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Analysis of the Economic Feasibility of Metal Oxide- Graphene Nanocomposites Compared to Traditional Water Treatment Technologies

Gajendra Kumar Tardia

Assistant Professor, Department of Education, SMT. Rukmani Devi Ramdev Ladha Govt. College, Nawa City, Rajasthan, India

ABSTRACT: Water, a simple molecule having two atoms of hydrogen (H) and one of oxygen (O) with the general formula H2O, is the most important need for living and nonliving organisms on the Earth. Many physical and biological properties of cells, macro-molecules, mainly proteins, and nucleic acids, originate from their interaction with water molecules of the surrounding medium. Water plays a profound and determinative role in biological evolution. All lives on the Earth depend on water (Henry, 2005). The physical and chemical properties of water support the environment, including living and non-living forms. For example, the formation of a thin layer of ice on the top of a lake protects all lives forms in the lake by avoiding the freezing process of the entire water in places where the temperature of the atmosphere falls below 0C. The water under the thin ice layer remains at 4C due to the unique behavior of water density. Generally, the density of the material increases with a decrease in temperature. However, water density has a maximum value of around 4C and starts to decrease at temperatures below or above this value. Thus, the ice is less dense than the liquid water in the lake, which leads to the formation of a thin solid layer on top of the water content. Solubility of gases like oxygen (O2) and carbon dioxide (CO2) in water is essential for sea life as well. This is highly significant for human life as our species also depend on food from the sea (Ball, 2001).

KEYWORDS: nanocomposites, grapheme, metal oxide, traditional, water, treatment, technologies

I. INTRODUCTION

Nanotechnology involves the use of particles that have a nano-size, known as nanoparticles. Nanoparticles are known for having large surface area and unique physiochemical properties. They have gained attention in the wastewater treatment sector as they possess adsorption properties that can be used for water purification. Additionally, nanoparticles can also be used in different applications in WWTPs, e.g., membrane filtration, heterogeneous photocatalysis, heterogeneous photo-Fenton, disinfection, and microbial control. Nanoparticles use an adsorption mechanism for heavy metal removal; they are capable of binding to contaminants such as heavy metals.[1,2,3]

This is caused by surface energy and the affinity of surface atoms to be occupied by surrounding atoms in their outer surface when an absorbent is positively charged. In some cases, spontaneous adsorption cannot occur, especially when interacting with uncharged heavy metals. Thus, sometimes, the metal oxidation state may require modification. This can be done by using adsorbents that can act as either an oxidizing or reducing intermediate, which are capable of exchanging electrons with aqueous species [19]. Nanoparticles have been shown to be effective in the removal of bacteria and toxic chemicals such as arsenic, mercury, etc. However, concerns have been raised regarding the risks that may arise as a result of the high reactivity of nanoparticles caused by large surface area to volume ratios. Nevertheless, it has been shown that water purification through nanoparticles does not cause any problems to human health or the environment [20]. The application of nanotechnology in WWTPs is discussed in the following paragraphs.

Photocatalysis Technology

Photocatalysis technology has been investigated for treatment of water contaminated with hazardous aromatic compounds. Titanium dioxide (TiO2) and Zinc oxide (ZnO) are among the highly used semiconductor photocatalysts. TiO2 is particularly preferred since it is inexpensive. ZnO has also gained popularity, despite the fact that it is likely to cause photocorrosion under irradiation as a result of its wide energy band gap. Photocatalysis generally uses semiconductor materials with electrons (e−) that can jump to a conduction band when irradiated by light; this results in positively charged holes (h+) in the valence band. This occurs when the energy of the photon in the incident light is higher or equal to the band gap energy. The pair of e− and h+ therefore move to the surface, where they undergo reduction and oxidation reactions. These reactions aid in the conversion of valence states in the treatment of various heavy metals. The drawback of photocatalysis is that high energy is required due to the wide band energy gap. Hence, research on developing photocatalysts that have suitable and efficient band gaps has gained popularity. Catalysts such as bio-based catalysts, C3N4, and ZnO have been shown to have efficient band energy gaps [19,20,21]. Another limitation of photocatalysts is that they work well when they are exposed to ultraviolet light (UV) irradiation. Their activity under visible and solar light is restricted; this is due to the fact that UV light only constitutes 4–6% of solar light, while visible light constitutes 45%. These drawbacks limit the application of photocatalysis in large-scale wastewater treatment systems [22].

Magnetic nanoparticles are also popular, since they have been shown to have greater photocatalytic abilities. Furthermore, magnetic nanoparticles have other interesting properties, such as a modifiable surface, compact size, elevated surface zones and volume ratios, and strong bio-compatibilities. Magnetic nanoparticles have been investigated, and their performance has been shown to depend on three aspects: material, composition, and dimensions of 1–100 nm. Different materials such as Fe2O3/Fe3O4, pure metals Fe and Co, and spinel-type ferromagnets MgFe2O4, MnFe2O4, and CoFe2O4 can be used for the synthesis of magnetic nanoparticles [23].

However, the application of magnetic nanoparticles for water purification may cause eugenol allergy, toxicity, genotoxicity, phytotoxicity, skin irritation, and several other health problems, including the risk of kidney disease. Additionally, some magnetic nanoparticles are carcinogenic as a result of precursor salts in the nanoparticles. Therefore, further investigations are still required to reduce the health hazards posed by the application of magnetic nanoparticles for water purification [24].

Adsorption Technology

Adsorption is one of the popular processes for heavy metal removal. The process of adsorption involves the accumulation of liquid solute (adsorbate) into the surface of the solid (adsorbent), thereby forming an atomic or molecular film. Several absorbents have been studied for their ability to treat heavy metals from wastewater, with the more frequently used adsorbents being activated carbons, zeolites, and clay minerals [25]. Nanotechnology-based adsorption has gained popularity due to its efficiency in treating wastewater, operational flexibility, and large surface area. Moreover, the reversible nature of nanoparticles make them great candidates for wastewater treatment since they can be regenerated. Adsorption offers many benefits, such as easy maintenance, high efficiency, and easy operation. Nano-sized metal oxides are among the adsorbents that have been intensively studied. Nano-sized ferric oxides, manganese oxides, aluminum oxides, titanium oxides, magnesium oxides, and cerium oxides (CeO2) have been shown to be promising for heavy metal removal in aqueous systems [26]. The synthesis of these adsorbents has evolved over the years, with more innovative and cost-effective synthesis methods emerging. The mechanism of heavy metal removal by adsorbents has been said to be similar to Lewis acids–bases. Moreover, nano-absorbents have been shown to a have high specific sorption capacity as a result of sorption sites at the surface [27].

Nano-Membrane Technology

Nano-membranes have also raised the interest of environmental researchers. Their low production costs compared to traditional membranes have made them a favorable alternative to traditional membranes. Carbon nanotubes (CNT) are a renowned alternative option for membrane technology, owing to their outstanding mechanical strength, flexible preparation, and high electron affinity [28]. Nano-membranes are produced from various materials, such as non-metal particles, nano-metal particles and nano-carbon tubes [29]. Nano-membranes are porous, thin-layered, and impermeable to salt, microorganisms, and heavy metals. Furthermore, they are ideal for wastewater treatment due to their selectivity. The treatment process with nano-membranes tends to be fast, and the fouling is lower in nano-membranes compared to traditional membranes. The combination of different nano-materials with polymer-based membranes has been shown to produce excellent nano-membranes for wastewater decontamination. Additionally, materials with antibacterial properties, such as carbon-based materials, have also been shown to efficiently reduce fouling while increasing the mechanical stability of nano-membranes. Another way of reducing fouling is doping with nano-materials such as alumina, TiO2, and zeolite. Doping with silver-like metal is said to present great potential for the reduction of membrane fouling and the prevention of bacterial growth on membranes [30].

Nanotechnology Disinfection

The non-specific nature of nanoparticles makes them capable of removing a wide range of contaminants as well as bacterial cells; this property is now exploited for the removal of pathogenic bacteria in wastewater treatment. Nanoparticles have been shown to be a promising technology in disinfection of wastewater as compared to traditional disinfectants, which produce toxic by-products. Silver is one of the popular nanoparticles; it has high specific area and outstanding antimicrobial properties. These properties make silver a great disinfectant alternative for wastewater. Additionally, silver is commonly used as a biocide in various household products. However, the release of silver nanoparticles into the environment affects naturally occurring microbes [31]. The mechanism of antibacterial activity of silver nanoparticles is different to that of magnetic nanoparticles. The antibacterial activity of silver nanoparticles is said to result from reactive oxygen species (ROS) generation. Moreover, other mechanisms have been documented in the literature, e.g. the interaction between silver nanoparticles and the surface structure of material cells, as well as the reaction between sulfur and phosphorous of cell macromolecules and silver ions. Silver nanoparticles have been shown to be efficient for disinfection of both gram-positive and -negative bacteria. In recent studies, [4,5,6]silver nanoparticles have been combined with magnetic nanoparticles to facilitate the recovery of silver; this combination has also been reported to be able to penetrate biofilm effortlessly compared to when silver nanoparticles are used alone. Nanoparticles with magnetic properties can also be used for microbial disinfection. Magnetite has been reported to be among the strongest magnetic species of transient mental oxides. The mechanism of disinfection by magnetic nanoparticles involves the release of reactive oxygen species, which destroy proteins and Deoxyribonucleic Acid (DNA) in the bacterial cells, thereby causing an antibacterial effect through chemical disinfection and the adsorption of ions. Additionally, their magnetic characteristics make them easily separable from aqueous solutions [32].

II. DISCUSSION

The properties typically associated with graphene oxide synthesized through the Staudenmaier method include:

1. Increased production efficiency: Researchers have explored modifications to the Staudenmaier method to enhance the production efficiency of graphene oxide. This includes optimizing reaction conditions, such as temperature, reaction time, and the concentration of oxidizing agents, to achieve higher yields of graphene oxide [64,65,66].

2. Improved control over oxygen content: The Staudenmaier method allows researchers to control the oxygen content in graphene oxide by adjusting the reaction parameters. By optimizing the oxidation process, it is possible to obtain graphene oxide with desired oxygen functionalities, which influences its properties and potential applications [67,68,69].

3. Enhanced dispersion in solvents: One challenge with graphene oxide is its tendency to agglomerate or form restacked sheets, limiting its potential applications. Researchers have made progress in improving the dispersibility of Staudenmaier-synthesized graphene oxide in various solvents, allowing for better incorporation into different matrices and facilitating its use in composite materials [70,71,72].

4. Tailored structural properties: The Staudenmaier method has been utilized to tailor the structural properties of graphene oxide. By controlling the oxidation parameters, such as the concentration of oxidants or the reaction time, researchers have achieved graphene oxide with different degrees of oxidation, layer thickness, and functional groups. These modifications influence the material's electrical, thermal, and mechanical properties [7,8,9]

5. Functionalization strategies: Staudenmaier-synthesized graphene oxide has been functionalized with various organic and inorganic compounds to introduce specific properties or enhance its compatibility with different matrices. Functionalization methods include covalent and non-covalent approaches, enabling the incorporation of graphene oxide into a broader range of applications, such as sensors, energy storage devices, and biomedical applications

III. RESULTS

The approaches for removing emerging contaminants can vary significantly based on the specific contaminant and the chosen treatment method. Here are some common strategies for eliminating emerging contaminants:

a) Adsorption: adsorption is widely employed to eliminate emerging contaminants from water or air. It involves the attachment of contaminants to a solid surface, like activated carbon or other adsorbent materials. Through physical or chemical interactions, contaminants adhere to the surface of the adsorbent, effectively extracting them from water or air [99,100,101,102,103].

b) Catalytic degradation: catalytic degradation uses catalysts to facilitate the breakdown of emerging contaminants. These catalysts can be either heterogeneous (solid-phase catalysts) or homogeneous (liquid-phase catalysts). Contaminants react with the catalyst, decomposing into simpler, less harmful substances [104, 105].

c) Membrane filtration: membrane filtration, a separation process, employs a semi-permeable membrane to separate contaminants from water or other liquids. The membrane contains small pores or channels allowing water molecules to pass while blocking larger contaminants. Various membranes, such as reverse osmosis (RO) or nanofiltration membranes, effectively remove a wide array of emerging contaminants, including micropollutants and nanoparticles [106, 107].

Other relevant approaches: Additional strategies for removing emerging contaminants exist, contingent on specific contaminants and treatment methods:

Advanced oxidation processes (AOPs): AOPs utilize highly reactive species, like hydroxyl radicals, to oxidize and degrade contaminants. Techniques such as ozonation, photocatalysis, or electrochemical oxidation achieve AOPs [108].

Biological treatment: Biological processes, including biodegradation or bioremediation, use microorganisms to break down contaminants into harmless byproducts via metabolic processes [109].

Chemical precipitation: Chemical precipitation involves adding chemicals to induce the formation of insoluble precipitates. These precipitates are then separated from water through sedimentation or filtration, commonly used for the removal of heavy metals or metalloids [110, 111].

Ion exchange: Ion exchange involves swapping ions between a solid-phase ion exchange resin and water. The resin selectively adsorbs certain ions, including emerging contaminants, releasing less harmful ions in exchange [112].

Physical separation: Certain emerging contaminants are removed through physical separation methods such as sedimentation, coagulation, or flocculation. These processes aggregate or settle the contaminants, facilitating their removal from water [113, 114].

It is crucial to note that the selection of the appropriate approach depends on specific contaminants, their concentration, and the desired treatment objectives. Often, a combination of multiple approaches is employed in water or wastewater treatment processes to efficiently remove emerging contaminants.

Effectiveness of graphene oxide in removing emerging contaminants

Graphene oxide (GO) has shown effectiveness in removing emerging contaminants from various environmental matrices [115]. Several studies have investigated the adsorption properties of GO towards different types of emerging contaminants, including pharmaceuticals, personal care products and pesticides. The unique physicochemical properties of GO contribute to its adsorption capabilities and make it a promising material for water treatment applications [116].

The large surface area and high adsorption capacity of GO enable it to effectively capture and remove emerging contaminants from water [117]. The π–π stacking interactions, hydrogen bonding, and electrostatic attractions between GO and contaminants facilitate their adsorption onto the GO surface. Additionally, the presence of oxygen-containing functional groups on GO, such as hydroxyl and carboxyl groups, enhances its adsorption capacity through additional interactions with the contaminants [117].

The adsorption efficiency of GO can be influenced by various factors, including the properties of the contaminants (e.g., molecular size, polarity, and charge), the concentration of contaminants in the water, pH, temperature, and contact time. Optimization of these parameters can enhance the removal efficiency of GO for specific contaminants [115].

Graphene oxide (GO) as an efficient adsorbent for the removal of contaminants from water[10,11,12]

There have been several case studies that have explored the effectiveness of graphene oxide (GO) in removing emerging contaminants. One example is the removal of pharmaceutical compounds from water.

In a study carried out by Banerjee et al. the effectiveness of graphene oxide nanoplatelets (GONPs) in removing ibuprofen from water was investigated [115]. The researchers characterized the GONPs using electron microscopy and X-ray diffraction to analyze any changes in structure and morphology caused by the adsorption process. Batch adsorption experiments were conducted to assess the impact of various process parameters on the percentage removal of ibuprofen. The obtained data were analyzed using isotherm and kinetic analysis to understand the distribution of ibuprofen between the liquid and solid phases in the batch studies. The researchers found that the Langmuir isotherm model best described the adsorption behavior, and the process followed pseudo-second-order kinetics. Thermodynamic parameters, including Gibbs' free energy, enthalpy, and entropy, were also evaluated. The results indicated that the adsorption of ibuprofen onto graphene oxide was an endothermic and spontaneous process. Based on their findings, the authors concluded that graphene oxide could serve as a suitable adsorbent for the efficient treatment of water contaminated with ibuprofen and similar anti-inflammatory drugs on a larger scale. The study highlights the potential of graphene oxide as an effective adsorbent for pharmaceutical removal from water.

Another case study was carried out by Baratta et al. focused on evaluating the efficacy of graphene oxide/single-walled carbon nanotube composite membranes (GO-SWCNT BPs) in removing three non-steroidal anti-inflammatory drugs (NSAIDs)—diclofenac, ketoprofen, and naproxen [116]. Various parameters were investigated, including pH conditions, graphene oxide content, and initial concentrations of NSAIDs. SEM analysis of the BP membranes revealed a consistent appearance with black and stable membranes, an average thickness of around 100 ± 2 µm, and an average diameter of 38 ± 1 µm (10a, b). The SEM images also exhibited clusters and bundles of single-walled carbon nanotubes (SWCNTs) due to intermolecular interactions (10c). The membranes demonstrated high permeability and large contact surface area, indicating effective adsorption. Incorporation of graphene oxide within the SWCNT BP membranes was observed, resulting in a homogeneous distribution of GO sheets (10d). The adsorption capacities of the GO-SWCNT BPs were influenced by the graphene oxide content, with the highest capacities achieved at 75 wt.% graphene oxide, specifically 118 ± 2 mg g−1 for diclofenac, 116 ± 2 mg g−1 for ketoprofen, and 126 ± 3 mg g−1 for naproxen at pH 4 (11). Overall, the study suggests that GO-SWCNT BPs offer a promising and cost-effective approach for the removal of NSAIDs from drinking water sources. The membranes possess characteristics such as easy recovery and reusability, making them a viable solution for addressing the presence of NSAIDs in water resources.

Nodeh et al. developed a magnetic graphene oxide-based adsorbent, GO-MNPs-SiO2, to enhance the removal of naproxen from wastewater [117]. The incorporation of magnetic nanoparticles and silica onto graphene oxide improved water permeability, prevented sheet aggregation, and facilitated easy recovery using an external magnet. The adsorbent was synthesized,[13,14,15] characterized, and applied for naproxen removal from sewage samples. The researchers investigated the effect of GO-MNPs-SiO2 dosage on naproxen removal, varying the adsorbent mass from 5 to 160 mg. The results showed that increasing the dosage from 5 to 30 mg led to an increase in removal efficiency from 20 to 90%, with a slight stabilization at 30–60 mg (12a). The influence of contact time on adsorption was also examined, and it was observed that the removal efficiency increased from 25 to 90% as the time increased from 5 to 60 min (12b). This indicated a rapid adsorption process occurring before reaching equilibrium. To understand the adsorption mechanism, the experimental data were fitted to Langmuir, Freundlich, and D-R isotherms, and free energy calculations were performed. The maximum adsorption capacity of the nanocomposite was determined to be 31.25 mg g−1 at pH 5 and a contact time of 60 min. The Freundlich model provided the best fit to the data (R2 = 0.999), suggesting multilayer adsorption with a physisorption mechanism for naproxen removal. The calculated free energy value (0.49 kJ mol−1) further supported this finding. In general, the GO-MNPs-SiO2 nanocomposite exhibited high sorption capacity and fast kinetics for the removal of naproxen from aqueous solutions. The study concluded that it holds promise as an effective adsorbent for wastewater treatment applications in the removal of naproxen and similar pollutants.[16,17,18]

IV. CONCLUSION

The environmental impact of graphene oxide (GO) use is an important consideration when assessing its potential applications in various fields. While GO offers unique properties and potential benefits, its potential adverse effects on ecosystems and the environment have raised concerns.

1. Ecotoxicity to aquatic organisms: GO can enter aquatic ecosystems through wastewater discharge or accidental releases. Studies have shown that GO can have toxic effects on various aquatic organisms, including fish, crustaceans, and algae. The high surface area and reactive properties of GO can lead to physical and chemical interactions with organisms, affecting their behavior, growth, reproduction, and survival. Additionally, the potential accumulation and persistence of GO in aquatic environments may have long-term ecological consequences that require further investigation [19]

2. Soil and terrestrial ecosystem impacts: The potential release of GO into soil can affect soil quality and terrestrial ecosystems. Studies have shown that GO can influence soil microbial communities, affecting their composition and function. Soil organisms, such as earthworms, may be exposed to GO, potentially leading to adverse effects on their behavior and reproductive success. The long-term impacts of GO on soil ecosystems and the broader consequences for plant growth, nutrient cycling, and soil health require further research [194,195,196,197].

3. Effects on beneficial microorganisms: GO's antimicrobial properties, while potentially useful in certain applications, can also have unintended consequences. The broad-spectrum antimicrobial activity of GO may affect beneficial microorganisms involved in nutrient cycling, soil health, and plant–microbe interactions. Disruption of these microbial communities can have cascading effects on ecosystem functioning and stability [198,199,200,201].

4. Fate and transport in the environment: Understanding the fate and transport of GO in the environment is crucial to assess its potential environmental impact. Research has shown that GO can adsorb other pollutants, such as heavy metals and organic contaminants, which may affect their mobility and bioavailability in the environment. The aggregation and sedimentation of GO can result in its accumulation in sediments, potentially impacting benthic organisms and sediment-dwelling microbial communities [202, 203].

5. Potential for bioaccumulation and biomagnification: The potential for GO to bioaccumulate and biomagnify in food chains is a concern. While studies have shown limited bioaccumulation of GO in certain organisms, the

accumulation potential may vary depending on the species, exposure duration, and environmental conditions. If GO accumulates in higher trophic levels, it may pose risks to predators and organisms at the top of the food chain [204, 205].

6. Life cycle considerations: Assessing the environmental impact of GO requires considering its entire life cycle, including production, use, and disposal [22, 206]. The production of GO typically involves energy-intensive processes and the use of chemicals, which can contribute to greenhouse gas emissions and other environmental impacts [207, 208]. The disposal of GO-based products and waste should also be carefully managed to prevent their release into the environment and potential long-term impacts [20]

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