to this complex mixture are multifaceted and include: Beyond direct automotive operations, wastewater is often aggregated with surface runoffs carrying contaminants from municipal, hospital, and agricultural discharges, thus amplifying the chemical and microbial loads. Typical pollutants include heavy metals such as cadmium, lead, chromium, and zinc from electroplating and metal finishing, as well as oils, greases, and synthetic fluids used in lubricants and coolants (Tian et al. 2020, Landrigan et al. 2018). The persistence of these pollutants in aquatic systems creates long-term ecological footprints, particularly in developing countries where effluent regulation and treatment capacities remain limited (Zhongming et al. 2020). According to Kabdasli et al. (2009), Singh et al. (2017), Ahn et al. (2008), automotive effluents (primarily from emulsion and paint processes) are highly variable depending on the process, but typically exhibit a range of materials (Fig. 4)

The composition of wastewater also dictates the selection of the treatment technologies. High salinity, turbidity, extreme pH levels, and the presence of refractory organics often necessitate multi-stage treatment trains that incorporate primary sedimentation, chemical coagulation–flocculation, and advanced oxidation processes. However, cost remains a critical limitation of this approach. For instance, the distillation-based recovery of high-quality water is prohibitively expensive because of the energy-intensive requirement of multiple consecutive treatment steps (Adham et al. 2018). Although membrane-based desalination and filtration systems are effective, they face constraints such as osmotic pressure thresholds, hydraulic energy demands, fouling, and scaling from mineral precipitation (Dieter et al. 2018, Gude 2018). Although adsorptive systems are cheaper, they often suffer from functional group selectivity and rapid saturation, limiting their long-term application (Crini & Lichtfouse 2019). Recent advances in nanotechnology have opened new pathways for addressing the multifaceted composition of automotive wastewater. Engineered nanomaterials, including metal oxide nanoparticles, graphene-based composites, MXenes, and functionalized nanofibers, offer superior adsorption capacities, catalytic degradation, and antimicrobial properties, enabling the removal of contaminants and the recovery of valuable resources such as metals and oils (Zhou et al. 2024). Moreover, nanotechnology-enabled processes facilitate water reuse and energy recovery, directly supporting industrial sustainability goals and reducing dependence on freshwater withdrawal (Bagyalakshmi et al. 2025, Zhao et al.

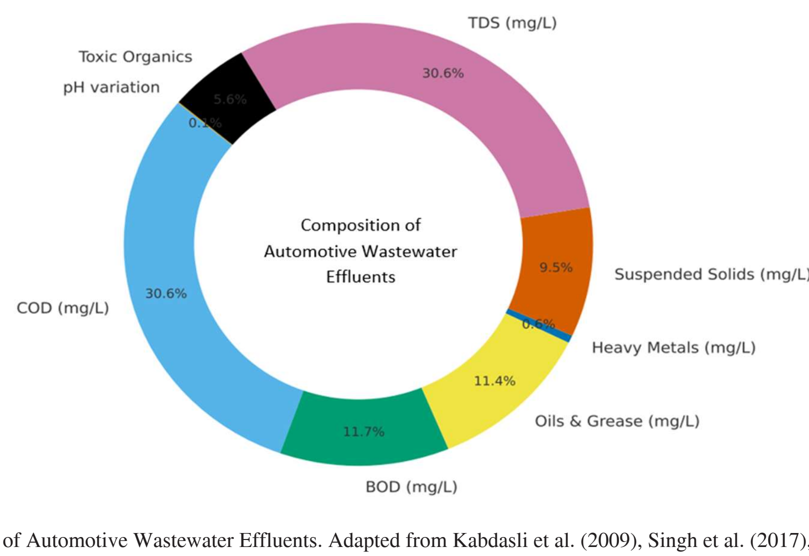

Fig. 4: Composition of Automotive Wastewater Effluents. Adapted from Kabdasli et al. (2009), Singh et al. (2017), and Ahn et al. (2008).

2022). Despite these promising outcomes, several limitations impede the large-scale application of nanotechnology in automotive wastewater remediation. Concerns include the potential ecotoxicity of residual nanomaterials, high production costs, poor stability of nanostructures in complex wastewater matrices, and inadequate frameworks for life cycle management (Crini & Lichtfouse 2019). Furthermore, current research remains fragmented, with insufficient focus on integrating the functional roles of nanotechnology with techno-economic viability, regulatory compliance, and environmental safety assessments. The rapid expansion of the automotive industry has intensified freshwater consumption and wastewater generation, creating critical challenges for global water security. Conventional treatment technologies often fail to adequately remove the diverse pollutants present in automotive effluents, whereas nanotechnology, despite offering superior performance, faces barriers to scalability, safety, and sustainability. Addressing these gaps is urgent, given the escalating climate-driven water scarcity and stricter environmental discharge standards.

This study systematically examines the functional applications, roles, drawbacks, and prospects of nanotechnology in automotive wastewater remediation. The complex mixture of contaminants in Fig. 4 reflects high biodegradability demands. For example, the dominance of COD/BOD fractions (organic load) and suspended solids suggests the need for high-capacity treatments that can be deployed in large-scale facilities in the future. Nanomaterials such as nano-TiO_2, ZnO, and CNT-based composites can be tailored for photocatalysis and adsorption and scale well in membrane or packed-bed systems. Hence, in terms of scalability, the dominance of COD/BOD fractions (organic load) and suspended solids suggests the need for high-capacity treatments that can be deployed in large-scale facilities. Nanomaterials such as nano-TiO_2, ZnO, and CNT-based composites can be tailored for photocatalysis and adsorption and scale well in membrane or packed-bed systems. Regarding safety, the presence of toxic metals (Cr, Ni, Pb, and Cu) and toxic organics (phenols and PAHs) underscores the importance of nanomaterials with selective binding capacity (e.g., functionalized graphene oxide and nano-zero-valent iron). By removing carcinogenic and mutagenic contaminants at trace levels, nanotechnology directly addresses the issues of ecotoxicity and public health risks. Furthermore, the presence of oil, grease, and high TDS levels highlights the need for multifunctional materials. Nanocomposites that combine adsorption, photocatalytic degradation, and antimicrobial activity (e.g., GO/Fe_3O_4 and rGO/$ZnCo_2O_4$) reduce the need for multi-step conventional treatment. This integration lowers operational costs and energy inputs compared to classical methods (e.g., coagulation–flocculation + tertiary oxidation). Finally, by mapping the proportional contributions of pollutants, the Fig. prioritizes the contaminants that require urgent attention. Nanotechnology can then be directed toward high-impact removal targets, such as nanoadsorbents and nZVI for selective binding (heavy metals), photocatalytic nanomaterials for oxidative breakdown (toxic organics), and nano-enhanced membranes for combined organic degradation and microbial disinfection (COD/BOD loads). This demonstrates that no single treatment suffices, but integrated nano-enabled systems offer the scalability, safety, and cost efficiency needed for sustainable automotive wastewater management.

2.1. Classification of Nanomaterials

Different architectures based on features guide nanomaterial classification. For instance, the dimensions of 1-D nanostructures, such as nanowires, nanotubes, and nanofibers, range from 1 to 100 nm. The classifications are presented in Table 1.

2.2. Mobility of Emissive Nanoparticles

Environmental releases of nanoparticles can originate from a variety of sources, including manufacturing facilities, wastewater treatment plants, landfills, and diffuse nonpoint sources such as washing machines, textiles, and consumer products embedded with nanomaterials (Nowack et al. 2007). For example, commercial nanosilver-infused socks have been shown to leach as much as 25% of their total silver content within minutes when exposed to alkaline conditions (pH 10), illustrating the potential for significant nanoparticle discharge from everyday products (Xiu et al. 2012). As shown in Fig. 4, nanoparticle mobility in water bodies is determined by their fundamental characteristics, including solubility in water, physical attachment to other substances, and chemical reactivity, such as oxidation and reduction. These elements, together with the surface charge of the nanoparticles, could cause immobilization.

The process shown in Fig. 5 includes metabolism, water solubility, accumulation in the organism, depot effect, chemical reactivity (oxidation-reduction behavior), physical binding, and aggregation. According to the EPA (2007), biotic or abiotic degradation processes, sunlight-induced photoreactions based on water turbidity, and the anaerobic transformation of some organic and metallic nanomaterials into complex compounds are some of how nanoparticle degradation pathways in aqueous systems can be affected (Nurmi et al. 2005). Several ecotoxicity studies have been conducted to evaluate the environmental concentrations of common nanomaterials. For example, Gottschalk et

Table 1: Categorization of Nanomaterials.

S/ No.	Conditions	Classification	Specific Details	Nanoparticle Examples	Reference
1		0-D	All 3 dimensions are below 100nm with electrons in 3D space. No electron delocalization, meaning freedom to move.	Fullerene	(Rafiei-Sarmazdeh et al. 2020, Afolalu et al. 2023)
2	Numerical Dimension	1-D	Nanostructure has two characteristic dimensions between 1 and 100 nm.	Tubes, fibers, wires, platelets, etc.	
3		2-D	Nanostructure has thin layers that may have a thickness.of at least one atomic layer, having many atoms on its surface.	Graphene, hexa-gonal boon nit-ride (hBN), metal dichalcogenides (MX2), etc.	
4		3-D	Composed of dispersions of nanoparticles, bundles of nanowires, nanotubes, and multi-nanolayers.	Particles, quantum dots, hollow spheres, etc.	
5	Pore Dimension	Microporous	With their <2 nm narrow pores, they are significant for small gases or linear molecules of gases that have high interaction characteristics and slow diffusion rates.	Excellent examples of naturally occurring clay materials and Na-Y are utilized in gas purification.	(Mekuye & Abera 2023)
6		Mesoporous	Their x-pore diameter ranges from 2 nm to 50 nm. frequently seen in adsorbing devices for liquids or vapors, or nanoreactors for polymerization.	MCM-41, MCM-48, SBA-15, and carbon meso-porous materials are a few examples.	(Mekuye & Abera 2023)
7		Macroporous	With pores larger than 50 nm, they can accommodate tiny biological molecules or polyaromatic systems.	Examples are Carbon micro tubes, porous gels, and porous glasses. They are mostly used as sensing materials and scaffolds to graft functional groups, such as catalytic centers.	(Mekuye & Abera 2023)
8	Phase Composition	Single-phase solid	Crystalline, amorphous particles and layers, etc.	High entropy oxide nanoparticles	
9		Multi-phase solid	Matrix composites, coated particles, etc.	Nanorods, nanofibers, CNTs, etc.	(Mekuye & Abera 2023)
10		Multi-phase system	Colloid, aerogels, ferrofluids, etc.	Chitosan, Quantum dot, nanocrystals, etc.	
11	Manufacturing Process	Gas phase reaction	Deposition of thin film onto a substrate is called chemical vapor deposition (CVD). Involves chemical reaction, and the gaseous by-products are toxic.	Silica nanoparticle is a good sample	(Saeed et al. 2020)
12		Liquid phase reaction	Through a heterogeneous reaction including chemical solution precursor, precipitation, and hydrothermal processing, sol-gel creates nanostructured materials. They create a variety of nanogeometries, including nanospheres, nanosheets, nanowires, and nanorods.	includes aerosol-based nanoparticles	(Bokov et al. 2021)
13		Mechanical procedures	Ball milling, plastic deformation, etc.	Includes milled Cuo nanoparticles	(Joy et al. 2022)
14	Origin/Basis	Incidental nanomaterials	Particles from natural combustion, vehicle exhaust (20–130 nm in size for diesel engines and 20–60 nm in size for gasoline), and cosmic dust	CNTs, nanodiamonds, organic-based nanoparticles	(Khan & Hossain 2022, Cho et al. 2019, Westerdahl et al. 2005)
15		Artificial or Engineered nanomaterials	Quantum dots, nanoshells, nanocages, and nanobranches manufactured by humans for use in drug delivery nano-vehicles or immunological sensing devices	Carbon nanoparticles, TiO2 nanoparticles, and hydroxyl-apatites.	(Khan & Hossain 2022, Cho et al. 2019, De Volder et al. 2013)
16		Naturally produced nanomaterials	Binding soluble metals to actinomycetes, plant viruses, nanoorganisms, and nanobes, then precipitating the mixture to create nanoparticles.	Alloys, Non-magnetic oxides, Metal sulfide quantum dots	(Khan & Hossain 2022, Cho et al. 2019).

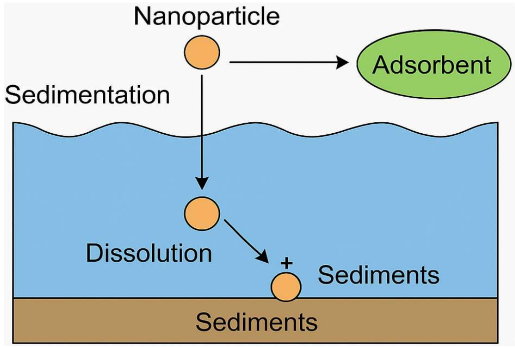

Fig. 5: Mobility characteristics of nanoparticles in water bodies. Adapted from Su et al. (2020), Hanif et al. (2020), and Matlochova et al. (2014).

al. (2009) calculated the risk quotients associated with nanosilver, nano-TiO2, and nano-ZnO in surface water and sewage treatment effluents in the United States, Europe, Switzerland, and Nigeria (Table 2). The brewery wastewater from Enugu, Nigeria, and the oil refineries from Niger-Delta, Nigeria, share a common wastewater composition, as indicated in Table 2. Wastewater treatment greatly depends on the intensive efforts and monitoring of industrial effluents.

The risk quotient of the projected (calculated) environmental concentration and predicted no-impact concentration determines the risk quotient for various nanoparticles in surface water and STP effluents in Europe, the USA, Switzerland, and Nigeria. The table shows that the effluent from sewage treatment plants contains significant ecotoxicity hazards due to nanosilver, nano-ZnO, and nano-TiO2. Even at the surface, the expected concentration of nanosilver in the environment was extremely high.

3. NANOREMEDIATION OF WASTEWATER

Nanotechnology comprises all branches of engineering, including nanosystem physics, nanochemistry, nanomaterials science, nanobiology, nanoelectronics, nanoprocessing, and nanomechanics (Soni & Jha 2024, Malik et al. 2023). In contrast to traditional water purification methods, nanotechnology employs novel techniques such as efficient photocatalysis, membrane filtration to impede microbial

Table 2: Associated risk quotient for different nanoparticles in surface water and STP effluent in Europe, USA, Switzerland, and Nigeria (Gottschalk et al. 2009, Durotoye et al. 2018, Theoneste et al. 2020).

S/No.		Europe	USA	Switzerland	Nigeria			
1	Surface Water STP Effluent	Nano-TiO2 0.015 3.5	0.002 1.8	0.2 3.4	n/a			
2	Surface Water STP Effluent	Nano-ZnO 1.1 61.1	0.17 30.1	1.03 55.6	n/a			
3	Surface Water STP Effluent	Nanosilver <0.0005 <0.0005	<0.0005 <0.0005	<0.0005 <0.0005	n/a			
4	Surface Water STP Effluent	CNT <0.0005 <0.0005	<0.0005 <0.0005	<0.0005 <0.0005	n/a			
5	Surface Water STP Effluent	Fullrenes <0.0005 0.026	<0.0005 0.023	<0.0005 0.019	n/a			
6	ORENDN (I & E)	n/a	n/a	n/a	O & G 15 10	Zinc n/a	Iron n/a	Nickel n/a
7	BR	n/a	n/a	n/a	O & G 2	Zinc 0.01	Iron 28	Nickel 0.01
8	RW	n/a	n/a	n/a	O & G 1	Zinc <0.01	Iron 2	Nickel <0.01

Note: STP - Sewage Treatment Plant, ORENDN – Oil Refinery Effluent in Niger Delta, Nigeria, I & E -, BE - Brewery Effluent, RW – River Water, O & G – Oil and Grease, n/a – not applicable/available/

growth, and disinfection to effectively absorb nanometals and non-metal oxides. According to Yadav et al. (2023), the toxicity of wastewater containing non-biodegradable heavy metals can negatively affect the life of plants, animals, and other living organisms. With metal oxides (Ti, Zn), membranes (ceramic, polymer, nanowire, polymer), carbon nanotubes (CNTs), nanopowder NPs, and other materials, the metal and harmful ions in wastewater can be subjected to photocatalysis, electrochemical oxidation, nanofiltration, and adsorption to improve water quality (Yadav et al. 2022a). Carbonaceous NMs, nano adsorbents, nanofibers, nanoclays (Biswas et al. 2020), zeolites (Murukutti & Jena 2022), dendrites, and nanomaterials (NMs) play vital roles in water treatment. Table 3 lists some of the roles of nanomaterials in water cleanup.

3.1. Nanotechnology-Driven Treatment of Automotive Wastewater

Automotive wastewater streams originating from vehicle wash facilities, paint shops, plating operations, and cooling systems are complex mixtures containing oils, surfactants, dyes, heavy metals (Pb, Cu, Zn, and Cr), and organic solvents, many of which are toxic and non-biodegradable (Egbosiuba et al. 2023, Ullah et al. 2024). Conventional treatment methods often fail to simultaneously address the diversity of pollutants, underscoring the need for advanced nanoremediation approaches.

Nanomaterials (NMs), such as graphene oxides, carbon nanotubes (CNTs), zero-valent iron nanoparticles (nZVI), and metal oxides (TiO_2, ZnO, Fe_3O_4), have shown promise in enhancing the removal of automotive wastewater contaminants. For instance, graphene-based adsorbents exhibit a high surface area and tunable functional groups, enabling the efficient sequestration of heavy metals such as Pb(II) and Cd(II), which are commonly discharged from plating baths (Wu et al. 2020, Luo et al. 2023). Similarly, nZVI and Fe_3O_4 nanocomposites provide reductive and magnetic functionalities, facilitating the removal of Cr(VI) and Ni(II) while allowing easy recovery of the adsorbent (Feng et al. 2022). In paint- and dye-rich effluents, photocatalytic nanomaterials such as TiO_2 and ZnO have been employed to degrade methylene blue, rhodamine B, and other complex organics under UV or solar irradiation, achieving high mineralization efficiency (Shi et al. 2023, Anil et al. 2022). Moreover, nanocomposite membranes integrating TiO_2 or Ag/TiO_2 enhance dye rejection while offering antibacterial and antifouling resistance, making them particularly suitable for car wash water recycling systems (Habib et al. 2020, Yang et al. 2012).

Overall, nanoremediation offers multifunctional benefits by combining adsorption, photocatalysis, and membrane separation to address the multifaceted nature of automotive wastewater. By improving pollutant removal efficiency and enabling water reuse, nanomaterials contribute directly to sustainable automotive operations and compliance with stringent environmental discharge regulations.

3.1.1. Applications of Nanomaterials in Wastewater Remediation

An inclusion of broader industries contaminants ensures wider caption of various automotive-relevant studies, and are justified by mapping contaminants to automotive sources, for example, methylene blue/rhodamine dyes to paint/coating rinses, Pb^{2+}/Cu^{2+}/Zn^{2+}/Cr^{6+} to plating/corrosion, oils/greases to wash bays/maintenance, and units/abbreviations are standardized ($mg \cdot g^{-1}$, %, $L \cdot m^{-2} \cdot h^{-1}$) for cross-comparison (Seyrek et al. 2023, Rajoria et al. 2022), as illustrated in Table 3

Where the units of COD, BOD are in $mg \cdot L^{-1}$, adsorption capacity in $mg \cdot g^{-1}$, membrane flux in $L \cdot m^{-2} \cdot h^{-1}$, TOC (%), removal (%) (Alazaiza et al. 2024).

Table 3 summarizes a wide spectrum of nanomaterials (Nano-adsorbents: Nads) applied for wastewater remediation, including carbon- and graphene-based adsorbents, zero-valent iron (nZVI), metal oxides, nanocomposites, and membrane-supported nanostructures. Across these classes, the adsorption capacities vary significantly from moderate values. For example, in a separate study, Chufa et al. (2021) used a GO nanoadsorbent to achieve a 4.71 qo ($mg.g^{-1}$) fluoride removal compared to the 35.6 $mg.g^{-1}$ fluoride removal reported by Xu and Wang (2017). This is an exceptionally high uptake, such as RGO–PVP at 1689 $mg.g^{-1}$ for Cu(II) (Zhang et al. 2014). This variation underscores the tunability of nanomaterials through structural modification, functionalization, and hybridization with other nanophases.

Contaminant removal is achievable in automotive wastewater treatment, where complex effluents often contain dyes (from paint shops), heavy metals (Pb, Cu, and Zn from plating and corrosion), oils, and organic contaminants. For example, in heavy metal removal, functionalized graphene and nZVI-based composites are deployed (Zou et al. 2016, Feng et al. 2022) to exhibit superior adsorption of Pb(II), Cd(II), Ni(II), and Cr(VI) contaminants, which are common in automotive plating wastewater, and dye degradation GO and $MnFe_2O_4$/rGO systems show high efficiency for methylene blue, malachite green, and rhodamine B (Shi et al. 2023, Chilakapati et al. 2021), directly relevant for treating residues from automotive paint and coating operations (Kusworo et al. 2021), multifunctional nanocomposite membranes (TiO_2 and Ag/TiO-$_2$based membranes not only achieve dye removal but also impart antibacterial and antifouling resistance (Yang et al. 2012, Habib et al. 2020),

Table 3: Automotive-relevant studies on nano-wastewater remediation.

S/N	Class	Nads Type	Adsorption capacity [$mg.g^{-1}$]	Contaminants/Remarks	References
1	Carbon & Graphene related Nads	Graphene	35.6, 89.37	Fluoride, Phosphate	Xu and Wang (2017), Vasudevan and Lakshmi (2012)
2		Graphene-CNT	81.97	Methylene blue	Ai and Jiang (2012)
3		Graphene Oxide (GO)	108.342, 80.775, 71.378	Au(III), Pd(II), Pt (IV), Zn(II)	Liu et al. (2013), Abdullah et al. (2019)
4			149.4	Endocrine-disrupting chemicals (17βEstradiol)	Mohebbi et al. (2025), Zhao et al. (2021)
5			16.83, 63.69	Methyl orange, Basic red 12	Robati et al. (2016)
6			5.496 [$mmoL.g^{-1}$]	Methyl green	Sharma & Das (2013)
7			Enrofloxacin (ENF): 45.035, Rhodamine B (RhB): 107.230	ENF and RhB	Yang et al. (2022)
8		GO- Fe_3O_4	MB: 37.5–108 [at 25 C and 9 pH]	MB	Shi et al. (2023)
9		RGO-PVP, MWCNTs, Nano-sized zero-valent iron	1689, 364.66 $mg.g^{-1}$, NA	Cu(II)	Zhang et al. (2014), Egbosiuba et al. (2023), Li et al. (2014)
10		RGO/Poly (acrylamide), CNTs/MnO_2, MWCNTs-kOH	1000, 78.74, 68.4%±5.0%	Pb (II)	Egbosiuba et al. (2022)
11		Polyethylenimine modified-GO hydrogel	N/A	Pb (II)-602, Hg (II)-374 and Cd (II)-181	Arshad et al. (2019)
12		RO membrane containing Si, Al, and Fe	105 [pH 7.5]	polysaccharides, proteins, and aromatic compounds	Ahmed et al. (2022)
13		$MnFe_2O_4$/reduced GO (MrGO)	Malachite green dye (MG): 156, and MB: 105	MG & MB	Anil et al. (2022)
14		GO/Fe_3O_4/chitosan	MB	Maximum monolayer capacity: 30.10$mg.gm^{-1}$	Tran et al. (2017)
15		rGO/$ZnCo_2O_4$	N/A	Antimicrobial, electrochemical and photocatalytic effect	Gnanamoorthy et al. (2021)
16		rGO/$CuNiO_2$	N/A	MB	Gnanamoorthy et al. (2022)
17		rGO/nZVI		Doxycycline	Abdelfatah et al. (2022)
18	Nano-sized zero-valent iron (nZVI)	nZVI	N/A	Cd(II), Ni (II), Pb (II), Hg(II), Cr(VI)	Feng et al. (2022)
19		Hydrotalcite-supported nZVI	N/A	Nitrate	Fan et al. (2023)
20		Nzvi-Cu bimetals, Solid carbon source/nZVI	N/A	Nitrate	Zhang et al. (2022), Sun et al. (2021)
21	Metal oxide-based NPs	ZnO	MB: 64-83%, COD: 15-53%, TOC: 31-74.12% N/A	MB, COD, TOC MB Dye, Ampicillin (Antibiotic) and MB, Zn (II), Cd (II), Hg (II)	Modi et al. (2023a) Modi et al. (2023b), Soltani et al. (2023), Sheela et al. (2012)
22		Amorphous IONPs from incense sticks ash (ISA)	N/A	Congo Red (CR)	Yadav et al. (2022a)
23		Mesoporous and floral shaped SiO_2 from CFA	N/A	Al, Pb, Cd, Cu, Cr, Ni, Co, Zn, Mn	Yadav et al. (2023)
24		$CaCO_3$ (calcite & vaterite) from ISA	N/A	Methyl Red Dye	Yadav et al. (2022b)
25		Fe_3O_4 NPs (leaf extract of Cola nitida)	MB [530.406 $mg.g^{-1}$] within 1hr.	MB	Mbachu et al. (2023)

Table Cont....

S/N	Class	Nads Type	Adsorption capacity [$mg.g^{-1}$]	Contaminants/Remarks	References
26		ZnO-W	MB: 20-88.21%, COD: 25-85.2, TOC: 46.5-92.04%	MB, COD, TOC	Modi et al. (2023b)
27		ZnO-Sb	MB: 21-91%, COD: 27-88.5, TOC: 48-95.34%	MB, COD, TOC	Modi et al. (2023a)
28	Nanocomposite membrane	Nano-TiO_2	12.2 [$L.\ m^{-2}.h^{-1}$]	Fouling resistance (FR), anti-bacterial, concurrent separation, and photo-catalytic oxidation, TiO2 nanowire growth via hy-drothermal processing photocatalytic under UV degradation of pharmaceuticals	Zhang et al. (2022)
29		Poly (vinylidene fluoride-hexafluoropropylene)-loaded with yttrium carbonate and Fe_3O_4		Removed arsenite (92.82) and arsenate (137.08) mg g−1	Salazar et al. (2022)
30		Cu-Al LDH@ polyvinylidene fluoride (PVDF) membrane (Cu-Al LDH/PVDF)	Adsorption capacity: 17.36 mg g-1	Erythrosin B dye	Abbasi et al. (2021)
31		Boron nitride nanosheets/PVDF	MB dye: 142.86 mg g^{-1}	100% removal of MB 2.2 times higher than the PVDF alone	Bangari et al. (2022)
32		Mesoporous TiO_2/PVDF	N/A	Photocatalytic membrane utilised in the removal of CR: 84%/71% and Reactive Yellow 145 (RY 145): 100%/87%	Erusappan et al. (2021)
33		Chitin nanowhisker/ PVDF (1%:15%)	72.6 mg g^{-1}	The ChNW reinforced PVDF material developed via electrospinning technique achieved an IR dye removal upto 88.9%.	Gopi et al. (2017)
34		NZVI/PVDF		Removed RhB (~80%), 2,4-dichlorophenol (2- CP) and 4-nitrophenol (4-NP) almost 100% within half an hour	He et al. (2020)
35		Ag/TiO_2 nano filter membrane	Bacteria	Authors utilized dip coating method to modify the vsurface of a composite polyamide Nanofiltration (NF) membrane different nanoparticles concentration for enhanced antifouling property. Modification led to bacterial (Bacillus subtilis and Escherichia coli)) growth reduction by 93% and 91% compared to the unmodified.	Habib et al. (2020)
36		Alumoxane-derived alumina membrane	Dye	Authors utilized Fumarate-alumoxane nanoparticles (Fum-ANPs) incorporated into a PES nanofiltration membrane in the enhancement of dye removal and antifouling capacity. It was reported that with the ANPs incorporated PES membrane, the removal efficiency of Direct Red 16 dye with the Fum-ANPs blended PES membrane was 99%, while it was 88.2% for the bare membrane sample.	Moradi, et al. (2023)

Table Cont....

S/N	Class	Nads Type	Adsorption capacity [mg.g^{-1}]	Contaminants/Remarks	References
37		Amino acid homopolymers derived silica membranes	Metal removal using physical (membrane separation, filtration, etc.), chemical (adsorption, ion-exchange, flocculation, etc.), Biological (microbes assisted reme-diation)) and electrochemical technologies.	Authors reviewed the applicability in aqueous media. Various nanomaterials used in heavy metal removal includes carbon based (Graphene, GO, RGO), silicone-based (nanospheres), zero-valent iron (nanoscale zerovalent iron), and magnetic nanoparticles (Iron-oxide based magnetic NP and NC).	Kumar et al. (2021)
38		Polymeric or alumina membranes with Au nanoparticles	4- Nitrophenol-based wastewater treatment using metathesis and anion exchange reactions to stabilize silver (AgNPs) nanoparticles.	Authors developed a stable catalyst for the growing needs in wastewater treatment by catalytic reduction of 4-nitrophenol (4-NP) to 4-aminophenol (4-AP) in the presence of $NaBH_4$. The results indicated that 100% of 4-NP was converted to 4-AP within 6 min and the rate constant (k) was found to be 8.33×10^{-3} s^{-1}.	Naushad et al. (2022)
39		Ruthenium oxide (Ti/ RuO_2)	Polycyclic aromatic hydrocarbons (PAHs) removal from oil and gas wastewater streams. They possess mutagenic, carcinogenic, and teratogenic potential; hence, they are toxic to deoxyribonucleic acid (DNA).	The authors electrochemically oxidised utilising a ruthenium oxide (Ti/RuO_2) anode in a lab-scale electrolytic batch cell. They reported that electrocatalytic oxidation with a Ti/RuO_2 anode is a potentially effective technique for removing PAHs from aqueous solutions.	Isa et al. (2023)
40	Nanocomposite Catalysts	Palladium/sodium borosilicate nanocomposite using *Euphorbia-milii* extract	Chromium (VI), nitro compounds, and organic dyes	Authors reported the timely removal of constituents, thus Cr (VI) – 900s 4-NP - 170s MB – 3s CR – 210s MO – 277s	Nasrollahzadeh et al. (2018)
41		Fe_2O_3 + (GO– Fe_2O_3)	Rhodamine B and 4-nitrophenol	Authors treated wastewater containing pollutants under visible-light irradiation (>420 nm) along with H_2O_2.	Guo et al. (2013)

critical for maintaining long-term performance in recycling car wash wastewater), and catalytic oxidation systems: (nanocomposite catalysts such as Pd/sodium borosilicate (Nasrollahzadeh et al. 2018) demonstrate rapid degradation of nitro-compounds and dyes, offering opportunities for rapid treatment of organic-rich automotive effluents). Overall, the table highlights that nanomaterials provide multi-target remediation capacity (metals, dyes, and microbes), high adsorption efficiencies, and functional versatility. Therefore, their integration into automotive wastewater treatment systems can enhance pollutant removal, support water reuse, and contribute to compliance with stringent environmental regulations in the transportation sector. Despite the many positive attributes of nanomaterials, as indicated in Table 3, they have some limitations, as noted in the next section.

4. DRAWBACKS OF NANOTECHNOLOGY IN WASTEWATER REMEDIATION

The performance impact of nanotechnologies is high when dye-rich paint/coating effluents and mixed-metal streams (Pb, Cu, Zn, Cr), selective adsorbents (GO, nZVI), and photocatalysis (TiO_2/ZrO_2/ZnO, TiO_2–Ag membranes) deliver high removal and antifouling benefits, enabling modular reuse (Seyrek et al. 2023, Fazekas et al. 2024). In contrast, high-oil emulsions lacking effective pre-demulsification and antifouling/self-cleaning surfaces promote fouling, and flux loss persists unless hydrophilic or underwater super-oleophobic and photocatalytic self-cleaning layers are integrated (Huang et al. 2018, Baig & Waheed 2023). Meanwhile, the associated risks and benefits can be quantified via weight fouling, nanotoxicity/release, cost, and stability against measured gains ($mg\cdot g^{-1}$, %, flux, cleaning interval) and include regulatory/LCA perspectives (NNI 2024, Nizam et al. 2021).

The treatment of automotive-related wastewater remains a global issue owing to its heterogeneous and often recalcitrant composition. Conventional wastewater treatment processes, including coagulation, flocculation, sedimentation, activated sludge systems, filtration, and chemical oxidation, have been widely applied in industrial sectors for decades. However, their performance in addressing the complexity of automotive effluents has been questioned, particularly in the context of oily wastewater and emerging pollutants. Fig. 6 highlights the persistent limitations of these conventional methods, which undermine their effectiveness and sustainability (Abuhasel et al. 2021).

One of the most significant issues is membrane fouling, which occurs in pressure-driven processes such as ultrafiltration, nanofiltration, and reverse osmosis. Fouling results from the accumulation of oil droplets, suspended solids, and microbial biofilms on membrane surfaces, leading to rapid permeability loss, shortened operational life, and increased chemical cleaning requirements (Medeiros et al. 2022, Sisay et al. 2023, Jang et al. 2021). Similarly, corrosion in metallic treatment units caused by acidic and saline conditions compromises the durability of the infrastructure, while also generating secondary contaminants such as dissolved iron, copper, or zinc ions (Ekerenam et al. 2025). Sedimentation and sludge generation are also problematic in coagulation–flocculation systems, which are traditionally applied to automotive effluents to remove suspended solids, oil, and dyes. These processes often yield large volumes of sludge containing heavy metals and toxic hydrocarbons, creating further challenges for safe disposal and increasing operational costs (Muvel et al. 2013, Crini and Lichtfouse 2019). Furthermore, these methods typically require high chemical inputs, raising concerns about sustainability and potential secondary pollution (Kadadou et al. 2024).

Another limitation is the high energy consumption of conventional treatment trains. For example, distillation and thermal evaporation processes, while effective in reducing salinity and recovering water, are highly energy-intensive and economically impractical for large-scale deployment in automotive manufacturing plants (Adham et al. 2018, Gude 2018). Pressure-driven systems similarly require high operational pressures to overcome osmotic gradients in oily or saline effluents, further increasing costs (Dieter et al. 2018). The complex nature of oily wastewater presents additional challenges to its treatment. Automotive effluents frequently contain free oil, emulsified oil, and chemically stabilized oil–water emulsions (O/W). Conventional gravity separation or skimming systems are insufficient to destabilize these emulsions, which remain stable owing to the presence of surfactants, lubricants, and fine particulates in automotive processes (Medeiros et al. 2022, Abuhasel et al. 2021). Advanced chemical demulsifiers and electrocoagulation techniques offer improvements but are often expensive and may still leave residual oil fractions (Zhang et al. 2022).

In addition to these technical challenges, environmental and regulatory issues persist. Many conventional treatment systems do not adequately remove emerging contaminants, such as microplastics, nanoparticles, and recalcitrant organic molecules, which accumulate in receiving water bodies and pose risks to ecosystems and public health (Hanif et al. 2020, Singh et al. 2017). Moreover, the variability in wastewater composition between facilities (painting shops, electroplating lines, radiator manufacturing, and car washes) complicates the standardization of treatment protocols, necessitating costly site-specific customization.

To address these challenges, scientific and technological advancements have increasingly shifted toward modern and integrated treatment systems. These include hybrid membrane bioreactors (MBR), electrochemical oxidation coupled with adsorption, advanced oxidation processes (AOPs) such as ozonation and photocatalysis, and nanotechnology-enabled separation systems (Aziz et al. 2025, Asheghmoalla & Mehrvar 2024). Integrated approaches aim to overcome the limitations of individual methods. For example, coupling adsorption with photocatalysis enhances both the removal efficiency and degradation of persistent pollutants, whereas hybrid membranes with nanomaterial coatings mitigate fouling and extend their lifespan (Paiu et al. 2025, Ahmed et al. 2025). Nevertheless, while integrated methods show promise, challenges remain regarding their scalability, cost-effectiveness, and environmental safety. Thus, the limitations of conventional wastewater treatment highlight the urgent need for innovative, multifunctional, and sustainable technologies that can address the diverse contaminant profile of automotive wastewater while minimizing energy and resource footprints.

Although improved heat transmission in base fluids can be a significant benefit of nanotechnology, which has allowed for the execution of sophisticated mathematical computations using smartphones instead of supercomputers or portable chips with hundreds of memory cells, the high thermal conductivity (TC), specific heat, and thermoelectric properties of nanoparticles in the advancement of nanotechnology in general production, especially in the manufacturing of pharmaceuticals and atomic weapons, have resulted in contamination that has negatively affected the

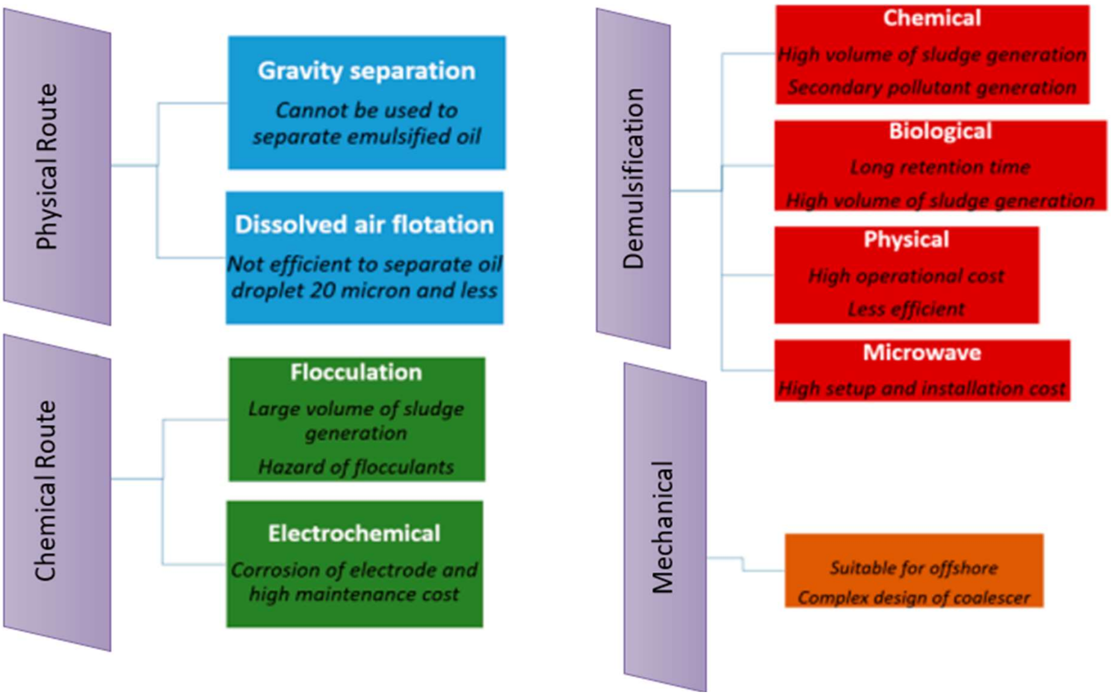

Fig. 6: Limitation of the conventional Greasy-oil wastewater removal technique. Adapted from Abuhasel et al. (2021).

environment (Del Prado-Audelo et al. 2021, Phillips 2021, Almuallim et al. 2022, He et al. 2022). Two examples of these features are the high TCs of metal nanoparticles (NPs) and carbon nanotubes (CNTs), which have TCs twice as high as diamonds and are therefore excellent heat conductors (Kumanek and Janas 2019).

Although beneficial in the domains of engineering, material sciences, and medicine, nanotechnology comes with high costs because of increased operating and raw material costs. Additionally, nanotoxicity is a risky feature associated with nanoparticles. These NPs may enter the ecosystem through a variety of channels, including wastewater, which could lead to nanotoxicity (Ray and Bandyopadhyay 2021), particularly causing metal-associated diseases, such as those caused by the use of silver (Ag), titanium dioxide (TiO_2), and zinc oxide (ZnO) in toothpaste and cosmetic products. Furthermore, MXenes are challenging to synthesize and have poor stability properties, particularly at high temperatures. Carbon nanotubes (CNTs) have low selectivity in adsorption with low adsorption capacity, and carbon nitride (C3N4) has low capacity for sorption of metal ions and has high photocatalytic decomposition of organic pollutants (Alharbi et al. 2020).

4.1. Regulatory and LifeCycle Assessment Considerations

The governance of engineered nanomaterials is increasingly shaped by evolving regulatory frameworks, such as the EU REACH regulation, which now includes nanospecific information requirements but continues to face challenges related to inadequate test methods, incomplete datasets, and difficulties in defining and grouping nanoforms (Blue Frog Scientific 2025). Complementing REACH, international bodies such as the OECD have developed nanospecific test guidelines and harmonized methodologies to support safety evaluation, exposure assessment, and cross-national regulatory consistency (OECD 2025). From a sustainability perspective, life cycle assessment (LCA) provides a structured means of evaluating the environmental impacts of nanomaterials across their full lifespan. However, nanoparticle LCAs face significant methodological barriers, including limited fate and exposure data, a lack of nano-specific characterization factors, challenges in quantifying nanomaterials within complex matrices, and uncertainties associated with particle transformation during use and disposal (Schwirn et al. 2020). Therefore, integrating regulatory requirements with improved LCA methodologies is essential for developing nanomaterials that are not only effective but also aligned with safety, environmental protection, and longterm sustainability goals.

5. CONCLUSIONS

Nanotechnology can significantly improve the removal of dyes, metals, and oils under defined operating conditions and in combination with complementary processes, rather than universally transforming pollutants into safe, clean water, with emphasis on modular integration, targeted applications, and evidence-based adoption supported by regulatory and LCA assessments, as supported by Kholopo & Rathebe (2025) and Corominas et al. (2020). This study shows that nano-enhanced bioremediation is a conceptual framework for future research. Integrated trains (e.g., biofilm carriers + UV-Fenton, adsorption + AOP + MBR) show promise but require pilot-scale validation on real automotive effluents to quantify fouling, nanoparticle release, and life-cycle footprints, as noted by Pottekkatt et al. (2025) and Malik et al. (2023).

For automotive-based production and maintenance operations, clean water can be produced by treating a variety of pollutants with nanoengineered materials such as photocatalysts, nanometals, nanoadsorbents, and nanomembranes. Nevertheless, nanotechnology in wastewater treatment has advantages that conventional water treatment approaches cannot match.

Nanofilters' effectiveness in comparison to traditional systems, for instance:

- Compared to conventional methods, they are more efficient, have large surface areas that are readily cleaned by back-flushing, and require less pressure to move water across the filter, which significantly lowers operating expenses.
- Many of the technologies can be easily incorporated or modified as modules to improve particle retention and remove impurities from systems that are already in place. As a result, nanotechnology is crucial to the purification of water, especially when using nanocomposite membranes that have higher process efficiency.

Notable drawbacks also exist that should put nanoparticle applications in check. For example, functional nanomaterial-modified surfaces have the potential to release or emit nanoparticles to the environment over a long period, which makes national and international regulations necessary. Meanwhile, with consideration for decentralized treatment, point-of-use, and heavily degradable contaminants, as is the case in the automotive setting, nanotechnology/nanoparticle is extremely essential for wastewater purification.

Lastly, the proposal states that different degrees of treatment are necessary for suspended particles and hydrocarbons from car wash or equipment wash facilities, such as

- Pre-treatment (oil-water separator) to remove floatable materials from raw wastewater by means of a grit chamber or screening.
- Primary treatments, which involve chemically treating the wastewater (coagulation, flocculation, and neutralization). For additional treatment, the principal sludge (heavy solids) is separated from the floating oil, grease, and other lighter solids.
- Secondary treatments include biological processes that eliminate suspended and dissolved biological matter (BOD and COD), which include ion-exchange, coagulation, ozonation, neutralization, adsorption, and chlorination.
- Tertiary treatments include the use of UV radiation, ozone, and chlorine to sterilize wastewater that has been treated. At this stage, the last of the residual suspended solids from earlier treatment stages are eliminated.

While removing physical, biological, and chemical impurities from wastewater is the main objective of nanotechnology, it also aims to soften the water. Highly porous nanoparticles can be used to absorb water in a spongy manner, but they can also be utilized to resist salt and other pollutants. For instance, membrane-embedded hydrophilic nanoparticles can repel bacteria and organic chemicals that eventually clog conventional membranes. In addition to photocatalysis, electrochemical oxidation, nanofiltration, and adsorption using metal oxides (Ti, Zn), membranes (ceramic, polymer, nanowire, polymer), CNTs, and nanopowder NPs, for improved water quality, nanotechnology has greatly enhanced the drawbacks of treatment technologies, however, the drawbacks highlighted in this study are that oil-based wastewater treated with magnetic sorbent nanoparticles acts as emulsifiers, containing microbes and resulting in micro-organism-infested wastewater. Therefore, nanoenhanced bioremediation is an efficient way to treat wastewater with a variety of compositions. To accomplish nano-enhanced bioremediation for completely enhanced wastewater remediation, a nanotechnology technique that combines bioremediation and nano-remediation is thus proposed. Therefore, further research is still needed to understand the best ways to combine the various treatment systems to create several of the finest treatment methods for automotive water treatment.

5.1. Future Prospect

Multifunctional and hybrid systems that combine nano-remediation with biological processes for increased treatment efficiency are the key to the future of nanotechnology in automotive wastewater remediation. For the removal of hydrocarbons, heavy metals, and persistent organic pollutants from vehicle effluents while using the least amount of energy possible, emerging nano-enabled membranes, photocatalysts, and adsorbents show great promise. However, more research is required to address challenges, including nanoparticle release, long-term environmental stability, and compliance with changing regulatory frameworks. Therefore, future studies should focus on developing nanocomposites that are environmentally safe, recyclable, and affordable and can be easily integrated into current treatment infrastructure. Furthermore, developing decentralized point-of-use devices specifically for car washes and vehicle repair shops will be essential for ensuring scalability. One important avenue is nano-enhanced bioremediation, which offers a sustainable solution for complex wastewater streams by fusing microbial degradation pathways with the high reactivity of nanoparticles. In the end, a methodical comprehension of treatment synergies will make it possible to create durable, flexible, and adaptable nanotechnology-based solutions that satisfy industrial and environmental requirements.

6. ACKNOWLEDGMENTS

Authors acknowledges the support of the University of South Africa for the completion of this study.

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