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

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Abstract: An estimated 2.73×10^{12} gallons of water is generated in the automotive sector annually, generating complex wastewater streams, and pollutants-free water from this sector is essential for a safe environmental footprint impact for various applications since wastewater causes corrosion, equipment blockages, and chemical costs increment 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, Cr). Average water-contaminant loads, including grease and oil (1100 mg/L), COD (4500 mg/L), overall suspended solids (3500 mg/L) create some level of health risk, and treatment methods have shifted from the physical techniques of gravity separation and dissolved air flotation, and demulsification which involves nanotechnology to hybridization. With a per-wash prediction of globally in use vehicles in 2015, 218 billion litres of wastewater runs off to potential water stream, 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 act as emulsifiers, thereby containing microbes, and causing micro-organism infested wastewater, therefore, an effective means of treating such wastewater with varieties of compositions is by nanoenhanced bioremediation. Hence, a nanotechnology technique which fuses bioremediation and nano-remediation to achieve nano-enhanced bioremediation for a totally enhanced wastewater remediation is proposed to abate environmental pollution. However, long-term risks and lifecycle assessments of nanomaterials 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 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 Automotive World report, producing a single car requires over 39,000 gallons of water, and the inclusion of tyre production in the process may lead to variation of the estimate, with total annual consumption exceeding 2.73 × 10^{12} gallons due to the production of ~70 million cars worldwide (Membracon; Karchiyappan 2022). In addition to direct vehicle production, ancillary processes such as electroplating, leather tanning, and textile finishing add substantially to the industry's environmental footprint. Recent statistics confirm that global car production surpassed 90 million units annually, including passenger cars and commercial vehicles (Figure 1; Statista 2025). Moreover, the global car wash industry alone consumes ~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).

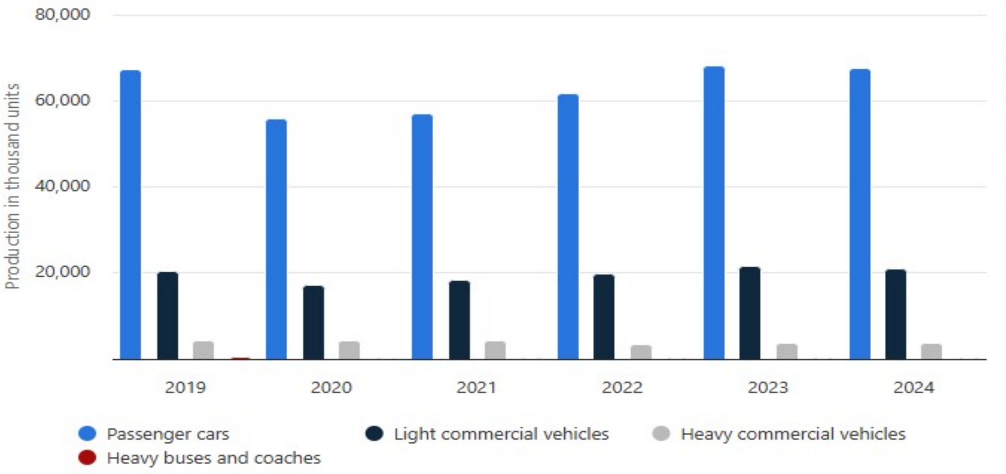

Figure 1: Global motor vehicle production estimate, 2019-2024, by type (in 1,000 units, Statista 2025)

The extensive use of water in automotive-related 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 the food chain (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 surrounding environments (Figure 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 (WWDR4 2014). Beyond conventional pollutants, nanomaterials and nano-sized particles released from industrial and automotive sources raise additional concerns.

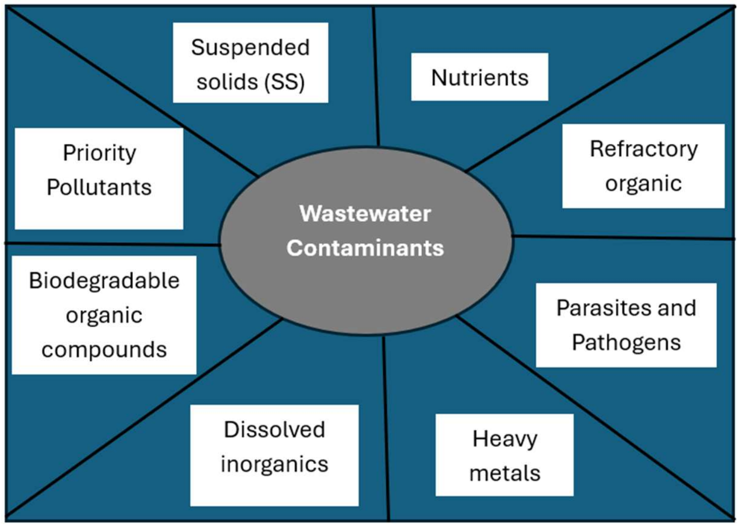

Figure 2: Categorical wastewater contaminants. (Adapted from Gavrilescu, 2005)

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; and while being 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 (refer to Figure 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. 2024).

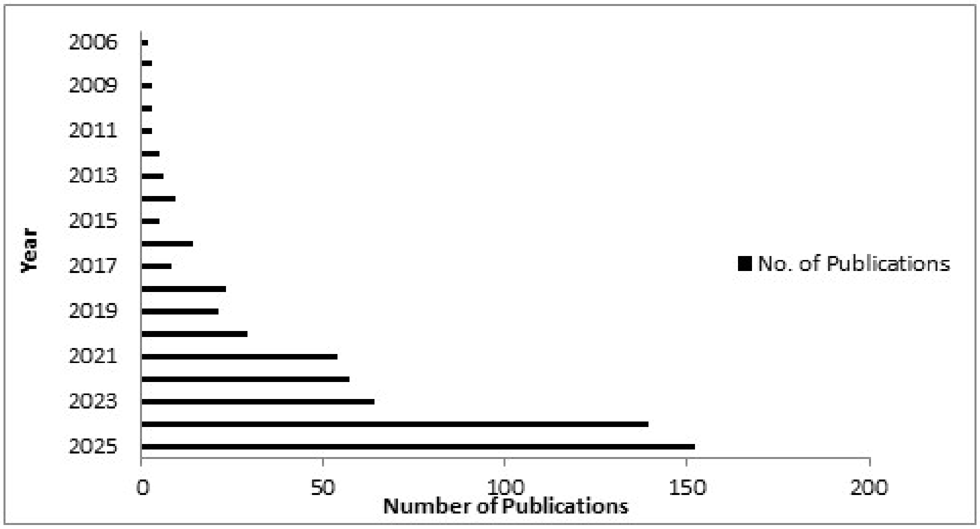

Figure 3: Number of yearly publications on automotive nano-remediated wastewater [Sciencedirect.com].

Figure 3 illustrates the increasing research attention devoted to nanotechnology-enhanced wastewater remediation in the automotive sector, as reflected in the rising number of annual publications indexed in Figure 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·L^{-1}), COD (~4500 mg·L^{-1}), and TSS (~3500 mg·L^{-1}), 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. We provide one consolidated composition figure/table and reference it later rather than repeating constituent summaries (Fall et al., 2007; Fayed et al., 2023). A consolidated composition showing constituent detail is given in is Figure 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 operations. Each of these processes generates complex wastewater streams containing diverse organic, inorganic, and sometimes toxic contaminants that, if discharged untreated, pose serious risks to the environment. Documented impacts include aquatic toxicity, oxygen depletion, eutrophication, and bioaccumulation of heavy metals in aquatic organisms, thereby threatening both ecosystems and human health (Ionescu et al. 2013; Bhat et al. 2021; Koul et al. 2022). Although automotive wastewater is predominantly water

(≈99.9%), the remaining 0.1% comprises a broad array of pollutants with high variability depending on process inputs and wastewater sources. These include suspended solids (350–1200 mg/L), 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, reflecting high organic load. In addition, automotive effluents contain toxic compounds such as hydrocarbons, surfactants, phosphates, and phenolic derivatives that 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 removal and exacerbating eutrophication risks when discharged into receiving water bodies (Google Books 2021; Deshpande et al. 2020).

The sources of wastewater contributing to this complex mixture are multifaceted. 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 load. 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 capacity 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 (Figure 4).

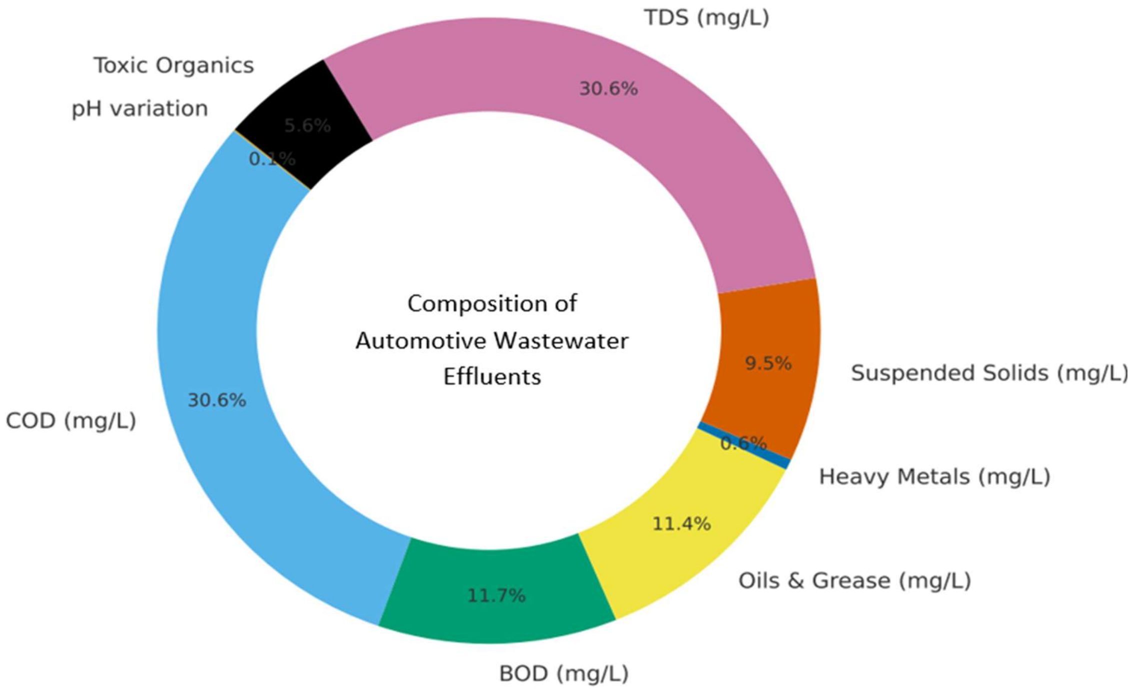

Figure 4: Composition of Automotive Wastewater Effluents. Adapted from Kabdasli et al. (2009); Singh et al. (2017); Ahn et al. (2008).

The composition of wastewater also dictates the selection of treatment technologies. High salinity, turbidity, extreme pH levels, and the presence of refractory organics often necessitate multi-stage treatment trains, incorporating primary sedimentation, chemical coagulation–flocculation, and advanced oxidation processes. However, cost remains a critical limitation. For instance, distillation-based recovery of high-quality water is prohibitively expensive due to the energy-intensive requirement of multiple consecutive treatment steps (Adham et al. 2018). Membrane-based desalination and filtration systems, though effective, face constraints such as osmotic pressure thresholds, hydraulic energy demands, fouling, and scaling from mineral precipitation (Dieter et al. 2018; Gude 2018). Adsorptive systems, while cheaper, 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 tackling 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 not only the removal of contaminants but also 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 withdrawals (Bagyalakshmi et al. 2025; Zhao et al. 2022). Despite these promising outcomes, several limitations impede 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 lifecycle management (Crini & Lichtfouse 2019). Furthermore, current research remains fragmented, with insufficient focus on integrating nanotechnology's functional roles 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 a critical challenge for global water security. Conventional treatment technologies often fail to adequately remove the diverse pollutants present in automotive effluents, while nanotechnology, though offering superior performance, faces barriers of scalability, safety, and sustainability. Addressing these gaps is urgent, given escalating climate-driven water scarcity and stricter environmental discharge standards.

This study aims to systematically examine the functional applications, roles, drawbacks, and future prospect of nanotechnology in automotive wastewater remediation. The complex mixture of contaminants range in the Figure 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. Nanomaterials such as nano-TiO_2, ZnO, and CNT-based composites can be tailored for photocatalysis and adsorption, which scale well in membrane or packed-bed systems. Hence, on 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, which scale well in membrane or packed-bed systems. On safety, the presence of toxic metals (Cr, Ni, Pb, Cu) and toxic organics (phenols, PAHs) underscores the importance of nanomaterials with selective binding capacity (for example, functionalized graphene oxide, nano-zero-valent iron). By removing carcinogenic and mutagenic contaminants at trace levels, nanotechnology directly addresses ecotoxicity and public health risks. Furthermore, oils, grease, and high TDS levels highlight the need for multifunctional materials. Nanocomposites that combine adsorption, photocatalytic degradation, and antimicrobial activity (for example, GO/Fe_3O_4, rGO/$ZnCo_2O_4$) reduce the need for multi-step conventional treatment. This integration lowers operational costs and energy inputs compared with classical methods (for example, coagulation–flocculation + tertiary oxidation). Finally, by mapping the proportional contributions of pollutants, the figure prioritizes contaminants requiring urgent attention. Nanotechnology can then be directed toward high-impact removal targets, for example, 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 the classification of nanomaterials. For instance, the dimensions of the 1-d nanostructures of nanowires, nanotubes, and nanofibres range from 1 to 100 nm. The classifications can be found in table 1.

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 delocalizati-on, meaning freedom to move.	Fullerene	Rafiei-Sarmazdeh et al. 2020**;**

2	Numerical Dimension	1-D	Nanostructure has two characteristic dimensions between 1 and 100 nm.	Tubes, fibers, wires, platelets, etc.	Afolalu et al. 2023
3		2-D	Nanostructure has thin layers that may have a thickness of at least one atomic layer, having many atoms on their surface.	Graphene, hexagonal boon nitride (hBN), metal dichalcogenides (MX2), etc.	
4		3-D	Composed of dispersions of nanoparticles, bundles of nanowires, nanotubes, and multi-nanolayers.	Particles, quantum dots, hallow 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 natural occurring clay materials and Na-Y 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.	Mekuye & Abera 2023

				They are mostly used as sensing materials and scaffolds to graft functional groups, such as catalytic centers.	
8	Phase Composition	Single-phase solid	Crystalline, amorphous, parti-cles and layers, etc.	High entropy oxide *nanoparticles*	
9		Multi-phase solid	Matrix composites, coated particles, etc.	Nanorods, nanofibre, 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 called chemical vapour deposition (CVD). Involves chemical reaction and 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	includes aerosol-bassed nanoprticles	**[**Bokov et al. 2021**]**

			nanospheres, nanosheets, nanowires, and nanorods.		
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 and 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 and 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 and Hossain 2022; Cho et al. 2019].

2.2 Mobility of Emissive Nanoparticles

Environmental releases of nanoparticles can originate from a variety of sources, including manufacturing facilities, wastewater treatment plants, landfills, as well as 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 Figure 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 behavior. These elements together with the nanoparticles' surface charge could cause immobilization.

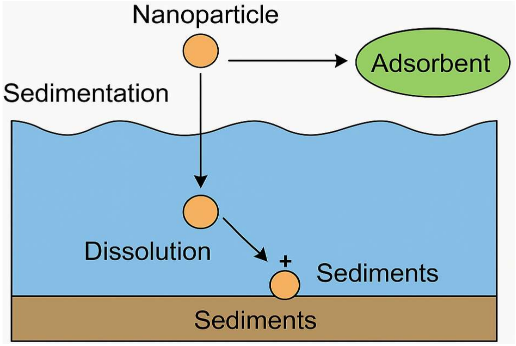

Figure 5: Mobility characteristic of nanoparticles in water bodies. Adapted from Su et al. (2020); Hanif et al. (2020); Matlochova et al. (2014).

The process in Figure 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 photoreaction based on water turbidity, and the anaerobic transformation of some organic and metallic nanomaterials into complex compounds are some of the ways that nanoparticle degradation pathways in aqueous systems can be affected (Nurmi et al. 2005). Several ecotoxicity studies have been carried out to evaluate the environmental concentrations of common nanomaterials. For example, Gottschalk et al. (2009) calculated risk quotients associated with nanosilver, nano-TiO2, and nano-ZnO in surface water and sewage treatment effluents for the United States, Europe, Switzerland, and Nigeria (Table 2). Enugu, Nigeria's brewery wastewater and Niger-Delta, Nigeria's oil refineries share a common wastewater composition, as is indicated in Table 2. Treatment of wastewater greatly depends on intense efforts and monitoring of industrial effluents.

Table 2: Associated risk quotient for different nanoparticles in surface water and STP effluent in Europe, USA and 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	0.002	0.2	n/a			
		3.5	1.8	3.4				
2	Surface Water STP Effluent	Nano-ZnO						
		1.1	0.17	1.03	n/a			
		61.1	30.1	55.6				
3	Surface Water STP Effluent	Nanosilver			n/a			
		<0.0005	<0.0005	<0.0005				
		<0.0005	<0.0005	<0.0005				
4	Surface Water STP Effluent	CNT			n/a			
		<0.0005	<0.0005	<0.0005				
		<0.0005	<0.0005	<0.0005				
5	Surface Water STP Effluent	Fullrenes	<0.0005	<0.0005	n/a			
		<0.0005	0.023	0.019				
		0.026						
6	ORENDN	n/a	n/a	n/a	O & G	Zinc	Iron	Nickel
	(I & E)				15 10	n/a	n/a	n/a
7	BR	n/a	n/a	n/a	O & G	Zinc	Iron	Nickel
					2	0.01	28	0.01
8	RW	n/a	n/a	n/a	O & G	Zinc	Iron	Nickel
					1	<0.01	2	<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/

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 effluent in Europe, the USA, Switzerland, and Nigeria. The table showed that the effluent from sewage treatment plants contained 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

The field of 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 growth, and disinfection to effectively absorb nanometals and non-metal oxides. The toxicity of wastewater containing non-biodegradable heavy metals can have a negative effect on the life of plants, animals, and other living things, according to Yadav et al. (2023). 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 for improved water quality (Yadav et al. 2022a). As carbonaceous NMs, nano adsorbents, nanofibers, nano clays (Biswas et al. 2020), zeolites (Murukutti and Jena 2022), and dendrites, nanomaterials (NMs) play vital role in the treatment of water. Table 3 lists a few of the roles that nanomaterials play 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, 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 this 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 high surface area and tunable functional groups, enabling efficient sequestration of heavy metals like Pb(II) and Cd(II) 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 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 a multifunctional benefit, combining adsorption, photocatalysis, and membrane separation that addresses 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 tightening 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.

Table 3: Automotive-relevant studies on Nano-wastewater Remediation

S/N	Class	Nads Type	Adsorption capacity (mg/g)	Contaminants/ Remarks	Refere
1	Carbon & Graphene related Nads	Graphene	35.6; 89.37	Fluoride; Phosphate	Xu & & Lak
2		Graphene-CNT	81.97	Methylene blue	Ai & J
3		Graphene Oxide (GO)	108.342, 80.775, 71.378	Au(III), Pd(II), Pt (IV), Zn(II)	Liu et (2019)
4			149.4	Endocrine-disrupting chemicals (17βEstradiol)	Mohel al (202
5			16.83, 63.69	Methyl orange, Basic red 12	Robati
6			5.496 (mmol/g)	Methyl green	Sharm

7			Enrofloxacin (ENF): 45.035, Rhodamine B (RhB): 107.230	ENF and RhB	Yang
8		GO- Fe_3O_4	MB: 37.5–108 (at 25 ° C and 9 pH)	MB	Shi et
9		RGO-PVP; MWCNTs; Nano-sized zero-valent iron	1689; 364.66mg/g; NA	Cu(II)	Zhang et al. (
10		RGO/Poly (acrylamide); CNTs/MnO_2; MWCNTs-kOH	1000; 78.74; 68.4%±5.0%	Pb (II)	Rajabi et al.,
11		Polyethylenimine modified-GO hydrogel	N/A	Pb (II)-602, Hg (II)-374 and Cd (II)-181	Arsha
12		RO membrane containing Si, Al, and Fe	105 (pH 7.5)	polysaccharides, proteins, and aromatic compounds	Ahme
13		$MnFe_2O_4$/reduced GO (MrGO)	Malachite green dye (MG): 156, and MB: 105	MG & MB	Anil
14		GO/Fe_3O_4/chitosan	MB	Maximum monolayer capacity: 30.10mg.gm^{-1}	Tran
15		rGO/$ZnCo_2O_4$	N/A	Antimicrobial, electrochemical and photocatalytic effect	Gnana
16		rGO/$CuNiO_2$	N/A	MB	Gnana
17		rGO/nZVI		Doxycycline	Abdel
18	Nano-sized	nZVI	N/A	Cd(II), Ni (II), Pb (II), Hg(II), Cr(VI)	Feng
19		Hydrotalcite-supported nZVI	N/A	Nitrate	Fan et

20		Nzvi-Cu bimetals; Solid carbon source/nZVI	N/A	Nitrate	Zhang (2021
21		ZnO	MB: 64-83%; COD: 15-53%; TOC: 31-74.12%	MB; COD; TOC	Modi
			N/A	MB Dye; Ampicillin (Antibiotic) and MB; Zn (II), Cd (II), Hg (II)	Modi al. (20
22		Amorphous IONPs from incense sticks ash (ISA)	N/A	Congo Red (CR)	Yadav
23		Mesoporous and floral shaped SiO_2 from CFA	N/A	Al, Pb, Cd, Cu, Cr, Ni, Co, Zn, Mn	Yadav
24		$CaCO_3$ (calcite & vaterite) from ISA	N/A	Methyl Red Dye	Yadav
25		Fe_3O_4 NPs (leaf extract of Cola nitida)	MB (530.406mg/g) within 1hr.	MB	Mbach
26	Metal oxide-based NPs	ZnO-W	MB: 20-88.21%; COD: 25-85.2; TOC: 46.5-92.04%	MB; COD; TOC	Modi
27		ZnO-Sb	MB: 21-91%; COD: 27-88.5; TOC: 48-95.34%	MB; COD; TOC	Modi
28	Nanocomposite membrane	Nano-TiO_2	12.2 (L/ m2 h bar)	Fouling resistance (FR), anti-bacterial, concurrent separation, and photo-catalytic oxidation, TiO2 nanowire growth via hydrothermal processing photocatalytic under UV degradation of pharmaceuticals	Zhang
29		Poly (vinylidene fluoride-hexafluoropropylene)-		Removed arsenite (92.82) and arsenate (137.08) mg g−1	Salaza

	loaded with yttrium carbonate and Fe_3O_4			
30	Cu-Al LDH@ polyvinylidene fluoride (PVDF) membrane (Cu-Al LDH/PVDF)	Adsorption capacity: 17.36 mg g-1	Erythrosin B dye	Abbas
31	Boron nitride nanosheets/PVDF	MB dye: 142.86 mg g^{-1}	100% removal of MB 2.2 times higher than the PVDF alone	Banga
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%	Erusap
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 e
34	NZVI/PVDF		Removed RhB (~80%), 2,4-dichlorophenol (2- CP) and 4-nitrophenol (4-NP) almost 100% within half an hour	He et a
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
36	Alumoxane derived Alumina membrane	Dye	Authors utilized Fumarate-alumoxane nanoparticles (Fum-ANPs) incorporated 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	Morad

				membrane was 99% while it was 88.2% for the bare membrane sample.	
37		Amino acid homopolymers derived silica membranes	Metal removal using physical (membrane separation, filtration, etc.), chemical (adsorp-tion, ion-exchange, floc-culation, etc.), Biological (microbes assisted reme-diation)) and electrochemical technologies.	Authors reviewed nano-adsorbents 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).	Kuma
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 catalysts for the growing needs in wastewater treatment for by catalytic reduction of 4-nitrophenol (4-NP) to 4-aminophenol (4-AP) in the presence of $NaBH_4$. Result indicated that 100% of 4-NP were converted to 4-AP within 6 min and the rate constant (k) was found to be $8.33 \times 10^{-3}\ s^{-1}$.	Naush
39		Ruthenium oxide (Ti/RuO_2)	Polycyclic aromatic hydrocarbons (PAHs) remo-val from oil and gas wastewater stream. They possess mutagenic, carcinogenic, and tera-togenic potential, hence, are toxic deoxyribonucleic acid (DNA).	Authors electrochemically oxidised utilising ruthenium oxide (Ti/RuO_2) anode in a lab-scale electrolytic batch cell. They reported that lectrocatalytic oxidation with a Ti/RuO_2 anode is a potentially effective technique for removing PAHs from aqueous solutions.	Isa et
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	Nasrol

			MO – 277s	
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 e

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, spanning carbon- and graphene-based adsorbents, zero-valent iron (nZVI), metal oxides, nanocomposites, and membrane-supported nanostructures. Across these classes, adsorption capacities vary significantly from moderate values, for example, in a separate study, Chufa et al (2021) used GO nanoadsorbent to achieve a 4.71 qo (mg/g) fluoride removal compared to the graphene removal of 35.6 mg/g for fluoride reported by Xu & Wang (2017) to exceptionally high uptake, such as RGO–PVP at 1689 mg/g for Cu(II), (Zhang et al. 2014). This variation underscores the tunability of nanomaterials through structural modification, functionalization, and hybridization with other nanophases.

For automotive wastewater treatment, where complex effluents often contain dyes (from paint shops), heavy metals (Pb, Cu, Zn from plating and corrosion), oils, and organic contaminants, contaminants removal are achievable, for example, in heavy metal removal, functionalized graphene and nZVI-based composites are deployed (Zou et al. 2016; Feng et al. 2022), for exhibition of 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), 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, microbes), high adsorption efficiencies, and functional versatility. Their integration into automotive wastewater treatment systems can thus enhance pollutant removal, support water reuse, and contribute to compliance with stringent environmental regulations for 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 are 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, promotes fouling and flux loss persist 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 weigh 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, especially in the context of oily wastewater and emerging pollutants. Figure 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 infrastructure, while also generating secondary contaminants such as dissolved iron, copper, or zinc ions (Ekerenam et al. 2020). Sedimentation and sludge generation are also problematic in coagulation–flocculation systems, which are traditionally applied to automotive effluents to remove suspended solids, oils, 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 & Lichtfouse 2019). Furthermore, these methods typically require high chemical inputs, raising concerns about sustainability and potential secondary pollution (Kadadou et al. 2024).

Another limitation lies in 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 demand high operational pressures to overcome osmotic gradients in oily or saline effluents, further escalating costs (Dieter et al. 2018). The complex nature of oily wastewater presents additional challenges. Automotive effluents frequently contain free oil, emulsified oil, and chemically stabilized oil–water emulsions. Conventional gravity separation or skimming systems are insufficient to destabilize these emulsions, which remain stable due to surfactants, lubricants, and fine particulates present in automotive processes (Medeiros et al. 2022; Abuhasel et al. 2021). Advanced chemical demulsifiers or 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 concerns 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. 2023). Moreover, the variability in wastewater composition between facilities (painting shops, electroplating lines, radiator manufacturing, and car washes) complicates the standardization of treatment protocols, requiring costly site-specific customization.

To address these challenges, scientific and technological evolution has 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 individual method limitations, for example, coupling adsorption with photocatalysis enhances both removal efficiency and degradation of persistent pollutants, while hybrid membranes with nanomaterial coatings mitigate fouling and extend lifespan (Paiu et al. 2025; Ahmed et al. 2025). Nevertheless, while integrated methods show promise, challenges remain regarding 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.

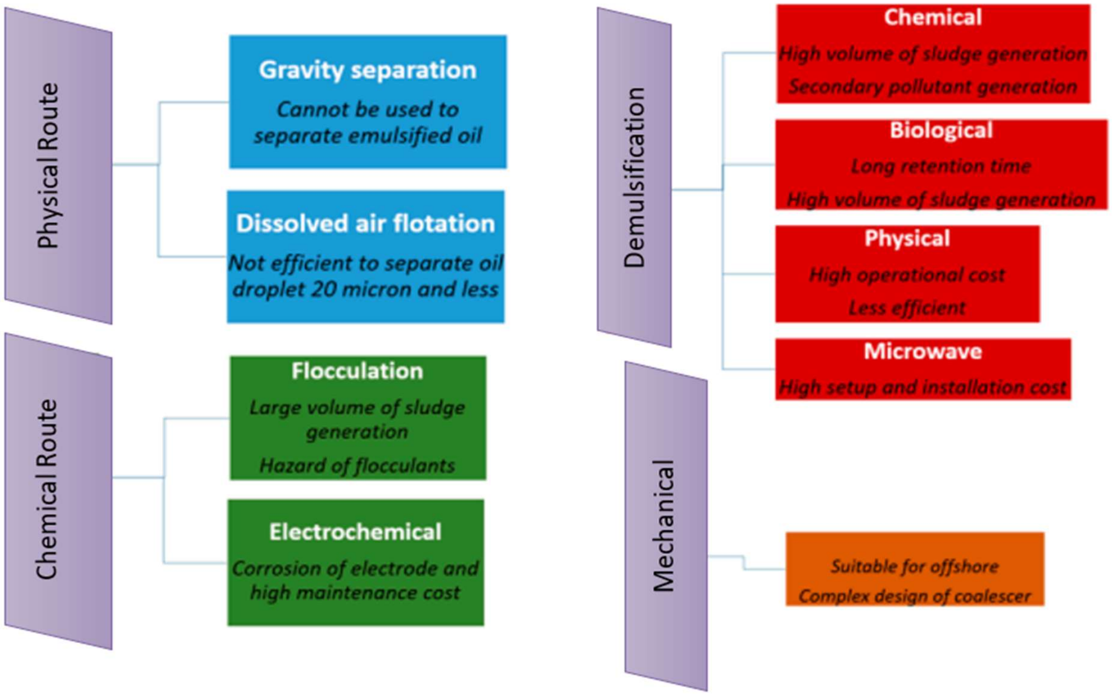

Figure 6: Limitation of conventional Greasy-oil wastewater removal technique. Adapted from Abuhasel et al. (2021).

While improved heat transmission in basefluids 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, has resulted in contamination that has negatively affected the 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 TC 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 medical, nanotechnology comes with high costs because of increased operating and raw material costs. Additionally, nanotoxicity is a risky feature connected to the nanoparticles. These NPs may enter the ecosystem through a variety of channels, including wastewater, and this could lead to nanotoxicity (Ray and Bandyopadhyay 2021), particularly causing metal-associated diseases, like those brought on by the use of silver (Ag), titanium dioxide (TiO2), and zinc oxide (ZnO) in toothpaste and cosmetic products. Furthermore, MXenes are challenging during synthesis 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 Life-Cycle Assessment Considerations

The governance of engineered nanomaterials is increasingly shaped by evolving regulatory frameworks such as the EU REACH regulation, which now includes nano-specific 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 nano-specific 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 environmental impacts across the full lifespan of nanomaterials; however, nanoparticle LCAs face significant methodological barriers, including limited fate and exposure data, lack of nano-specific characterization factors, challenges in quantifying nanomaterials within complex matrices, and uncertainties linked to particle transformation during use and disposal (Schwirn et al., 2020). Integrating regulatory requirements with improved LCA methodologies is therefore essential for developing nanomaterials that are not only effective but also aligned with safety, environmental protection, and long-term 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 and future research pathway; 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 lifecycle footprints, as noted by Pottekkatt et al. (2025), and Malik et al. (2022).

For automotive-based production and maintenance operations, clean water may be produced by treating a variety of pollutants with nanoengineered materials like photocatalysts, nanometals, nanoadsorbents, and nanomembranes. Nevertheless, there are advantages of nanotechnology in wastewater treatment 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 surfaces 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 long period, which makes national and international regulations neccessary. Meanwhile with consideration for decentralized treatment, point-of-use, and heavily degradable contaminants, as is the case in automotive setting, nanotechnology/nanoparticle is extremely essential for wastewater purification.

Lastly, the proposal stating 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 includes 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 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 concentrate on creating nanocomposites that are safe for the environment, recyclable, and affordable and that can be easily integrated into the current treatment infrastructure. Furthermore, developing decentralized point-of-use devices made especially for car washes and vehicle repair shops will be essential to guaranteeing 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.

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