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A Review on the Functions of Nanomaterials in Wastewater Treatment

[1]Deepmala Dalal, [2] Dr. Shameema Rana, [3] Dr. Renu Kumari Rohal

[1] Research Scholar, School of Sciences, Geeta University, Panipat (Haryana)

[2 & 3] Assistant Professor, School of Sciences, Geeta University, Panipat (Haryana)

[1]Email: deepmaladalal@gmail.com

[2]Email: **ranasanchu@gmail.com**

[3]Email: **ap.chemistry@geetauniversity.edu.in**

Abstract

Indeed, the availability of potable water is a major global concern, and nanomaterials have shown great promise in tackling the problems associated with water pollution. As previously mentioned, nanomaterials have special qualities that make them very efficient at filtering impurities from contaminated water. However, it is crucial to take into account a few crucial factors and difficulties related to their application, although nanomaterial-based approaches for pollutant removal are effective, they frequently call for additional energy inputs for procedures like membrane filtration or photocatalysis. Nanomaterials can also be expensive to produce and use, which might prevent their wide adoption. Therefore, in order to make technologies economically viable, it is imperative to develop cost and energy-efficient ones. It is critical to evaluate the potential environmental impacts of any technology, including impacts of nanomaterials used in water treatment. Because it is still unknown how long-term exposure to nanomaterials will affect ecosystems and human health, it is important to limit their release into the environment. To ensure the secure disposal or recycling of products based on nanomaterials, appropriate waste management techniques should be put into place difficulties with commercialization. Nanomaterial-based water treatment technologies have demonstrated promising outcomes in research settings, but their widespread application and successful commercialization present difficulties. Processes that are being scaled up from laboratory to industrial levels need to be carefully optimized, scalable, and integrated with the current water treatment infrastructure adaptability and flexibility. Depending on the type and source of the pollutants, the composition of the wastewater can vary significantly. Therefore, it is essential to create adaptable systems based on nanomaterials that can efficiently handle a variety of contaminants. The creation of multipurpose nanomaterials or the blending of various nanomaterials can increase the adaptability and efficiency of water treatment processes. Regulations and precautions: As with any method of water treatment, it's critical to make sure that nanomaterial-based technologies abide by rules and standards for the safety and quality of water. To avoid any negative effects on human health or the environment, it is important to closely monitor any nanoparticle releases or by products that may occur during treatment. In conclusion, nanomaterials offer significant potential in addressing water pollution challenges, but their successful application in large-scale wastewater treatment requires addressing energy and cost considerations, minimizing environmental impacts, overcoming commercialization barriers, ensuring flexibility, and adhering to regulations and precautions. Continued research and development efforts are necessary to optimize nanomaterial-based technologies and make them accessible and practical for widespread implementation.

Keywords: Nanomaterial applications, waste water treatment, pollutants, nanomembranes, nanosorbents.

1. Introduction

Since life is unimaginable without water, water is a natural resource on earth and its availability in its pure form is crucial for both humans and other living things. Due to its potential qualities, such as solubility power, etc., water is also known as the universal solvent. Water contamination is currently the biggest issue facing the entire world. This is because of a number of factors, including poor sewage treatment, industrial wastes, marine dumping problems, radioactive waste material, certain agricultural perspectives, etc. [1, 2]. Water pollution harms the environment and contributes to air pollution, which has hazardous effects on human health. Additionally, the economic development and social perspectives of the affected societies and countries are negatively impacted by water pollution. According to a recent UN report, the availability of clean, fresh water has become a problem for the entire world in the twenty-first century because contaminated water poses a threat to life as we know it [3, 4]. When unwanted substances enter water bodies or reservoirs, the water becomes contaminated and is no longer fit for human consumption or other uses. There are numerous chemical, physical, and mechanical solutions to this new issue. Additionally, researchers are still investigating various novel technologies to enhance low-cost water purification methods [5, 6]. A potential solution to purify water with low cost, high working efficiency in removing pollutants, and reusable capability is now being offered by the newly emerging field of nanotechnology [7]. Nanomaterials have been successfully used in the past in a variety of places, such as in science related to medicine, catalysis, etc. Due to their unique properties, such as their nano size, large surface area, high reactivity, strong solution mobility [8], strong mechanical property, porosity characters, hydrophilicity, dispersibility, and hydrophobicity [9-11], experts recently discovered that nanomaterials are a better option for treating wastewater. It has been reported that the use of various nanomaterials has successfully removed some heavy metals like Pb, Mo, etc., organic and inorganic pollutants, and various harmful microbes [12-16]. The World Health Organization (WHO) reported that four billion cases of various health issues were reported annually due to waterborne diseases, and nearly 1.7 million people died due to water pollution [17].

Recent years have seen significant progress in the field of nanomaterials, particularly in the fields of nanophotocatalysts, nanomotors, nanomembranes, and nanosorbents. These materials have enormous potential for use in the treatment of water, especially in tackling the problems of water scarcity and tainted water. For instance, nanosorbents, which have a high capacity for sorption, have many uses in water treatment processes.

In a review article, the positive perspectives of applications of nanomaterials in water purification were assessed. The role of nanomaterials in wastewater treatment was summarized, highlighting their potential in overcoming water crises. Nano-engineered materials offer promising approaches to water treatment that are adaptable and can be easily implemented. However, it is important to acknowledge the existing imperfections and limitations that still require attention. These imperfections are specifically addressed in the article, along with the Nanomaterials have advantages, drawbacks, and potential uses in the future.

The dangers posed by nanomaterials is also discussed in the context of their applications in wastewater treatment. Understanding the potential risks and considering the toxicity of these materials is crucial for researchers when developing new strategies.

Overall, the review article gives a thorough description of the position of nanomaterials in wastewater treatment, highlighting their potential, limitations, and future directions. It aims to guide researchers in planning new strategies and considering the various aspects related to nanomaterials in water treatment applications.

2. Water treatment techniques

2.1. Nanophotocatalysts

The Greek words "photo" and "catalysis," which mean compound decomposition in the presence of light, are combined to form the English word "photocatalysis." Typically, there is no accepted definition of photocatalysis in the scientific community [18]. However, this phrase can be used to describe a procedure that uses light (UV, visible, or sunlight) to activate or stimulate the substance. a photocatalyst that affects the rate of reaction during a chemical reaction without being actively involved. Additionally, the primary distinction between a photocatalyst and a conventional thermal catalyst is that the latter is activated by light photons, whereas the former is activated by heat [19]. Due to their increased surface ratio and shape, nanophotocatalysts are frequently used for wastewater purification because they help to increase the catalyst's reactivity [20]. Due to their unique surface properties and quantum effects, materials with nanoscale dimensions respond differently than bulk materials. It helps to improve their optical, electric, mechanical, magnetic, and chemically reactive properties as well [21]. It has been demonstrated that nanophotocatalysts can increase oxidation capacity due to efficient oxidising species production at material surfaces, which aids in the efficient degradation of pollutants from polluted water [22].To treat environmental pollutants like azo dyes, chlorpyrifos [23-25], organochlorine pesticides, nitroaromatics, etc., nanoparticles like zero-valence based metal, semiconductor, and some bimetallic type are typically used [26]. Additionally, several studies have shown that TiO_2 based nanotubes can be used to remove pollutants from waste water, including organic pollutants like azo dyes, Congo red, phenol aromatic base pollutants, toluene, dichlorophenol trichlorobenzene, chlorinated ethene, etc. [27-31]. SiO_2, ZnO, TiO_2, Al_2O_3, and other metal oxide nanophotocatalysts are, however, the most popular and significant ones [32-33]. Since it is inexpensive, toxic-free, chemically stable, and readily available on Earth, titanium dioxide (TiO_2) stands out among all other materials as a superior photocatalyst. In addition, TiO_2 is real. Anatase is currently thought of as a good nanophotocatalyst material [34]. This state's bandgap is 3.2 eV, and it can absorb ultraviolet light (light with a wavelength below 387 nm) [35]. But other photocatalysts, like ZnO, have also been developed to effectively remove contaminants from wastewater and have reusable properties [36-40].When using CdS/TiO2 composite as a catalyst to treat water, it was also investigated how the degradation of the reference material (dimethyl sulfoxide) affected the photocatalytic performance of the process [41]. Due to their ferromagnetism, iron-doped nanomaterials are easily recyclable and reusable [42-45]. Similar to this, Pd-incorporated ZnO nanomaterial has been used to remove Escherichia coli from wastewater due to properties like high photocatalytic reactivity [46]. Although new efforts have been made to modify metal oxides with other elements such as metals or metal ions [6, 23], carbonaceous-based materials, dye sensitizers [47], and many others in order to improve the photocatalytic performance under visible light irradiation, there is still a need for additional modifications. Additionally, the nanophotocatalysis process can take place in either a homogeneous or heterogeneous state. Due to its broad range of applications in water decontamination and environmental-related fields, heterogeneous nanophotocatalysis is the state that has been studied the most extensively in the modern era. The development of an interface between a fluid (both reactants and products of the reaction) and a solid photocatalyst (such as a metal or semiconductor) is necessary for heterogeneous photocatalysis [48, 49]. When a light-based semiconductor photocatalyst is used and interacts with a gaseous or liquid phase, the term "heterogeneous photocatalysis" is typically used [50]. Applications based on heterogeneous photocatalysis heavily rely on scaled-up reactors built on newly developed designs with higher efficiency [51]. Mass transfer optimisation and effective nanocatalyst illumination are the main tasks in reactor design.Although light-emitting diodes and optical fibres can help with photon transfer, there haven't been any significant advances in this area. Additionally, a significant amount of work has been put into developing solar photoreactors [53-54]. According to the literature, nanophotocatalysts have been successfully used in research lab settings to treat water and clean the air. At the commercial level, it's still not the best solution to lessen the issue.

Additionally, the lack of efficient photoreactor configurations and the photocatalytic incompetence of photocatalysts are to blame for the current dearth of extensive commercial applications. Despite everything, heterogeneous nanophotocatalysts suggest fascinating benefits, such as inexpensive chemical usage, additive-free operation, ability to function even at low concentrations, and chemical stability (for example, TiO_2 stable in aqueous medium) [55]. Consequently, recent heterogeneous photocatalysis is achieving the pre-industrial scale.

2.1.1. Nanophotocatalyst benefits and drawbacks

For the detoxification of water contaminated with dangerous organic substances. Nanophotocatalysis, which utilizes nanophotocatalysts, has proven to be a highly efficient and environmentally friendly method. With the aid of nanophotocatalysts, nanophotocatalysis has demonstrated a crucial role in the mineralization of hazardous organic substances at 25 °C and has proven to be a very effective and efficient method for water detoxification [56].

Nanophotocatalysts offer several advantages in water treatment applications. They are less toxic, cost-effective, chemically stable, readily available, and exhibit excellent photoactive properties due to their nano size, typically ranging from 1 to 100 nanometers [57]. Among various nanophotocatalysts, titanium dioxide (TiO_2) is widely used due to its good photostability. However, many other Nanophotocatalysts like copper-based materials, metal sulphide materials, and zinc oxide, suffer from low chemical stability and are prone to photocorrosion [58]. When these materials they experience oxidation or reduction when they are exposed to light, leading to the decomposition of the photocatalysts and reduced efficiency of the photocatalytic reaction.

To address this challenge, it is crucial to develop nano composites that can achieve stable photocatalysis performance over extended periods. The advantages of nano-sized materials are attributed to the quantum-size effect, which enhances the energy bandgap and reduces particle size [59]. Photodegradation, as a process, offers additional advantages such as low cost, reusability, and the potential for complete degradation of organic pollutants. However, despite these developments, nanophotocatalysts still face issues related to toxicity and the recovery of catalysts from the reaction mixture, which limit their broader applications [60].

The scientific community is actively concentrating on the synthesis of new photocatalysts that can function in the visible range of the electromagnetic spectrum, enabling long-lasting and effective results. This is done to mitigate these difficulties. It is suggested that doping photocatalysts with various substances, such as graphene and its derivatives, will lessen their toxicity and improve their efficiency. The application of magnetic nanophotocatalysts in wastewater treatment is a significant strategy to address the problem of catalyst recovery. With magnetic nanophotocatalysts, the catalyst is easily recovered using external magnetic fields, enabling multiple recycling of the nanocatalyst and producing more efficient and quick water decontamination processes.

Section A-Research paper
ISSN 2063-5346

In summary, nanophotocatalysis has emerged as a highly effective approach for removing pollutants from water. By synthesizing new photocatalysts that operate in the visible range, reducing toxicity through material doping, and utilizing magnetic nanophotocatalysts for catalyst recovery, the scientific community aims to further enhance the efficiency and applicability of nanophotocatalysis in water treatment processes. Figure 1 illustrates some novel uses of nano photocatalysts [61].

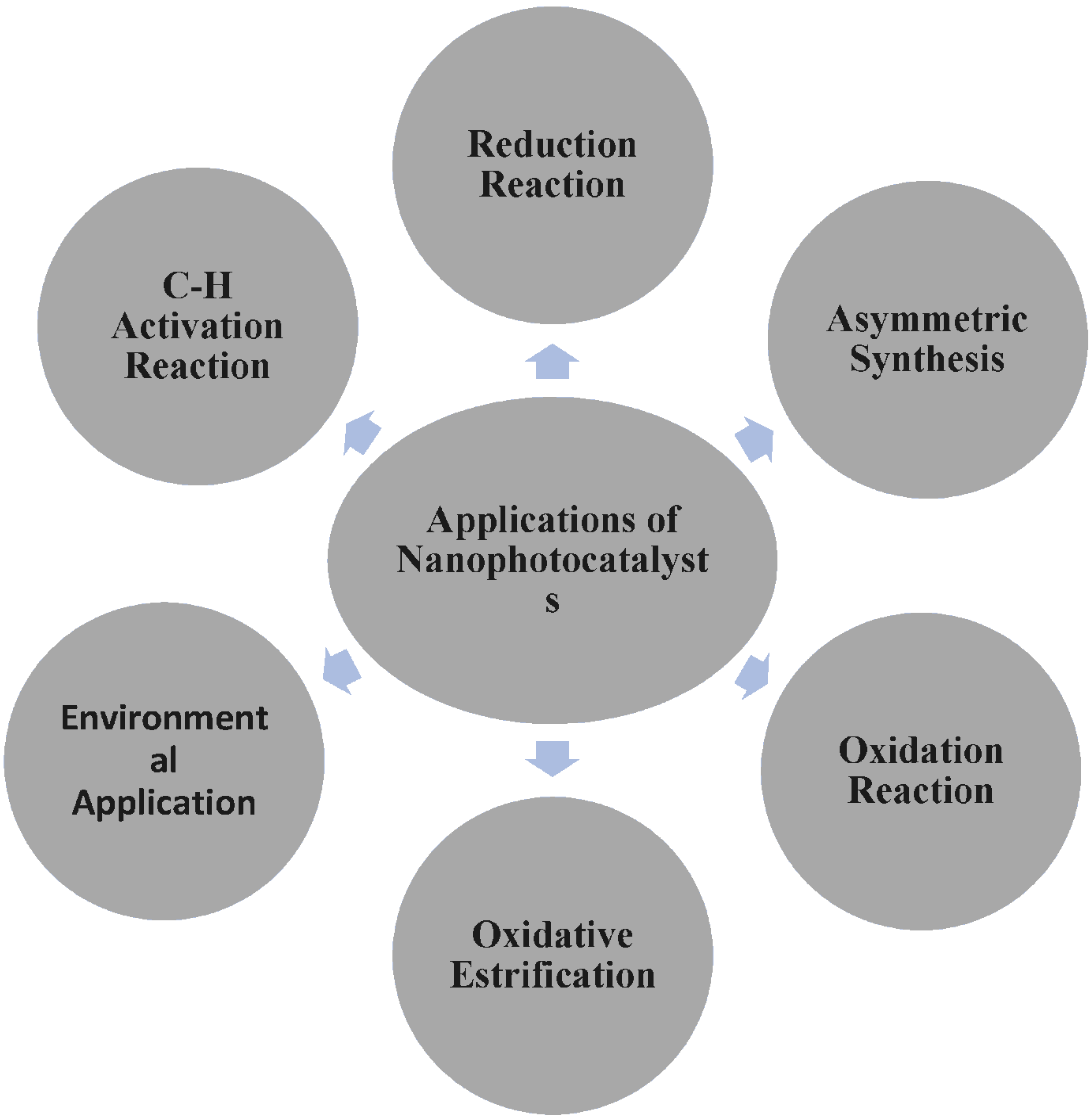

Figure 1. A few novel uses of nanophotocatalysts [61].

2.1.2. Perspectives for nanophotocatalysts in the future

The field of nanophotocatalysis has seen significant research focused on nanomaterials, reactor design, and modifications of nanophotocatalysts. While progress has been made in developing nanophotocatalytic materials, there are still vital questions regarding their characteristics. Overcoming mass transfer constraints and lowering the higher photon consumption are two major challenges in the intensification process [62].

One promising approach to address the electron pair recombination problem is the use of nanocomposites combined with nanophotocatalytic reactor structures. Nanocomposites can help prolong the recombination process and improve overall efficiency. Microfluidic reactors, also known as micro-reactors, have emerged as a new avenue for studying intense characteristics in both the reaction and synthesis phases [63, 64]. These reactors operate on a micro-level with reactants and offer advantages such as a They are more ideal than conventional reactors due to their high surface-to-volume ratio, enhanced diffusion effects, high mass transfer coefficient, stable hydrodynamics, low Reynolds flow, and ease of handling.

Despite these advancements, there are still difficulties in using photocatalysis on a large scale to treat wastewater. It is possible to conduct in-depth research on the synthesis of significant nanomaterial structures with improved structural and functional characteristics, such as nanorods, nanospheres, nanoflowers, nanoflakes, and nanocones. We urgently require novel nanophotocatalysts with outstanding performance, affordability, environmental friendliness, and high stability. Additionally, a variety of strategies, including electrocatalysis, adsorption, and various thermodynamic processes, should be combined in a synergistic way to effectively exploit pollutant treatment.

The preparation of nanocomposites using materials like ZnO, TiO_2 has been extensively explored for water pollutant treatment. Although still in its infancy, the synthesis of nanocomposites using carbonaceous, polymer, and ceramic materials holds the promise of producing ideal nanocomposites with enhanced properties. There are technical challenges inhibiting the widespread use of heterogeneous photocatalysis for wastewater remediation, which require effective study and resolution.

In the future, significant advancements in photocatalytic treatment, driven by solar energy, with quick assessment and development, excellent efficacy and reduced site area requirements can be anticipated.

2.1.3. Pathway for photocatalytic degradation and mineralization

Superoxide radicals ($\bullet O^{2-}$) and hydroxyl radicals ($\bullet OH$) function as potent oxidising agents and start a number of oxidation reactions when organic pollutants are present. The organic pollutants are oxidized and broken down into smaller, less harmful molecules. This process is known as degradation.

On the other hand, on the verge of mineralization, the organic pollutants are completely transformed into simpler, inorganic compounds such as water, carbon dioxide, and inorganic ions. This complete destruction of the organic pollutant is desirable as it ensures the removal of the pollutant from the environment.

The excitation of a semiconductor material like TiO_2 by absorbing light with energy equal to or greater than its band gap width is the mechanism of pollutant degradation in the presence of light. The electron-hole pairs (e-h+) produced by this excitation. If the charge separation is kept, the electrons and holes can move to the catalyst's surface and engage in redox reactions with species that have been adsorbed.

Specifically, the electrons in the conduction band (ecb) react with oxygen to produce radical anions (superoxide radicals), while the holes in the valence band (h+vb) react with water (adsorbed on the catalyst surface) to produce hydroxyl radicals (•OH). These highly reactive hydroxyl and superoxide radicals act as strong oxidising agents during the degradation process.

Overall, the use of nanomaterials, such as TiO_2, in photocatalysis offers a promising approach in order to degrade and mineralize harmful organic pollutants. The unique physiochemical properties of nanomaterials, coupled with their photocatalytic activity, make them effective in breaking down and transforming pollutants into less harmful substances.

$$TiO_2 + hv \rightarrow e{-}cb + h{+}vb \qquad (1)$$
$$O^{2+}\ e{-}cb \rightarrow O^{2-} \qquad (2)$$
$$H_2O + h{+}vb \rightarrow OH + H^{+} \qquad (3)$$

In the process of utilizing nanomaterials for pollutant degradation in the presence of light, it is important to assess the toxicity of the resulting degraded products relative to the parent compound. This can be done through toxicity testing. The analysis of the degraded products is typically performed using techniques such as HPLC-MS (High-Performance Liquid Chromatography-Mass Spectrometry) or GC-MS (Gas Chromatography-Mass Spectrometry).

The mineralization concept aims to avoid the generation of undesirable products and focuses on degrading organic compounds efficiently. Figure 2 illustrates a possible mechanism for pollutant mineralization, which is coupled with the photodegradation mechanism [61].

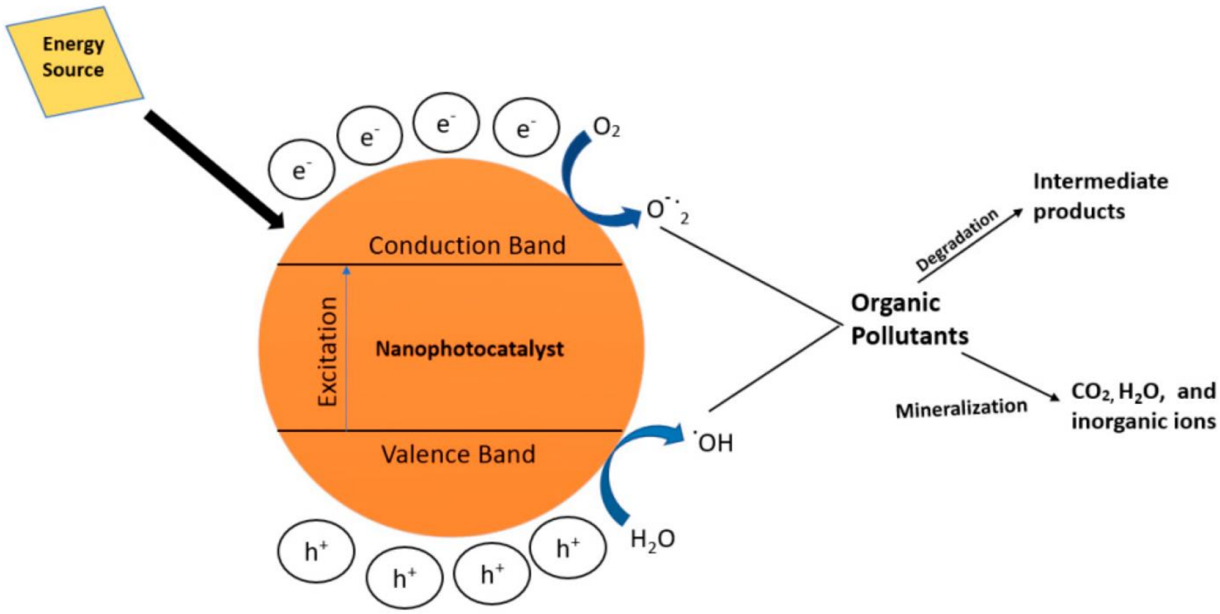

Figure 2. General mechanism for the degradation of toxic organic compounds by nanophotocatalysts [61].

Mineralization is a term used to describe complete photodegradation, where a compound is degraded into carbon dioxide (CO_2) and water (H_2O). During mineralization, other minerals may also be released, Sulphate, ammonia, sulfite, fluoride, sulphide, chloride, phosphate, nitrite, and other substances [66]. The mineralization rate is generally slower compared to degradation, possibly due to the formation of stable intermediates during the process. Consequently, extended irradiation periods may be necessary to achieve complete removal of Total organic carbon (TOC), also known as the sum of all the carbon atoms bound to organic compounds and can be measured using a TOC analyzer.

To assess the toxicity of the obtained degradation products, further toxicity testing is required. This involves subjecting the products to appropriate toxicological assays to determine if they are either more toxic than the parent compound or less toxic. It is crucial to consider the potential formation of intermediate products during the degradation process, as these intermediates may possess different toxicological properties compared to both the parent compound and the final mineralized products.

3. Self-toxicity of nanomaterials

Nanomaterials have indeed gained significant attention and are widely used in various fields because of their special qualities and potential uses. They have shown promise in agriculture, wastewater treatment, electronics, and energy generation, and other scientific disciplines. In the setting for water treatment, nanomaterials such as doped metal oxides, double- and single-walled doped carbon nanotubes, and nanosorbents have all been studied for their capacity to filter contaminants from wastewater.

While nanomaterials offer numerous benefits, it is crucial to understand their potential self-toxicity effects. Some studies have reported the toxic effects of certain nanomaterials, as documented in Table 1. Some metal oxides have demonstrated toxic characteristics at high concentrations, while others may exhibit toxicity even at lower concentrations. Carbon nanotubes (CNTs) also exhibit varying degrees of toxicity, depending on properties such as length, surface area, distribution ratio, degree of aggregation, and initial material concentration. In comparison to double-walled CNTs, single-walled CNTs are typically thought to be less toxic. Inflammation, oxidative stress, granuloma formation in the lungs, inflammation, apoptosis, and fibrosis are some of the toxic effects of CNTs.

In the case of titanium dioxide (TiO_2), the toxicity depends on the composition ratio, initial concentration, and exposure time. Typically, TiO_2 is regarded as harmless even at higher concentrations for a 24-hour period. However, ongoing scientific studies are focused on examining the toxic and side effects of nanomaterials, as well as elucidating the mechanisms involved in their transport, degradation, elimination, accumulation, and other interactions within the body.

It is crucial to remember that nanomaterials may endanger human health through a variety of exposure routes. Therefore, it is imperative to thoroughly research the effects of nanoparticles on health and comprehend their potential consequences. The goal of this research is to reduce potential risks to the environment and human health while ensuring the safe and responsible development and application of nanomaterials in numerous fields.

Table 1. Observation of self-toxic effect of some common nanomaterials.

Nanomaterials	**Observations**	**References**
A composite of gold nanorods with hexadecylcetyltrimethylammonium bromide (CTAB) as a dopant	High toxicity at a specific concentration	[67]
Composite of Fe_2O_3 and carbon nanotubes	Even at the lowest concentration, it showed toxic effects and damaged DNA	[68]
CdSe-core quantum dots	Cytotoxic under certain conditions	[69]

Section A-Research paper
ISSN 2063-5346

Nanomaterials	Observations	References
Carbon nanotubes (single and multi-walled)	Beyond 15 µg/cm concentration, there is an increase in toxicity	[70]

4. Nanomaterial challenges for water treatment

(a) The mechanism of removing nanoparticles from wastewater can vary depending on the specific method employed. Some common mechanisms include:

1. Adsorption: Nanoparticles can be adsorbed onto surfaces of materials such as activated carbon, zeolites, or other adsorbents. This process relies on the attractive forces between the nanoparticle and the adsorbent material.
2. Coagulation/Flocculation: Chemical coagulants or flocculants are added to wastewater to destabilize and aggregate nanoparticles into larger flocs, which can then be easily removed through filtration or sedimentation.
3. Membrane filtration: Nanoparticles can be removed through various membrane filtration techniques like reverse osmosis, nanofiltration, or ultrafiltration. The nanoparticle size determines the appropriate membrane type and pore size required for effective removal.
4. Precipitation: Some nanoparticles can be precipitated by adjusting the pH or adding chemical agents that induce the formation of insoluble compounds, leading to their removal from the wastewater.

(b) The During wastewater treatment, the impact of nanoparticles on other waste substances depends on their interactions and chemical properties. Nanoparticles can potentially interact with other pollutants in several ways:

1. Adsorption competition: Nanoparticles may compete with other pollutants for adsorption sites on adsorbents or surfaces, reducing the removal efficiency of these pollutants.
2. Catalytic effects: Certain nanoparticles, such as metal-based nanoparticles, can exhibit catalytic activity and potentially influence the degradation or transformation of other waste substances during treatment processes.
3. Aggregation: Nanoparticles can aggregate with other colloidal or suspended particles present in the wastewater, forming larger particles that may be easier to remove.

Section A-Research paper
ISSN 2063-5346

The specific effects of nanoparticles on other waste substances would require consideration of the characteristics of the nanoparticles and the wastewater composition, as well as the chosen treatment method.

(c) Coagulation and carbon adsorption methods can be effective in wastewater treatment, but their efficacy depends on a number of variables, such as the pollutants, the characteristics of the wastewater, and the dosage of coagulants or carbon adsorbents.

Coagulation involves adding substances known as coagulants to the mixture, which destabilizes the suspended particles and promote their aggregation. This process is followed by flocculation, where gentle mixing is applied to encourage the development of more substantial particles (flocs), which easily settled or filtered. Coagulation is effective for the elimination of suspended solids, organic matter, some heavy metals, and certain colloidal particles.

Carbon adsorption, typically, it is common practise to use activated carbon to remove organic pollutants from wastewater. Activated carbon has a large surface area and a porous structure, which contribute to its high adsorption capacity. It can effectively remove various organic contaminants, including pharmaceuticals, pesticides, and organic dyes.

Both coagulation and carbon adsorption methods have limitations and may not be equally effective for all types of pollutants. Optimal dosages, contact times, and operating conditions need to be determined for each specific case to achieve efficient removal.

To understand the intermediate products formed during wastewater treatment processes, comprehensive analytical techniques such as chromatography, spectrometry, and mass spectrometry can be employed to identify and quantify the transformation products or degradation intermediates. These analyses can provide insights into the fate and potential toxicity of the pollutants during treatment processes.

Continuous methodology improvement is crucial to analyze nanomaterials for cheap and compatibility for complex nanomaterials. This involves advancing characterization techniques, toxicity assessment methods, and scalability of nanomaterial synthesis. Collaboration between researchers, regulatory bodies, and industry stakeholders is necessary to address these challenges and ensure using nanomaterials in wastewater treatment in a secure and efficient manner.

5. Conclusive remarks and future perspectives

You are correct in highlighting the importance of water and the challenges associated with ensuring sufficient clean water for human needs. The availability of Water that is safe to drink is indeed crucial the welfare of people, sanitation, and overall development.

Section A-Research paper
ISSN 2063-5346

The scientific community and research institutes have been actively working to address these water challenges. One area of research that has gained momentum is the use of nanotechnology for water treatment. Nanomaterials have shown promising results in effectively treating water pollutants and improving water quality.

Nanomaterial approaches, such as nanosorbents and nanostructured catalytic membranes, offer several advantages. They are highly efficient in removing pollutants, require less time and energy compared to traditional methods, and can be environmentally friendly. These advancements in nanotechnology have the potential to completely transform water treatment techniques and contribute to solving water scarcity issues.

However, as you rightly pointed out, there are challenges in implementing these technologies in a significant way. Cost is one significant factor that hinders the commercial use of nanomaterials for water purification. Further research and development are needed to enhance the production decrease the processes overall costs associated with nanomaterial-based water treatment.

Additionally, it is essential to consider the scalability and practicality of these approaches. While laboratory-scale experiments have shown promising results, transitioning these technologies to real-world applications requires careful consideration of factors such as system design, maintenance requirements, and long-term performance.

To overcome these challenges, collaboration between scientific communities, research institutions, governments, and industry is crucial. Funding and support for research in nanotechnology and water treatment should be encouraged to accelerate the development and deployment of cost-effective and scalable solutions.

Furthermore, a comprehensive strategy must be used to water management that includes not only technological innovations but also considerations of water governance, policy, and education. Encouraging water conservation practices, promoting sustainable water use, and raising awareness about the importance of water resources can all contribute to overcoming the challenges associated with water scarcity and pollution.

In conclusion, while nanotechnology holds great potential for addressing water treatment challenges, further research, development, and collaboration are needed to overcome barriers such as cost and scalability. By combining technological advancements with comprehensive water management strategies, we can strive towards ensuring sufficient and clean water resources for present and future generations.

Nanomaterials indeed demonstrate high efficiency in various applications, including water treatment. They have a high rate of reaction as a result of their high surface area to volume ratio, which them to interact more effectively with contaminants in water. However, some issues still need to be resolved in order to completely leverage the benefits use of nanomaterials in the treatment of water.

One significant challenge is the lack of operational methods for digital monitoring can provide reliable in-the-moment measurement data on the effectiveness of nanoparticles, especially when present in modest amounts in water. Having such monitoring techniques would allow for better control and optimization of the water treatment processes.

Another important consideration is the potential risks to one's health from using nanomaterials. Research institutes and international research communities should collaborate to create appropriate rules and regulations to ensure the responsible and safe use of nanoparticles in water treatment. This includes studying their potential toxic effects and implementing measures to lessen any adverse impacts on environmental and human health.

Mechanical limitations also exist in the implementation of nano-engineered water treatment approaches. These technologies are often not easily scalable to mass production and may not be compatible with conventional treatment methods in some cases. Overcoming these mechanical restrictions requires further research and development to make nanomaterial-based water treatment technologies more practical and accessible.

Despite these challenges, nanotechnology-based materials hold excellent potential for water treatment innovations, particularly in independent water treatment systems, point-of-use techniques and the removal of highly persistent pollutants. The unique properties of nanomaterials can contribute to significant advancements in water treatment processes.

Moreover, there is a need for the creation of modified nanomaterials not only effective and efficient in water treatment but also environmentally friendly and simple to handle. The creation of these materials will further enhance the application of nanotechnology in the water treatment sector.

Cost considerations and the commercialization of these technologies are also crucial aspects to address. While nanomaterial-based water treatment methods have promising potential, it is crucial to develop cost-effective solutions that can be readily adopted and implemented on a large scale, especially for the treatment of sewage.

In summary, nanomaterials offer a wide range of applications and have the potential to completely change how water is treated. However, challenges such as the lack of real-time monitoring techniques, health risks, mechanical restrictions, and cost considerations need to be addressed to fully harness their benefits to make sure the widespread accessibility to clean drinking water worldwide.

Data availability statement

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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