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Engineered Nanomaterials for Wastewater Treatment: Opportunities, Biological Integration and Nanotoxicology Challenges

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Abstract

The growing complexity of wastewater pollution caused by rapid industrialization, urbanization, and emerging contaminants has exposed the limitations of conventional treatment technologies. This review explores the transformative role of engineered nanomaterials (ENMs) in addressing these challenges through advanced adsorption, photocatalysis, and disinfection mechanisms. Various nanomaterials—including carbon nanotubes, titanium dioxide, metal oxides, nano-clays, and hybrid nanocomposites—have demonstrated significant potential in removing heavy metals, dyes, pesticides, and microbial contaminants from wastewater. The study also discusses green synthesis approaches that promote environmentally benign nanomaterial production and the integration of nanotechnology with biological systems for enhanced pollutant degradation. Such nano-bioremediation techniques leverage the synergistic effects of nanoparticles and microorganisms to achieve higher treatment efficiency and resource recovery. However, despite their promising capabilities, concerns regarding nanotoxicity, bioaccumulation, and environmental persistence pose critical challenges to large-scale implementation. The paper underscores the need for standardized assessment frameworks, sustainable synthesis strategies, and risk mitigation measures to ensure that nanotechnology advances wastewater remediation without compromising ecological and human health.

Keywords: Engineered nanomaterials, wastewater treatment, nano-bioremediation, green synthesis, nanotoxicology, environmental remediation.

1. INTRODUCTION

The escalating challenge of water pollution and wastewater mismanagement has emerged as a critical global concern, largely fuelled by unchecked urban expansion, rapid industrialization, and inadequate environmental awareness at both public and policy levels. Globally, around 42% of household (domestic) wastewater remains untreated, resulting in approximately 113 billion m^3 of sewage being released annually [1]. Industrialization and urbanization have intensified water use in production processes, generating large volumes of industrial effluents that contaminate freshwater sources such as rivers and lakes. Discharge of heavy metals from industrial wastewater has become a serious threat to both the environment and human health [2]. Major contributors to water contamination include improper sewage management, marine pollution, microplastics, eutrophication, improper medical waste disposal, unsafe handling of radioactive substances, and harmful agricultural practices [3]. In addition, synthetic dyes, heavy metals, and organic pollutants pose severe risks due to their toxicity, persistence, and long-term accumulation. Even after filtration, contaminants can still enter drinking water, causing waterborne diseases such as dysentery, hepatitis, typhoid, and parasitic infections, while chronic exposure leads to long-term health issues. Eutrophication-driven algal blooms disrupt ecosystems, and bioaccumulation transfers toxins into keystone species, threatening food chains and degrading aquatic habitats. These combined threats are destabilizing aquatic ecosystems. Over 4.4 billion people—more than half the global population—lack access to truly safe drinking water, often due to faecal contamination in sources classified as “improved” [4]. As a joint global effort, the UN introduced the Sustainable Development Goals to achieve a more sustainable world by 2030, with SDG 6: Clean Water and Sanitation specifically addressing the urgent need to ensure the availability and sustainable management of water resources for all, aiming to combat pollution, poor sanitation, and ecosystem degradation through coordinated global action. In response to these challenges, various conventional treatment approaches have been developed and implemented over the years, however these methods are increasingly falling short as escalating pollution complexity and urban demands outpace their design capacities.

Physical methods such as sedimentation, centrifugation, membrane separation, adsorption, etc, and chemical methods such as coagulation, flocculation, chlorination, etc, are traditional methods currently used to tackle the problem. These traditional wastewater treatment technologies, although widely adopted, often suffer from various limitations. The inability to remove resistant bacteria from the water/sludge often results in its persistence in the water have become a major threat to public health. Rivers in UK national parks, deemed “pristine,” actually contain antibiotics, antidepressants, and anti-inflammatory drugs because conventional sewage plants fail to remove these properly, raising risks of antimicrobial resistance.[5] Inefficient plastic and microcontaminants removal from pharmaceutical products, personal care products can sometimes even exhibit higher concentrations of these compounds in the effluent than in the influent due to incomplete degradation. Older facilities for these treatments, built with a centralized point of view in mind, are becoming less and less effective as treating the ever-increasing amounts of wastewater from growing cities overloads facilities, leading to increased energy consumptions, limited adaptability, generation of secondary waste and malfunctions. Additionally, these facilities are now engulfed by the cityscape, demolishing land, value and truly becoming unsustainable in the long run. [9] These cumulative shortcomings not only compromise the effectiveness of pollution removal but hamper long term sustainability and management of wastewater. Because of all these issues pertaining to disposal, attention has been shifted to a more efficient and sustainable alternative, nanotechnology.

Nanotechnology is the science of manipulating matter at atomic and molecular level. Its highly efficient, modular, and multifunctional processes are envisaged to provide high performance, affordable wastewater treatment solutions that rely less on large infrastructures [10]. The application of this technology is primarily done using nanomaterials. Their small size, typically between 1 and 100 nm, confers properties such as high mechanical strength, high specific surface area, improved thermal and electrical conductivity, and enhanced optical behaviour are useful in bridging the gap between wastewater treatment and disposal of nanoparticles including emerging contaminants like pharmaceuticals, endocrine-disrupting chemicals, and microplastics. Nanoparticles are antimicrobial, inactivating viruses and bacteria directly, and have size exclusion capabilities that allow them to physically filter out pollutants smaller than what conventional membranes can remove. These unique properties are yet to be seen in regular materials used for wastewater purification. Additionally, they are involved in cost effective purification of wastewater such as effluents, brackish water and polluted surface water, thereby bringing a solution on table for water scarcity in the world. Nanotechnology offers a diverse toolkit for addressing water treatment challenges through four main functional categories. Nanoadsorbents, such as activated carbon nanocomposites and metal oxide nanoparticles, provide high surface area and strong binding sites for removing heavy metals, dyes, and other persistent pollutants [10][11]. Nanocatalysts, including titanium dioxide (TiO_2) and zinc oxide (ZnO), enable advanced oxidation processes like photocatalysis to degrade organic contaminants and inactivate pathogens [10]. Nanomembranes, such as carbon nanotube and graphene oxide membranes, achieve size-selective filtration with high permeability and fouling resistance, making them suitable for desalination and ultrafiltration [10]. Nanosensors, utilizing materials like gold nanoparticles, quantum dots, and CNT-based systems, allow real-time detection of trace contaminants with exceptional sensitivity and specificity [10]. Altogether, these methods provide an effective way of treating wastewater in the modern world.

Microwaste, such as microplastics and biomedical waste, is increasing at an alarming rate, posing complex challenges that traditional treatment methods still struggle to address. Coupled with the everyday intensifying impacts of climate change, such as droughts, floods, and shifting water quality patterns, there is an urgent need for more advanced and adaptable solutions. Hence, nanotechnology, specifically over the past decade, has gained significant attention, driving innovations that offer precise, efficient, and sustainable approaches to mitigate these emerging threats. Different types of nanomaterials have been a part of this industry for quite some time, such as carbon nanotubes, nanoclay, nanoparticles, titanium dioxide, and photodegrading gases. However, the need for cleaner, easier-to-use, and faster advancements in nanomaterials and their applications has become ever-growing. A few examples of this are: Green synthesis, which is more beneficial than traditional chemical synthesis because it costs less, decreases pollution, and improves environmental and human health safety [12]. Next is Hybriding nanoparticles whose usage was very crucial while incorporating of CNTs with CuS nanoparticles that helps in broadening the light absorption range and significantly improving charge carrier dynamics by facilitating efficient electron transport and suppressing electron–hole recombination, thereby enhancing overall photocatalytic performance [13]. Apart from these two, nanocomposites are also an emerging nanotechnology. Nanocomposites are advanced materials formed by combining two or more dissimilar components at the nanoscale to produce improved structures and enhanced properties that cannot be achieved by the individual materials alone. Recent research has further advanced nanocomposites through interface engineering, enabling better dispersion of nanofillers like carbon nanotubes or graphene oxide, which improves mechanical stability and catalytic efficiency. [15] all these are just a glimpse of where the field of nanotechnology is going and how it might develop in future for wastewater treatment. Nanotechnology offers targeted solutions for diverse wastewater contaminants, including heavy metals, dyes, and pathogenic microorganisms. For example, heavy metals such as lead, cadmium, and mercury persist in the environment due to their non-biodegradable nature, but nanomaterials like nano-zero-valent iron and functionalized nanoparticles can efficiently adsorb and immobilize these metals, significantly reducing their toxicity [2, 10]. Dye pollution from textile and industrial effluents poses serious environmental and health threats, with some synthetic dyes being carcinogenic and resistant to degradation; advanced nanomaterials, including photocatalytic nanoparticles and nanocomposites, have been shown to break down complex dye molecules into harmless byproducts [6, 9]. Microbial contaminants, including E. coli and antibiotic-resistant bacteria, are a growing global concern, affecting over four billion people who lack access to safe drinking water [4, 14]. Nanotechnology-based filtration membranes, silver nanoparticles, and photocatalytic systems offer promising antimicrobial action without relying solely on conventional chlorination methods [13]. Collectively, these nanotechnological applications not only address key pollutants but also enhance water recovery, making them a crucial component of sustainable water management strategies [7, 11]. All these target contaminants give an idea regarding how nanotechnology alone would not be as efficient as mixing it up with other treatment methods, so that it tackles the limitations of each of the approaches while boosting the overall treatment of the water. Using it with biological treatments would enhance microbial degradation by breaking complex molecules into smaller, more biodegradable forms, reducing toxicity, and even protecting microbial communities from heavy metal stress [2]. Similarly, if nanomaterials are used in constructed wetlands, they help in removing contaminants that are not naturally removed by the process of the wetlands, such as pharmaceuticals, dyes, pathogens, etc., to ensure that the forest's ecological condition is not hampered. Hence, the synergy between the two fields in this case is a must because it extends the treatment spectrum, reduces the need for high chemical storage, and minimizes secondary waste production.

Although seen as a promised future in the face of a crisis, it is important to take the implications of nanotechnology into consideration before making any longer-term decisions and/or starting any costly research. Nanoparticles' extremely small size enables them to travel through soil pores, aquatic systems, and even biological membranes, penetrating deep into both environmental and living systems. This high mobility raises concerns about their persistence, potential to accumulate in food chains, and unforeseen/unknown chemical or catalytic reactions when interacting with other particles or environmental components such as organic matter, minerals, or pollutants [15]. The reusability and recyclable properties of nanomaterials are highly variable, depending on the material type, size, concentration, and surrounding environmental conditions. A study shows that a magnetic polymer of $Co_3O_4@SiO_2$ magnetic nanoparticles coated with nylon 6 was able to adsorb 666.67 mg/g Pb (II) from wastewater at 298 K. The polymer was reusable up to six cycles with only a minor loss in adsorption capacity of <30% [22]. On the other hand, another study acknowledges that while these materials offer potential for pollutant removal and resource recovery, challenges such as long-term toxicity and the need for optimization remain, highlighting that the recovery and reuse of nanoparticles are not always straightforward [23]. Adding to this perspective, another paper discusses that even though the ability to reuse magnetic nanoparticles is a crucial advantage for economic feasibility, they may lose adsorption efficiency after multiple cycles due to surface fouling or structural degradation [24]. These findings collectively underscore that while nanomaterials hold a promising future, these research gaps need to be addressed in terms of reusability to ensure that this solution to a major problem does not itself become a new challenge. Moreover, occupational hazards and community exposure are still unaccounted for, as the long-term effects of inhalation and ingestion of the nanoparticles remain unknown due to the fact that nanotechnology has not yet been used on a very large scale. However according to predicted research and tests, nanoparticles are known to enter the human body through the lung, intestinal tract, or skin, and can be toxic to the brain, cause lung inflammation and cardiac problems [16] The level of toxicity of nanoparticles is suggested to be dependent on factors such as composition of the nanoparticle, size, surface functionality, crystallinity, and aggregation [17] While studies have highlighted potential risks of nanoparticles by drawing parallels with naturally occurring processes such as volcanic eruptions and wildfires, here remains limited understanding of how emerging synthetic nanotechnological processes will impact workers and human health over time. Furthermore, the generation of high performance nano particles require a substantial amount of energy in their synthesis, raising questions about their practical application on a large scale in the face of increasing carbon dioxide emissions. Carbon nanotubes (CNTs), for example, can be synthesized with energy inputs of 4.7 kJ/cm², highlighting both the potential for efficiency improvements and the inherent energy demands involved in production [18]. Similarly, titanium dioxide (TiO_2) nanoparticles, widely used as photocatalysts, involve high-temperature synthesis processes that contribute to significant energy consumption and environmental impact [19]. Gold nanoparticles (AuNPs) also face similar challenges, as conventional chemical methods require elevated temperatures, increasing both energy use and associated costs [20]. Likewise, the combination of nanoparticles with other wastewater treatment methods may introduce and create unknown chemical interactions or byproducts which might be detrimental to human health and the environment. Still research in this area remains narrow, raising concerns about the usage of this technology. This current lack of research into the cumulative behaviours of the particles stated, presents a major challenge in understanding and mitigating the ecological footprint and environmental damage that nanoparticles might cause. The rapid development of nanotechnology has also outpaced the establishment of standardized protocols for risk assessment. There is a pressing need for unified definitions, categorization methods, and predictive models to assess the environmental and health risks of nanomaterials effectively. Implementing such standards will facilitate more consistent and reliable evaluations across studies and efforts to make this technology more scalable and commercialised.[21]

In summary, this review paper focuses on the recent advancements and emerging trends in nanotechnology for wastewater remediation, emphasizing the different classes of nanomaterials, their functional mechanisms, target contaminants, and disinfection potential. It further explores how integrating nanotechnology with biological processes can enhance treatment efficiency and sustainability while addressing the limitations of conventional methods. Additionally, this review critically assesses the associated risks and nanotoxicological implications, aiming to provide a comprehensive understanding of both the opportunities and challenges in adopting engineered nanomaterials for effective wastewater treatment.

2. Wastewater Pollution: Sources and Challenges

2.1 Sources of wastewater pollution

Table 3: Illustrating the key characteristics of pollutants in relation to their respective sources and resultant impacts.

Sl. No.	Category of Pollutant	Examples / Composition	Primary Sources	Environmental & Health Impacts
1	Domestic Sewage	- Organic load (BOD, COD) - Nutrients (N, P) - Pathogens (bacteria, viruses, protozoa)	Household wastewater, septic tanks, untreated municipal sewage	Oxygen depletion, eutrophication, waterborne diseases (cholera, hepatitis, dysentery)
2	Industrial Effluents	- Heavy metals (Cd, Pb, Hg, Cr) - Dyes (azo dyes, tannins) - Pharmaceuticals &	Mining, textile dyeing, tanneries, chemical & pharma industries, paper mills	Bioaccumulation, carcinogenicity, antimicrobial resistance, aquatic

		PPCPs (antibiotics, hormones, solvents)		toxicity
3	Agricultural Runoff	- Fertilizers (nitrates, phosphates) - Pesticides (atrazine, glyphosate) - Veterinary antibiotics (tetracyclines, sulfonamides)	Irrigation runoff, livestock farms, aquaculture	Nutrient enrichment (algal blooms, dead zones), groundwater pollution, antibiotic resistance
4	Emerging Contaminants	- Microplastics & nanoplastics - Endocrine disruptors (BPA, phthalates, hormones)	Plastics degradation, packaging, cosmetics, personal care products, pharmaceuticals	Persistent in ecosystems, endocrine disruption, trophic transfer, reproductive toxicity
5	Other Pollutants (Physical, Biological, Radiological)	- Physical: sediments, debris, suspended solids - Biological: E. coli, norovirus, Giardia - Radiological: Uranium, Cesium, Radon	Construction runoff, fecal contamination, hospital waste, mining, nuclear plants	Turbidity, disease outbreaks, carcinogenic & mutagenic effects, ecosystem contamination

2.2 Limitations of conventional treatment methods

Conventional wastewater treatment methods comprise physical, chemical, and biological treatments to remove solid particles, pathogens, and chemicals, and are the main working mechanisms for wastewater and effluent treatment plants installed all around the world. However, the main problem with these methods (Table 3) is that it is unable to handle emerging contaminants such as major xenobiotic compounds, pharmaceuticals, personal care products, endocrine disruptors, resistant microbes, and microplastics. With so many of our industries growing, the need for better and more optimizing technology is a must.

A. Physical treatment (Primary)

The removal of solid particles through physical and mechanical screening and filtering is known as physical treatment of wastewater. These processes are usually the first stage (primary treatment) in treatment plants, preparing water for subsequent chemical and biological processes. It prevents blockage in filtration membranes, overloading in biological systems and reduced efficiency in chemical processes. This helps specific systems work on what they are designed for instead of focusing on stones and sand in the water. The process of the physical treatments starts from screening out the large floating materials in the water and then letting the water float to the grit removal chamber, where heavy materials such as stones and rocks are allowed to settle. This prevents abrasion of mechanical equipment and reduces pipe blockages. Then sedimentation, a process designed for separating insoluble or heavy particles from wastewater suspension, is done in the primary setting tank (primary clarifier) [25].

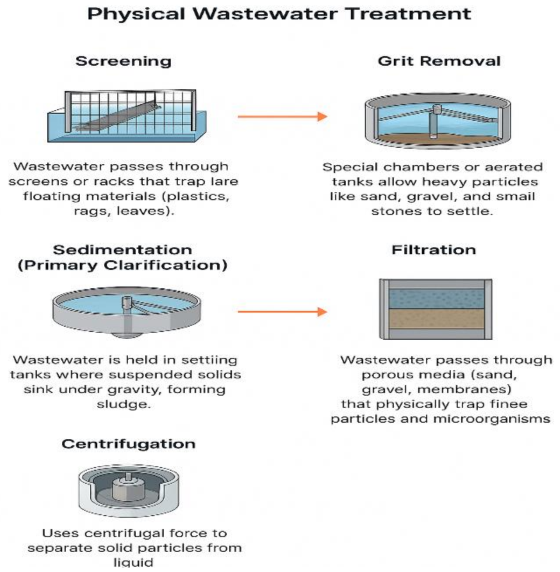

Figure 1: Process of physical wastewater treatment

The water gets separated once the insoluble particles settle down at the bottom. The wastewater is further filtered to ensure that no solid heavy particles remain. In recent years, nanofiltration techniques have been introduced to separate even finer particles and microorganisms in hybrid systems that combine both physical and biological processes. These advanced approaches are capable of removing bacteria, fungi, heavy metals, and other microbes, thus enhancing the effectiveness of conventional filtration methods. Finally, centrifugation is employed to ensure that the remaining fine suspended particles are settled and removed as sludge. The collected sludge, rich in organic matter and concentrated contaminants, is then pumped out for further treatment, stabilisation, or safe disposal, as improper handling of sludge can itself pose environmental and health hazards. [26]

B. Biological treatment (Secondary)

The secondary wastewater treatment is a biological process that removes dissolved and suspended organic matter. This method involves the use of both aerobic and anaerobic microorganisms that aid in the reduction of different pollutants and biochemical oxygen demand in the wastewater. [27] This can be done through aerobic, activated sludge, trickling filters, rotational aerobic contactor and aerobic granulation or anaerobic replication processes; aerated lagoon and anaerobic bioreactor. In aerobic systems, the Activated Sludge Process (ASP) uses aeration tanks where microbes degrade organics and form flocs, later settled in clarifiers [31]. Trickling filters pass wastewater over media covered in microbial films that oxidize pollutants with low energy use but require large land areas [30]. Rotating Biological Contactors (RBCs) employ rotating discs that alternately contact air and wastewater, allowing biofilms to remove organic matter efficiently with minimal maintenance (Sharma et al., 2021). Similarly, oxidation ponds or lagoons rely on sunlight, algae, and bacteria to degrade organics, offering a cost-effective but land-intensive option [28]. More advanced aerobic methods include Aerobic Granular Sludge (AGS), where dense microbial granules remove carbon, nitrogen, and phosphorus simultaneously, reducing land and energy needs compared to ASP (van Loosdrecht & Brdjanovic, 2023). In contrast, anaerobic treatment systems function without oxygen, such as anaerobic bioreactors that convert organic matter into biogas, suitable for high-strength industrial wastewater (Singh et al., 2023). Anaerobic Membrane Bioreactors (AnMBRs) further enhance this by combining anaerobic digestion with membrane separation, achieving over 97% organic removal while recovering energy (Zhang et al., 2025;29]

C. Chemical treatment (Tertiary)

Chemical treatment methods are crucial in wastewater remediation, including techniques like reverse osmosis, flocculation, ozonation, and adsorption [27].

Table 4: Tertiary wastewater treatment processes and their purposes

Treatment Method	Purpose	Target Contaminants	Key Notes	Source
Reverse Osmosis (RO)	To remove dissolved salts, organic molecules, and micro-pollutants by applying pressure across a semi-permeable membrane.	Heavy metals (lead, arsenic, mercury), nitrates, sulfates, pesticides, pharmaceutical residues, microbes.	Produces very high-quality effluent; energy intensive; brine management required.	Thamarai et al., 2024; Agarwal et al., 2022
Flocculation	To aggregate fine suspended particles into larger flocs for easier sedimentation or filtration.	Suspended solids, colloidal particles, organic matter, phosphates.	Uses coagulants like alum, ferric chloride, or polymers; improves clarity before secondary/tertiary steps.	Agarwal et al., 2022; Britannica, 2023
Ozonation	To disinfect and oxidize organic/inorganic pollutants using ozone (O_3).	Pathogens (bacteria, viruses, protozoa), organic micropollutants, color, odor-causing compounds, pharmaceuticals.	Strong oxidant, leaves no harmful residuals; costly and requires onsite ozone generation.	Thamarai et al., 2024; Britannica, 2023
Adsorption (Activated Carbon, Nanomaterials)	To trap contaminants on the surface of porous materials.	Organic micropollutants, dyes, pesticides, pharmaceutical residues, endocrine disruptors, heavy metals.	Effective for trace pollutants; nanomaterials (graphene oxide, CNTs) show higher efficiency.	Thamarai et al., 2024; Agarwal et al., 2022

While the above methods have been used for years now, the core problem is that old technologies are unable to keep up with the emerging contaminants and are only capable of removing waste in bulk. These methods are only capable of removing contaminants in bulk. Contaminants of emerging concern have been identified throughout the hydrological cycle, including groundwater, surface waterways, and wastewater treatment plant effluents. Their negative impact on terrestrial and aquatic life forms and human health is becoming a source of concern for scientists, engineers, and the general public. [36] Some notable examples of these are pharmaceuticals, hormones, pesticides, nanoparticles, microplastics/nanoplastics, personal care products, and industrial compounds. Due to their concentration in the environment (between ngL−1 and μgL−1), these products were previously not detectable and in most of the cases, there were no established concentration limits to protect living organisms from these contaminants [37, 38]. This persistence poses risks that go beyond ecological impacts: antibiotic residues contribute to antimicrobial resistance, endocrine disruptors affect reproductive health in both humans and wildlife, and nanoparticles interfere with cellular processes at the molecular level [39].

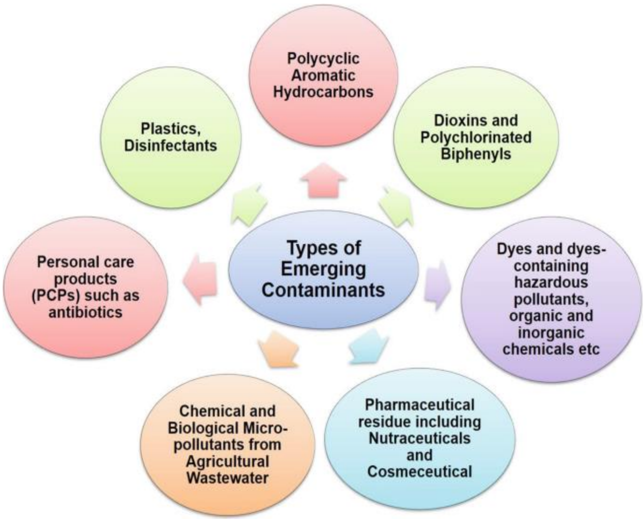

Figure 2: Types of emerging contaminants

The overloading of Urban Treatment Plants and Rising operational and maintenance (O&M) Costs are a big concern regarding the conventional methods. Globally, approximately 380 billion cubic meters (380 trillion litres) of wastewater are generated annually, with around 113 billion cubic meters of domestic wastewater and a significant, but poorly quantified, amount of industrial wastewater released without adequate treatment each year [41]. Operational costs (OpEx) for sewage treatment plants in India typically range between ₹5,000–₹50,000 per month, depending on plant capacity and technology. In global terms, unit costs are reported around $1.10–$1.46 per cubic meter of treated wastewater. [40] With such high costs and the ever-increasing volume of wastewater, not every developing country, household, or business can afford to install and operate an STP/ETP at their premises. This highlights the need for a solution that is both effective and cost-friendly, without requiring multiple treatment cycles to reduce waste from water. Additionally, as treatment plants are forced to operate beyond their designed capacity, energy demand rises exponentially, leading to higher fossil fuel consumption and further contributing to environmental pollution. Aeration alone can account for up to 60% of the total energy consumption in WWTPs [39], hence future technologies need to consider energy recovery and sustainability while being launched into the market.

The generation of secondary waste and its management have also become major concerns. As mentioned earlier, the activated sludge process used in conventional biological treatment produces sludge as a byproduct, which contains pathogens, heavy metals, and toxic organic compounds. With the increasing volume of wastewater, sludge production has also risen significantly. However, the treatment of sludge is a slow process and requires considerable time to be converted into a non-toxic substance. Sludge disposal presents several challenges across different methods. Landfilling, while being one of the most common and relatively inexpensive options, contributes to greenhouse gas emissions and poses risks of leachate contamination. Incineration effectively reduces sludge volume by converting it into inorganic ash, but it is costlier than landfilling and may lead to air pollution if emission controls are inadequate. Land application, where treated sludge is reused as fertiliser, soil amendment, or as feedstock for anaerobic digestion, offers a sustainable reuse pathway. However, it requires careful treatment and disinfection to ensure safety, since pathogens and contaminants in inadequately treated sludge can harm soil and human health. [40]

3. Nanotechnology in Wastewater Treatment

3.1 Properties of nanomaterials

To address the problems left unresolved by conventional methods, nanotechnology can be seen as a promising and sustainable advancement for treating wastewater. The main goal of nanotechnology is to create new structures, devices, and systems with superior electrical, optical, magnetic, conductive, and mechanical qualities by manipulating matter at the molecular and atomic levels [27].

Nanotechnology for wastewater treatment uses nanomaterials that are made of nanoparticles that target contaminants in the nanoscale range (1–100 nm). These nanoscale structures give rise to the material's unique properties, which make it feasible to be used for waste removal from water in future.

Starting with surface properties, high surface area (increasing adsorption capacity), surface reactivity, surface energy, and hydrophobicity are crucial in the removal of heavy metals, pharmaceuticals, and degradation of pesticides, phenols, hydrocarbons, and antibiotics, as well as the separation of oil, grease, and hydrophobic organic pollutants. An example of effective usage of these properties is TiO_2, whose high surface-to-volume ratio increases the number of adsorption sites on the sorbent's surface. At the same time, its optical properties, specifically the ability to absorb UV light, enable photocatalysis. Upon illumination, TiO_2 undergoes photoexcitation, where electrons are promoted from the valence band to the conduction band, leaving behind positively charged holes. These electron–hole pairs then drive redox reactions with water and dissolved oxygen, forming hydroxyl radicals ($\bullet OH$) and superoxide radicals ($O_2\bullet^-$), which are highly reactive and capable of degrading organic pollutants [19]. Beyond TiO_2, other nanomaterials such as ZnO and CdS also display tunable optical absorption properties. Unlike TiO_2, their band gaps can be adjusted into the visible spectrum, making them active under natural sunlight and expanding their applicability for both photocatalysis and antimicrobial processes [42].

The antimicrobial nature of nanomaterials is evident as many nanoparticles exhibit strong biocidal activity against bacteria, fungi, and viruses. Instead of one, each type of nanoparticle is capable of targeting different constraints, making them more diverse and usable, limiting the development of resistant strains. This is only possible because of their surface area and charge, but also their chemical composition and solubility. Metals and metal oxides (Silver (Ag), gold (Au), copper (Cu) etc) are the most effective antimicrobial nanoagents, solely because they can easily undergo redox reactions and them being soluble results in the transfer of electrons to oxygen molecules in water, in order to form reactive oxygen species (ROS) (Radicals). The three primary ways antimicrobial nanomaterials work are: disrupting the cell membrane by interacting with the phospholipid bilayer, binding to proteins inside the cell and blocking metabolic processes, and producing free radicals and ROS that damage essential biomolecules. [42].

The property of size exclusion removes contaminants based on their size. Water molecules can pass through nanoscale pores, while larger particles, microbes, or macromolecules are physically blocked and retained. This mechanism is especially effective for removing bacteria, viruses, and large organic molecules from wastewater [12,13]. Each nanoparticle in a material has a tunable pore size that is designed specifically for certain types of pollutants, making this a complementary property to adsorption and ROS-mediated antimicrobial action. This is the core fundamental used in nanofiltration and ultrafiltration, which are widely used in the selection of heavy organic compounds from wastewater. The most used example of these is carbon nanotubes, which are only permeable to particles smaller than 0.8 - 2 nm, effectively not allowing bigger contaminants to pass through, only water molecules.

3.2 Emerging nanotechnologies

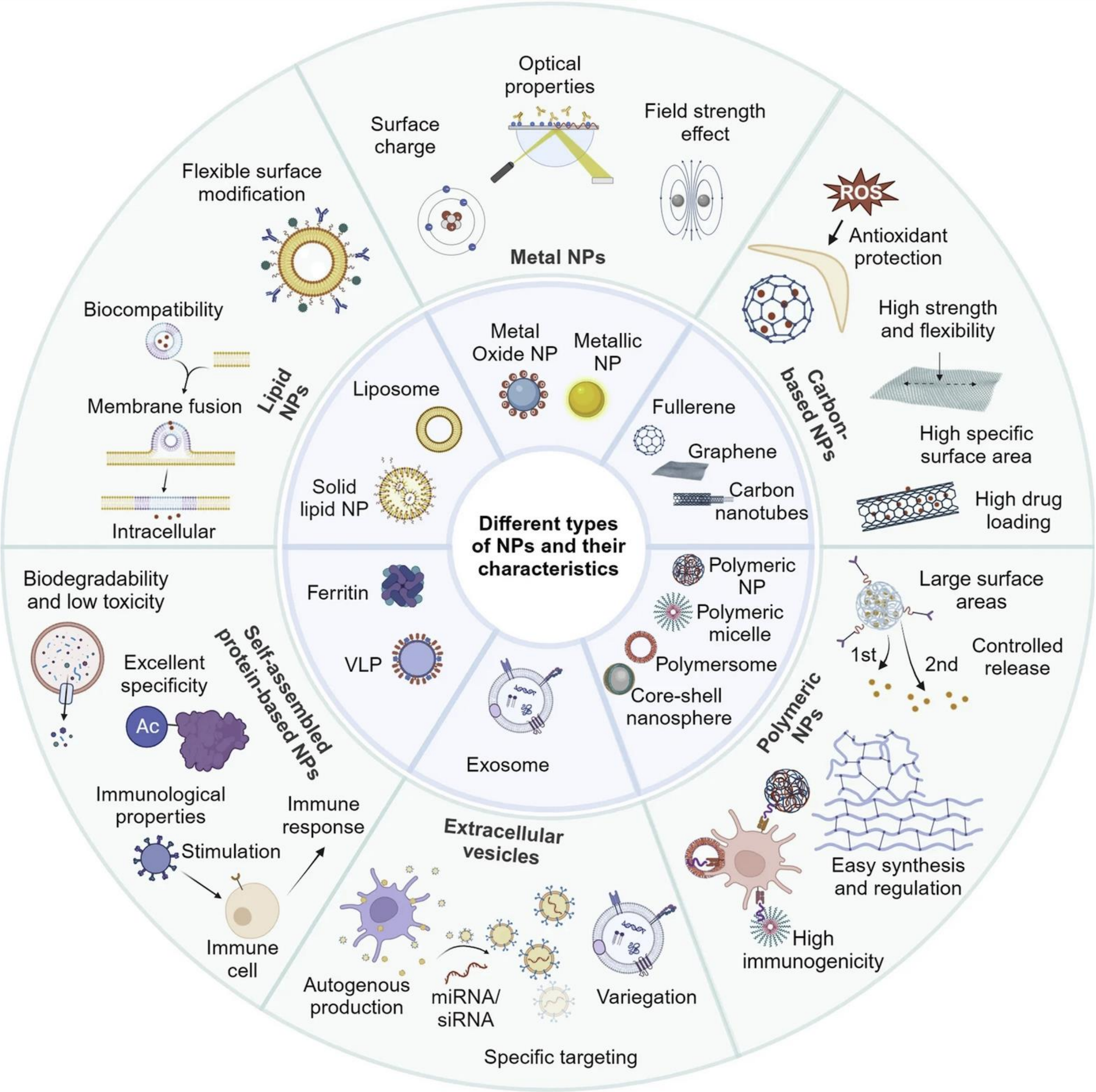

Figure 3: Different types of nanomaterials and their characteristics [60]

Table 5: classification of Nanomaterials with mechanism and other factors associated with them.

Class of nanomaterial	Examples	Mechanism	Target contaminants	% Removal	Reusability	Regeneration method	Scalability	Exposure time	Adsorption size range	

Nano-adsorbents	Activated carbon nanocomposites	Adsorption via high surface area and porosity	Dyes, heavy metals	85–98%	Moderate	Thermal/chemical washing	High (commercial AC base)	30–120 min	Small organics (0.5–5 nm), heavy metal ions (<1 nm)	[6, 8]
	Nano-zero-valent iron (nZVI)	Reductive adsorption, electron transfer	Arsenic, Cr(VI), nitrates	80–99%	Low–moderate	Stabilizers, surface modification	Medium (lab–pilot)	10–60 min	Metal ions (<1 nm), oxyanions (0.2–1 nm)	[25]
	Magnetic nanoparticles (Fe_3O_4)	Adsorption + magnetic separation	Pb^{2+}, Cd^{2+}, dyes	90–95%	High	Magnetic recovery	Medium–high	15–90 min	Ions (<1 nm), dyes (1–5 nm)	[23, 24]
Nanocatalysts	TiO_2 nanoparticles	Photocatalysis (UV-activated)	Dyes, antibiotics, phenols	85–100%	High	UV-regeneration	High (commercial)	30–120 min	Small molecules (0.5–2 nm)	[19]
	ZnO nanoparticles	Photocatalysis, oxidative degradation	Pharmaceuticals, pesticides	80–95%	Moderate	UV or sunlight	Medium–high	40–180 min	Organics (0.5–3 nm)	[27]
	Doped photocatalysts (TiO_2/Ag, Fe-TiO_2)	Enhanced photocatalysis (visible light active)	Antibiotics, endocrine disruptors	90–98%	High	Light-based activation	Medium	20–90 min	Organics, micropollutants (0.5–3 nm)	[7, 27]
Nanomembranes	Graphene oxide (GO) membranes	Size exclusion, adsorption	Heavy metals, dyes, salts	90–99%	High	Backwashing/chemical cleaning	Medium	Continuous flow	Ions (<1 nm), dyes (1–10 nm), salts	[10, 11]

									(<0.5 nm)	
	Carbon nanotube (CNT) membranes	Filtration, high flux	Salts, bacteria, viruses	85–98%	Moderate–high	Physical/chemical cleaning	Medium	Continuous flow	Ions (<1 nm), bacteria (200–1000 nm), viruses (20–200 nm)	[29, 53]
	Polymeric nanocomposite membranes	Hybrid size exclusion + adsorption	Pharmaceuticals, dyes	80–95%	High	Standard cleaning	High	Continuous flow	Small molecules (0.5–5 nm), ions (<1 nm)	[12]
Nanosensors	Gold nanoparticles (AuNPs)	Surface plasmon resonance sensing	Heavy metals, pesticides	ng–µg/L detection	Not reusable	Not applicable	Lab/field	Seconds–minutes	Ions/molecules (<2 nm)	[20]
	Quantum dots (QDs)	Fluorescence sensing	Organic pollutants, toxins	Very high sensitivity	Limited	Optical regeneration	Pilot scale	Seconds–minutes	Trace molecules (<2 nm)	[13]
	Graphene-based sensors	Electrochemical detection	Heavy metals, pharmaceuticals	ppb levels	Moderate–high	Recalibration	Emerging	Seconds–minutes	Metal ions (<1 nm), organics (1–3 nm)	[23]
Nanocoagulants / Nanoflocculants	Alumina nanoparticles	Charge neutralization + flocculation	Suspended solids, turbidity, dyes	80–95%	Moderate	Coagulant dosing	High	15–60 min	Colloids (100 nm–1 µm)	[8, 41]
	Fe_3O_4-based nanocomposites	Magnetic coagulation + sedimentation	Colloids, heavy metals	85–97%	High	Magnetic separation	Medium–high	20–90 min	Colloids (100 nm–1 µm), ions (<1 nm)	[23, 41]

Nano-Fenton / Photothermal agents	Fe_2O_3 nanoparticles	Fenton-like reaction	Refractory organics, phenols	80–99%	Moderate	pH/H_2O_2 adjustment	Pilot	30–120 min	Organics (0.5–3 nm)	[27]
	CuO nanoparticles + H_2O_2	Photo-Fenton oxidation	Dyes, antibiotics	85–98%	Moderate	H_2O_2 replenishment	Medium	30–90 min	Dyes (1–5 nm)	[7, 27]
Nanobiomaterials / Bio-nanocomposites	Chitosan nanoparticles	Adsorption (amine binding)	Dyes, Pb^{2+}, Cr(VI)	80–95%	High	Acid/base regeneration	High	30–90 min	Ions (<1 nm), dyes (1–5 nm)	[6, 51]
	Cellulose nanofibers	Adsorption + ion exchange	Dyes, heavy metals	75–92%	High	Mild washing	High	30–120 min	Ions (<1 nm), dyes (1–5 nm)	[6, 51]
Nano-encapsulated enzymes	Laccase on silica NPs	Enzymatic oxidation	Pharmaceuticals, pesticides	70–90%	Moderate	Enzyme reloading	Medium	Hours–days	Organics (0.5–2 nm)	[25]
	Peroxidase on polymeric carriers	Enzymatic degradation	Phenols, dyes	75–88%	Moderate	Re-immobilization	Lab–pilot	Hours	Organics, dyes (1–5 nm)	[20]

3.3 Recent advances in nanomaterials

3.3.1 Green synthesis (plant-based nanoparticles)

Green synthesis in nano technology refers to a sustainable and deco -friendly way of producing nano particles, with their medium being plants, bacteria, fungi, and algae instead of hazardous chemicals (toxic reducing and stabilizing agents such as sodium borohydride, hydrazine, formaldehyde) that create harmful byproducts) and energy-intensive physical processes (laser ablation, evaporation–condensation, and ball milling). In plant based green synthesis, plant extracts are the main constituents of the nano particles synthesis, where plant biomolecules such as phenolics, proteins/enzyme, flavonoids, terpenoids, alkaloids, and pigments act as stabilizers, coating and reducing agents assisting in dye reduction, heavy metal removal and antimicrobial action. [43] Greener syntheses of nanoparticles also provides advancement over other methods as they are simple, one step, cost-effective, environment friendly and relatively reproducible and often results in more stable materials [45] There are two ways of plant based green synthesis:intracellular and extracellular. The plant-mediated synthesis of nanoparticles (NP) can be performed by extracellular and intracellular methods. In extracellular methods, plant extracts or purified phytochemicals are utilized as raw materials used for NP synthesis, while in intracellular methods, NP synthesis occurs in plant cells [44]. The process of this synthesis starts with making the plant extracts to extract the biomolecule from the solid leaves using mainly water as solvent. After filtration, the solution of the metal precursor, which is usually $AgNO_3$ for silver nanoparticles and $HAuCl_4$ for gold nanoparticles, is mixed with the clear extract [47,48]. Depending on the nature of the phytochemicals involved, the mixture is kept at the optimum pH and temperature [49]. During synthesis, plant metabolites donate electrons to reduce metal ions ($Ag^+ \rightarrow Ag^0$, for instance), initiating the nucleation and growth of nanoparticles. At the same time, other phytochemicals stabilize the nanoparticles and prevent their agglomeration, modify their size and shape, and act as capping agents [50,51]. Next, the nanoparticles are purified through centrifugation or filtration to remove any residual plant matter and unreacted precursors, yielding eco-friendly, biocompatible nanostructures of great interest in the fields of biomedicine, environmental remediation, and catalysis. [52]

3.3.2 Carbon based hybrid nanocomposites

The remarkable mechanical, electrical, and thermal properties of polymer nanocomposites reinforced with carbonaceous nanomaterials have prompted extensive research.

a. Carbon nanotubes

Carbon nanotubes (CNTs) have emerged as highly promising nanomaterials for wastewater treatment due to their high surface area, porous structure, tunable surface chemistry, and strong adsorption capacity for heavy metals such as Hg(II), Pb(II), and Cd(II) [53]. CNTs are classified as single-walled (SWCNTs) or multi-walled (MWCNTs) depending on the number of concentric graphene cylinders [54]. While their smooth surfaces can limit dispersibility and adsorption efficiency, chemical modifications—particularly the formation of CNT composites—can significantly enhance their performance [55].

SWCNTs possess a hexagonal, porous structure that allows adsorption at exterior, intra-tubular, and inter-tubular sites [56]. Functionalization with oxygen-containing groups such as –C=O, –CHO, –COOH, and –OH, often through oxidizing treatments with HNO_3, H_2SO_4, $KMnO_4$, NaOCl, or H_2O_2, improves binding and increases heavy metal adsorption [57]. Adsorption efficiency is further influenced by factors such as molecular weight, dipole moment, critical temperature, and solution pH (Lithoxoos et al., 2010). SWCNTs have demonstrated high removal capacities for both organic pollutants and endocrine disruptors, including Bisphenol A (75–80%) and 17α-ethinyl estradiol (95–98%) (Joseph et al., 2011), as well as dyes such as Reactive Blue 4 (567.7 mg g^{-1}) (Machado et al., 2012). Their performance can be enhanced by combining SWCNTs with nanoparticles, for example, Fe_2O_3, for improved arsenic removal (Ma et al., 2018). Immobilization on substrates also allows SWCNTs to detect trace organochlorine pesticides in water (Lü et al., 2007).

MWCNTs, with diameters of 3–30 nm and multi-walled "Russian-doll" structures, provide high stiffness and strong adsorption performance for both metals and organic pollutants. Functionalized MWCNT composites, such as Fe_3O_4/MWCNTs, achieved nearly complete removal of total iron (98.97%) at pH 8.2 (Alimohammadi et al., 2017), while β-cyclodextrin-modified MWCNTs exhibited high adsorption of various dyes, including methylene blue (90.9 mg g^{-1}), methyl orange (172.41 mg g^{-1}), acid blue 113 (96.15 mg g^{-1}), and dispersion red 1 (500 mg g^{-1}) (Alimohammadi & Veisi, 2018). MWCNTs have also been used to immobilize microbial sorbents, enhancing both reusability and bioremediation stability (Fosso-Kankeu et al., 2014). Their ability to completely remove pesticides such as malathion and diazinon further demonstrates their versatility (Dehghani et al., 2017; Dehghani et al., 2019).

Unlike the usual use of CNTs mainly as adsorbents for pollutants, recent improvements in wastewater treatment have used lightweight carbon-metal oxide composites. These include Al_2O_3-

CNT, Al_2O_3/Fe_2O_3-CNT, Fe_2O_3-C, and ZnO-C. They are made through thermocatalytic methods that use waste plastics for carbon and aluminum or scrap iron for metal. These composites combine the strength and conductivity of CNTs with the adsorptive and catalytic qualities of metal oxides. This allows them to be used in filtration membranes and catalytic supports for removing pollutants while improving both structural strength and functional performance. Characterization through UV–vis, XRD, SEM, TEM, EDX, Raman spectroscopy, and nanoindentation confirms successful CNT formation in Al_2O_3 and Al_2O_3/Fe_2O_3 systems, while Fe_2O_3 and ZnO form CNT-free carbon composites. The Al_2O_3/Fe_2O_3–CNT composite demonstrates the highest density-normalized elastic modulus (9.66 GPa g^{-1} cm^3) and superior IG/ID ratio (2.05), reflecting high CNT quality, which contributes to enhanced mechanical and functional performance. By integrating strength, stability, and surface reactivity, these waste-derived composites represent a **scalable, eco-friendly approach** to advanced materials for water purification, bridging sustainability with high-performance functionality [58].

b. Reduced graphene oxide (rGO)

Reduced graphene oxide, unlike the normal graphene oxides, does not have a lot of oxygen-containing groups (–OH, –COOH, epoxide), but enough to have the properties of both graphene (conductivity mechanical strength,) and graphene oxide (retaining surface defects and functional sites useful for adsorption and hybridization.) A recent example is reduced graphene oxide@titanate hybrids (rGO@titanate), where rGO is layered or anchored with titanate structures. The main adsorption mechanism is ion exchange, as the titanate layers contain exchangeable sites (e.g., $Ti–O–Na^+$, $Ti–O–H^+$). These sites typically hold small cations such as Na^+ or Ca^{2+}, which can be swapped out and replaced by heavy metal cations. In this way, the toxic metals are effectively captured and removed from wastewater. Additionally, the titanate layers are supported by negatively charged functional groups (–OH, –COOH) on the rGO surface, which attract positively charged Pb(II) ions. The high surface area and layered structure of rGO further enhance the accessibility of these titanate ion-exchange sites, improving the overall adsorption efficiency [58].

The rGO's has a fixed bed system embedded in itself. A fixed bed system consists of multiple fixed bed columns which is a type of continuous water treatment setup where the adsorbent material is packed tightly inside a vertical tube or column. It lets contaminated water flow through the packed adsorbent, trapping pollutants as clean water exits below. Unlike batch tests, it mimics real industrial setups, enabling continuous operation and evaluation of breakthrough point, treatment capacity, and adsorbent stability [58]. The importance of fixed-bed column setups comes from their ability to closely resemble industrial flow conditions. This allows for continuous operation instead of just batch testing. They offer key insights into how the adsorbent performs, including breakthrough behavior, treatment capacity, and long-term stability under changing water flow [58].

c. CuS

Recent advancements in copper sulfide (CuS)-based nanomaterials have extended their application in wastewater treatment beyond conventional photocatalytic degradation. Novel CuS–graphene oxide (GO) and CuS–reduced graphene oxide (rGO) composites have shown enhanced adsorption and photocatalytic properties due to synergistic charge transfer and high surface area, enabling efficient removal of Pb^{2+}, Cd^{2+}, and Cr(VI) ions (RSC Advances 2025). CuS–ZnO heterostructures have demonstrated superior visible-light-driven degradation of antibiotics and dyes in real wastewater matrices, with improved stability over multiple cycles (ScienceDirect 2024). Furthermore, CuS–Fe_3O_4/rGO hybrids combine photocatalysis with magnetic separation, achieving rapid removal and recovery without secondary pollution (ACS Applied Nano Materials 2023). Recent studies have also highlighted hollow CuS nanostructures with oxygen vacancies that exhibit improved redox activity and reusability for heavy metal detoxification in continuous-flow systems (Elsevier 2024). These developments underline a shift towards multifunctional CuS-based composites that integrate adsorption, photocatalysis, and recyclability, positioning them as emerging candidates for scalable, sustainable wastewater treatment technologies.

4. Nanobioremediation: Synergy of Nanotech and Biological Processes

Bioremediation is an eco-friendly process using living microorganisms—such as bacteria, algae, fungi—or their enzymes to transform, degrade, or immobilize pollutants in water bodies (wastewater, surface water, groundwater), rendering them significantly less harmful [6] This includes the breakdown of organic compounds and heavy metals into benign end products like CO_2, water, and stable biomass. Bioremediation relies on several microbial mechanisms to clean water. In biodegradation, bacteria such as Pseudomonas and Bacillus metabolize pollutants, including oils and pesticides, breaking them down into less harmful compounds [5]. Under anaerobic conditions, microbes like Geobacter chemically reduce toxic metals into safer forms [7]. Biosorption involves pollutants passively sticking to microbial cell walls, especially in fungi and algae with metal-binding sites [6]. In bioaccumulation, microbes absorb contaminants into their cells for storage or transformation. Fungi such as Aspergillus niger produce enzymes like laccases that break down complex industrial chemicals, including dyes [4]. Microalgae like Chlorella also remove nutrients and heavy metals through a combination of biosorption and metabolic uptake [7]. To achieve even more efficient contaminant removal, nanotechnology is being rapidly integrated with bioremediation methods. Nanoparticles—such as iron, zinc oxide, or carbon-based nanomaterials—can support microorganisms by enhancing enzyme activity, increasing surface area for biosorption, or even delivering nutrients to microbes [7]. This technique, known as nanobioremediation, has begun to be implemented worldwide. A hybrid system incorporating TiO_2 nanoparticles on nanofiltration membranes was tested in Greece and Spain on real agro-industrial wastewater. It treated up to 15 m^3/day, removing ~41.5% of persistent fungicide thiabendazole, while recovering 95% of the water—demonstrating the feasibility of merging nanotech and microbial filtration in field conditions [8] To achieve even more efficient contaminant removal, nanotechnology is being rapidly integrated with bioremediation methods. Another example is a Fe_3O_4-biochar nanocomposite catalyst, which degraded ~89.3% of Fast Green dye within 60 minutes under optimal Fenton-like conditions (Fe_3O_4-biochar with H_2O_2, pH 4) and could be recycled for at least five successive cycles without significant loss of activity [10]. Similarly, a Fe_3O_4-graphene-biochar composite was developed to remove crystal violet from industrial wastewater, achieving a high maximum adsorption capacity ($\approx$ 436.68 mg/g) and allowing for magnetic recovery of the adsorbent [11]. These studies illustrate how biochar or carbon supports combined with magnetic or zero-valent metal nanoparticles enhance both the adsorption kinetics and reusability of bio-based materials in realistic treatment setups. Additionally, in one recent study, green-synthesized nanoscale zero-valent iron modified sludge biochar (TP-nZVI/BC) was used for Cr(VI) removal, showing strong performance both in batch isothermal adsorption and in fixed-bed column experiments, with models like ANN predicting removal behavior accurately under flow conditions [9].

5. Risks Associated with Nanomaterials - Nanotoxicology

Nanotechnology, in recent years, has benefitted various necessary fields such as engineering, medical, biological, environmental, and communication. However, the exponential growth of nanomaterials production would lead to severe complications related to their hazardous effects to the human health and environment. Moreover, the negative impact of nanomaterials toxicity on human health is one of the significant issues on exhausting nano-products [59].

This field of study concerned with finding out side effects of nanomaterials and particles is known as nano toxicology. Nanotoxicology is concerned with determining the negative consequences of nanoparticles on human health and the environment. Nanotoxicology seeks to define and identify the hazards of manufactured nanomaterials and necessitates a multidisciplinary team approach that includes toxicology, biology, chemistry, physics, material science, geology, exposure assessment, pharmacokinetics, and medicine [61]

Table: 6 Risks associated with nanomaterials

Nanomaterial / NP Type	**In Vitro Findings**	**In Vivo Findings**	**Major Exposure Route(s)**	**Key Recent Source(s)**
Graphene Oxide (GO) nanoflakes	Not always reported in vitro in this study, but characterized and assumed interactions with cells via their size, surface functional groups.	Short-term intravenous injection in SD rats (10 mg/kg) led to accumulation in liver, kidney, spleen; biochemical and serum parameter alterations; evidence of organ barrier permeability. [62]	Intravenous exposure	[62]
Graphene Oxide-Microplastic Hybrid (GO@PS)	In vitro: Apoptosis, oxidative stress markers elevated in embryonic zebrafish cells (molecular/cellular endpoints) due to the hybrid; blockage of chorion observed.	In vivo: Zebrafish embryo exposure showed developmental abnormalities, mortality, hypoxic conditions; GO@PS more toxic than GO alone or PS alone.	Aquatic model (embryonic exposure) via immersion in water	[63]
Carbon Dots (varied chemical compositions)	Different carbon dots induced varying degrees of cytotoxicity, ROS production and cell viability loss in A549 human lung cells; the nature of surface-chemistry (amine, carboxyl etc.) affected toxicity.	C57Bl6 mice exposed to carbon dots showed minimal overt organ toxicity at moderate doses; some inflammation; dose-dependence clear.	In vitro culture; intravenous or injection in animal models	[64]
Glycol Chitosan Nanoparticles (Polymeric NPs)	High uptake by cardiomyocytes (H9C2) and cancer cells;	Repeated high-dose IV injections (90 mg/kg) in mice produced cardiotoxicity:	Intravenous exposure in animal, plus	[65]

	necrotic cell death at high concentrations; lower toxicity in fibroblasts.	fibrosis, inflammation, organ dysfunction; lower repeated doses (22.5 mg/kg) had less severe effects.	cell-culture assays	
CuO Nanoparticles (green vs chemical synthesis)	In vitro: On zebrafish embryos and larvae, green-synthesized and chemically-synthesized CuO NPs (≈42-84 nm) caused developmental anomalies, increased mortality. Green ones had better dispersion.	In vivo: (embryonic fish model) mortality and developmental defects; no mammalian in vivo in that study, but strong environmental/ecotoxicity signal.	Immersion exposure in aquatic embryos (zebrafish)	[66]

Conclusion

The evolution of nanotechnology has opened transformative pathways for sustainable wastewater treatment through the use of engineered nanomaterials with exceptional adsorption, catalytic, and antimicrobial properties. By targeting contaminants such as heavy metals, dyes, pesticides, and pathogens, nanomaterials have demonstrated superior performance compared to traditional treatment methods. Furthermore, hybrid approaches that integrate nanotechnology with biological systems offer promising prospects for achieving energy-efficient and eco-friendly remediation. However, despite these advancements, significant challenges remain—particularly concerning nanomaterial recovery, reusability, large-scale application, and long-term toxicity. Establishing standardized protocols for nanotoxicological assessment and developing green synthesis routes are crucial for ensuring environmental safety and commercial scalability. Hence, the future of wastewater remediation lies in a balanced approach that leverages nanotechnology's potential while prioritizing human and ecological health.

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