5 Marine Green Nanotechnology for Remediation of Wastewater

O.D. Ogundele, J.O. Jayeola, O.S. Ilesanmi, D.A. Oyegoke, O.F. Adedugbe, and V.A. Olagunju

5.1 INTRODUCTION

Marine green nanotechnology (MGN) refers to the application of nanoscience principles and techniques to harness the potential of marine-derived biomolecules and microorganisms, particularly marine algae (both microalgae and macroalgae), for the development of novel nanomaterials and nanoscale devices (Abd-Elnaby *et al*., 2018; Duraia *et al*., 2016). This interdisciplinary field has gained significant attention in recent years, as it offers sustainable and eco-friendly alternatives to conventional chemical and physical synthesis methods for producing nanomaterials, which often involve high energy consumption, hazardous reagents, and toxic waste generation (Phang *et al*., 2015).

Marine algae are considered a promising source of bioactive compounds and functional biomolecules, such as proteins, polysaccharides, lipids, pigments, and phenolic compounds, which exhibit diverse biological activities and potential applications in various industries, including pharmaceuticals, nutraceuticals, cosmetics, and biotechnology (Kim *et al*., 2014; Rodrigues *et al*., 2015). These marine-derived biomolecules can serve as natural templates, stabilizers, and reducing agents for the synthesis of nanoparticles, such as metal nanoparticles (e.g., gold, silver, and platinum) and metal oxide nanoparticles (e.g., zinc oxide and titanium dioxide), with controlled size, shape, and surface properties (Abd-Elnaby *et al*., 2018; Duraia *et al*., 2016).

For example, phlorotannins, which are phenolic compounds found in brown macroalgae, have been shown to reduce metal ions and stabilize the formation of gold and silver nanoparticles, while sulfated polysaccharides, such as fucoidan and carrageenan, have been utilized for the green synthesis of metal oxide nanoparticles, such as zinc oxide and iron oxide (Jung *et al*., 2013; Kathiresan *et al*., 2009). These biogenic nanoparticles have demonstrated various biological activities, such as antimicrobial, antioxidant, anticancer, and anti-inflammatory properties, and have been proposed for applications in drug delivery, tissue engineering, biosensing, and environmental remediation (Abd-Elnaby *et al*., 2018; Kim *et al*., 2014).

MGN represents an emerging and promising field, which seeks to exploit the unique biochemical and structural properties of marine algae and microorganisms for the eco-friendly synthesis and development of innovative nanomaterials and nanodevices with diverse applications across various industries (Abd-Elnaby *et al*., 2018; Duraia *et al*., 2016). Further research and interdisciplinary collaboration between nanoscience, marine biology, and materials science are being explored for the full potential of MGN and to address the challenges associated with the scalability, reproducibility, and stability of the biogenic nanoparticles and nanoscale structures, as well as their integration into functional devices and systems (Phang *et al*., 2015; Rodrigues *et al*., 2015).

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5.2 IMPORTANCE OF WASTEWATER REMEDIATION

Wastewater remediation is the process of removing pollutants and contaminants from wastewater, which can originate from various sources, such as industrial processes, agricultural activities, and domestic sewage (EPA, 2021). The importance of wastewater remediation cannot be overstated, as untreated or inadequately treated wastewater can have severe consequences on public health, the environment, and socio-economic development (UN-Water, 2020).

One of the primary concerns related to untreated wastewater is the potential for the spread of waterborne diseases, which can result from the discharge of pathogens, such as bacteria, viruses, and parasites, into water bodies used for drinking, bathing, and recreational activities (Snyder *et al.*, 2003). Wastewater remediation helps mitigate this risk by employing physical, chemical, and biological treatment processes to eliminate or reduce the levels of pathogens and other harmful substances, such as heavy metals, organic pollutants, and nutrients, in wastewater (EPA, 2021).

Another critical aspect of wastewater remediation is the prevention of environmental pollution and degradation (Aransiola *et al.*, 2021). The discharge of untreated wastewater into rivers, lakes, and coastal areas can lead to eutrophication, which is characterized by excessive growth of algae and other aquatic plants due to high concentrations of nutrients, such as nitrogen and phosphorus (Conley *et al.*, 2009). This can cause oxygen depletion, fish kills, and loss of biodiversity, as well as negatively affecting the aesthetic and recreational value of water bodies (Smith *et al.*, 1999).

Furthermore, investments in wastewater remediation infrastructure and technologies can create employment opportunities, stimulate innovation, and foster economic growth in the water and sanitation sector, as well as related industries, such as agriculture, energy, and manufacturing (UN-Water, 2018). Wastewater remediation can also contribute to climate change mitigation and adaptation by reducing greenhouse gas emissions from untreated wastewater and sludge decomposition, as well as promoting the use of renewable energy sources, such as biogas, and enhancing water security and resilience to water scarcity and pollution (Metcalf & Eddy, 2014).

5.3 MARINE GREEN NANOTECHNOLOGY

MGN is an emerging interdisciplinary field that combines the principles of green chemistry, nanoscience, and marine biology to harness the unique properties and capabilities of marine organisms, such as algae and microorganisms, for the synthesis and assembly of nanoscale materials and structures (Azizi *et al.*, 2018). This approach offers a sustainable and eco-friendly alternative to conventional methods of nanomaterial production, which often rely on toxic chemicals, high energy consumption, and non-renewable resources (Rai *et al.*, 2016).

Marine algae, also known as marine greens, are particularly attractive candidates for the development of green nanotechnology due to their abundance, diversity, and ability to produce a wide range of biologically active compounds and biomolecules, such as polysaccharides, proteins, and lipids, that can serve as templates, stabilizers, and reducing agents for the synthesis of nanoparticles (Pankhurst *et al.*, 2017). Moreover, marine algae exhibit unique features, such as high surface area, porosity, and functional groups, which can facilitate the formation of nanoscale structures with controlled size, shape, and surface properties (Nagarajan *et al.*, 2018).

Various types of nanoparticles, such as metal, metal oxide, and semiconductor nanoparticles, can be synthesized using MGN (Siddiqi & Husen, 2020). For instance, gold and silver nanoparticles have been successfully produced using extracts from marine algae, such as *Sargassum muticum*, *Ulva lactuca*, and *Fucus vesiculosus*, which act as both reducing and capping agents, resulting in stable and biocompatible nanoparticles with potential applications in biomedical, environmental, and catalytic fields (Rajeshkumar *et al.*, 2018; Srinivasan *et al.*, 2018).

Marine microorganisms, such as diatoms and bacteria, can also be exploited for green nanotechnology applications. Diatoms are a group of photosynthetic microalgae that produce intricately patterned silica cell walls, known as frustules, which have unique optical, mechanical, and chemical properties (Gordon *et al*., 2009). The biogenic synthesis of silica nanoparticles and nanostructures using diatoms has attracted significant attention for applications in drug delivery, biosensing, and photonic devices (Losic *et al*., 2009; Sumper & Kröger, 2004).

Bacterial biosynthesis of nanoparticles, such as cadmium sulfide (CdS) quantum dots, has been demonstrated using marine bacteria, such as *Pseudomonas aeruginosa*, which can reduce metal ions and control the size and shape of the resulting nanoparticles through enzymatic and metabolic processes (Sweeney *et al*., 2004). This environmentally friendly and scalable approach can offer new opportunities for the development of advanced materials and devices for optoelectronics, photocatalysis, and solar energy conversion (Zhang *et al*., 2010).

MGN represents a promising and sustainable route for the synthesis and assembly of functional nanomaterials and structures using marine organisms, such as algae and microorganisms, as biofactories and templates that can overcome some of the limitations and challenges associated with conventional nanomaterial production methods, while also providing unique opportunities for the discovery and design of novel nanostructures with tailored properties and functions for various applications, such as biomedical, environmental, and energy-related technologies (Azizi *et al*., 2018; Rai *et al*., 2016).

5.4 EXAMPLES OF MARINE ORGANISMS FOR GREEN SYNTHESIS OF NANOPARTICLES

The use of marine organisms for the green synthesis of nanoparticles has emerged as a sustainable and eco-friendly approach, leveraging the unique properties of various marine species, including algae, bacteria, fungi, and other organisms, to produce metal and metal oxide nanoparticles (Mata *et al*., 2010; Parveen *et al*., 2021).

a) **Algae** are a prominent source for the green synthesis of nanoparticles, with several marine algae species demonstrating potential in nanoparticle production. For example, *Sargassum muticum* has been used for the synthesis of gold nanoparticles, with the algal extract serving as both a reducing and a capping agent (Azizi *et al*., 2018). Similarly, silver nanoparticles have been synthesized using extracts from *Ulva lactuca*, *Fucus vesiculosus*, and *Gelidium amansii* (Rajeshkumar *et al*., 2018; Velmurugan *et al*., 2016; Zhang *et al*., 2016).
b) **Marine bacteria** are also utilized for nanoparticle synthesis, offering a scalable and eco-friendly alternative to traditional chemical methods. For instance, silver nanoparticles have been synthesized using the marine bacteria *Bacillus subtilis* and *Bacillus licheniformis*, which can reduce silver ions through enzymatic processes (Kumar *et al*., 2015). Marine-derived actinobacteria, such as *Streptomyces* sp., have also been employed to produce gold and silver nanoparticles, exhibiting potential for applications in biomedical and environmental fields (Manivasagan *et al*., 2016).
c) **Marine fungi** is another group of marine organisms that have been explored for their potential in green nanoparticle synthesis. The marine fungus *Aspergillus terreus* has been used to synthesize silver nanoparticles, with the fungal culture filtrate acting as both reducing and stabilizing agent, resulting in the formation of stable and biocompatible nanoparticles (Gopinath *et al*., 2015). Additionally, the marine-derived fungus *Penicillium polonicum* has been employed for the synthesis of gold nanoparticles, displaying potential applications in catalysis and drug delivery.

5.5 TYPES OF NANOPARTICLES SYNTHESIZED FROM MARINE SOURCES

Nanoparticles synthesized from marine sources exhibit a wide range of properties, sizes, and shapes, which are highly influenced by the type of marine organism and synthesis method employed. The most common types of nanoparticles produced using marine sources include metal, metal oxide, and biopolymeric nanoparticles (Parveen *et al.*, 2021; Nagarajan *et al.*, 2018).

a) **Metal nanoparticles,** such as gold and silver nanoparticles, have been synthesized using a variety of marine organisms, including algae, bacteria, fungi, and sponges (Mata *et al.*, 2010; Rajeshkumar *et al.*, 2018; Sengani *et al.*, 2017). Gold nanoparticles have shown potential for applications in biomedicine, catalysis, and sensing, while silver nanoparticles have gained interest for their antimicrobial properties (Azizi *et al.*, 2018). Platinum nanoparticles, another type of metal nanoparticle, have been synthesized using marine bacteria, such as *Shewanella oneidensis*, demonstrating potential for applications in fuel cells and catalysis (Ramanathan *et al.*, 2013).
b) **Metal oxide nanoparticles,** such as zinc oxide (ZnO), titanium dioxide (TiO_2), and iron oxide (Fe_3O_4) nanoparticles, have also been synthesized using marine sources (Parveen *et al.*, 2021). ZnO nanoparticles have been produced using the marine alga *Gelidium amansii*, exhibiting antimicrobial and photocatalytic properties, with potential applications in environmental remediation (Velmurugan *et al.*, 2016). TiO_2 nanoparticles have been synthesized using the marine diatom *Amphora coffeaeformis*, demonstrating potential for applications in solar cells and photocatalysis (Khosravi *et al.*, 2015). Iron oxide nanoparticles have been produced using the marine bacterium *Marinobacter pelagius*, showing potential for applications in magnetic resonance imaging, drug delivery, and magnetic separation (Prasanna & Vijayaraghavan, 2015).
c) **Biopolymeric nanoparticles,** such as chitosan and alginate nanoparticles, have been produced using marine-derived polysaccharides, which are typically extracted from the cell walls of marine algae or the exoskeletons of crustaceans (Nagarajan *et al.*, 2018). Chitosan nanoparticles have been synthesized using chitosan derived from the shells of marine crustaceans, like shrimp and crabs, showing potential for applications in drug delivery, gene therapy, and tissue engineering (Kumari *et al.*, 2017). Alginate nanoparticles have been synthesized using alginate extracted from marine brown algae, demonstrating potential for applications in drug delivery, wound healing, and cell encapsulation (Kumari *et al.*, 2017). *et al.*,.
d) **Silica nanoparticles,** a common type of nanoparticles from marine sources, have been employed to synthesize other unique nanostructures produced by marine diatoms (Gordon *et al.*, 2009). They have gained significant attention due to their unique properties and potential applications in various fields. They possess a high surface area-to-volume ratio, which enables them to adsorb various compounds and biomolecules. These silica nanoparticles exhibit potential for applications in drug delivery, biosensing, and photonic devices due to their unique optical properties and biocompatibility (Losic *et al.*, 2009).

5.6 MAJOR POLLUTANTS IN WASTEWATER

Wastewater is a complex mixture of various substances, many of which can be harmful to both human health and the environment. Major pollutants in wastewater include organic compounds, nitrogen and phosphorus compounds, heavy metals, and pathogens (Asha *et al.*, 2019).

a) **Organic compounds** are among the most common pollutants found in wastewater. They can come from a variety of sources, including domestic wastewater, industrial effluent, and agricultural runoff (Li *et al.*, 2019). Examples of organic compounds found in wastewater include volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs), and endocrine-disrupting compounds (EDCs). These compounds can be harmful to both human health and the environment, and can be difficult to remove from wastewater (Jin *et al.*, 2018).

b) **Nitrogen and phosphorus compounds** are also major pollutants in wastewater. They are often found in domestic wastewater but can also come from agricultural runoff and industrial effluent. These compounds can contribute to the eutrophication of water bodies, which can lead to algal blooms and other harmful effects on aquatic ecosystems (Pandey & Pandey, 2020).

c) **Heavy metals** are another major pollutant in wastewater. They can come from a variety of sources, including industrial effluent, mining operations, and municipal wastewater (Yang *et al*., 2021). Examples of heavy metals found in wastewater include lead, mercury, cadmium, and chromium. These metals can be toxic to both human health and the environment, and can accumulate in the food chain (Ikhumetse *et al*., 2019; Aransiola *et al*., 2022).

d) **Pathogens** are also a major pollutant in wastewater. They can come from a variety of sources, including human and animal fecal matter, and can cause a range of diseases, including cholera, typhoid, and hepatitis A (Asha *et al*., 2019). Pathogens can be removed from wastewater using a variety of treatment methods, including disinfection and filtration.

5.7 APPLICATIONS OF MARINE GREEN NANOTECHNOLOGY IN WASTEWATER REMEDIATION

MGN offers promising and sustainable solutions for wastewater remediation, addressing the challenges associated with conventional wastewater treatment methods (Mohanpuria *et al*., 2008). The unique physicochemical properties of nanoparticles synthesized from marine organisms can enhance the efficiency and selectivity of contaminant removal processes, including adsorption, photocatalysis, and antimicrobial activity (Shah *et al*., 2019).

One application of MGN in wastewater remediation is the synthesis of nanoparticles with high adsorption capacity for the removal of pollutants, such as heavy metals, organic dyes, and nutrients (Suresh *et al*., 2011). For example, marine-derived chitosan nanoparticles have been used to effectively adsorb metal ions, including lead, copper, and cadmium, from contaminated water *et al*.,. Similarly, marine algae–derived carbonaceous nanoparticles have demonstrated high adsorption capacities for the removal of organic dyes, such as methylene blue and rhodamine B (Salama, 2013).

Another application of MGN is the development of photocatalytic materials for the degradation of organic pollutants and the inactivation of pathogens in wastewater (Gogoi *et al*., 2018). For instance, titanium dioxide (TiO_2) nanoparticles synthesized using marine macroalgae extracts have exhibited enhanced photocatalytic activity under visible light irradiation, enabling the degradation of organic contaminants, such as phenol and bisphenol A (Lee *et al*., 2017).

5.8 CASE STUDIES: SUCCESSFUL IMPLEMENTATION OF MARINE GREEN NANOTECHNOLOGY IN WASTEWATER TREATMENT

MGN has shown great potential in wastewater treatment due to its ability to remove heavy metals, degrade organic contaminants, and inactivate pathogens. Here, we present several case studies that demonstrate the successful implementation of MGN in wastewater treatment.

One such case study is the use of chitosan-coated iron oxide nanoparticles for the removal of heavy metals from wastewater. Chitosan is a biopolymer derived from marine sources such as shellfish and has been shown to be effective in binding heavy metals. The iron oxide nanoparticles provide a large surface area for the adsorption of heavy metals, while the chitosan coating enhances the selectivity of the nanoparticles toward heavy metals (Muthukrishnan *et al*., 2020). The use of chitosan-coated iron oxide nanoparticles in wastewater treatment has been found to be highly effective in removing heavy metals such as lead, copper, and zinc (Li *et al*., 2021).

Another case study involves the use of silver nanoparticles for the inactivation of pathogens in wastewater. Silver nanoparticles have been shown to have antimicrobial properties and can be used to inactivate a wide range of pathogens, including bacteria, viruses, and fungi. The use of silver nanoparticles in wastewater treatment has been found to be highly effective in reducing the levels of pathogens, leading to cleaner water (Das *et al*., 2020). Additionally, the use of silver nanoparticles is sustainable and eco-friendly, making it a promising approach for wastewater treatment.

In a third case study, the use of titanium dioxide nanoparticles for the degradation of organic contaminants in wastewater was investigated. Titanium dioxide nanoparticles are known for their photocatalytic properties, which allow them to degrade organic contaminants under the influence of UV light. The use of titanium dioxide nanoparticles in wastewater treatment has been found to be highly effective in removing organic contaminants such as dyes and pharmaceuticals (Yang *et al*., 2019). Furthermore, the use of titanium dioxide nanoparticles is a sustainable approach as it does not produce any harmful by-products.

Overall, the successful implementation of MGN in wastewater treatment has several advantages over conventional methods. MGN is sustainable, eco-friendly, and highly effective in removing heavy metals, degrading organic contaminants, and inactivating pathogens. Furthermore, MGN offers a promising approach for wastewater treatment in areas where conventional methods are not feasible or effective.

Real-world implementation of MGN in wastewater treatment has been reported in various scenarios. For example, in a study by Wu *et al.* (2018), a pilot-scale plant was constructed to treat wastewater from a paper mill using a combination of microalgae and silver nanoparticles. The study showed that the treatment process effectively removed pollutants from the wastewater, with a removal efficiency of over 90%.

In another study by Chen *et al.* (2019), a wastewater treatment plant in China was upgraded to include a nanofiltration system using carbon nanotubes. The system effectively removed pollutants from the wastewater, with a removal efficiency of over 95%. The study concluded that the nanofiltration system using carbon nanotubes was a promising technology for the treatment of wastewater.

In a study by Bai *et al.* (2020), a real-world pilot-scale plant was constructed to treat wastewater from a pharmaceutical company using magnetic iron oxide nanoparticles. The study showed that the treatment process effectively removed pollutants from the wastewater, with a removal efficiency of over 90%.

5.9 APPLICATION OF MARINE GREEN NANOTECHNOLOGY IN WASTEWATER TREATMENT

One successful application of MGN in wastewater treatment is the use of silver nanoparticles. In a study conducted by Chen *et al.* (2018), silver nanoparticles were added to wastewater to treat heavy metal ions. The results showed that the silver nanoparticles effectively removed heavy metal ions from the wastewater, with an efficiency of over 90%. The study concluded that the use of silver nanoparticles in wastewater treatment could significantly improve the removal efficiency of heavy metal ions.

5.10 CHALLENGES AND FUTURE PERSPECTIVES

As with any new technology, there are challenges and obstacles to overcome when implementing MGN in wastewater treatment. One of the primary challenges is the scalability of the technology. While promising results have been achieved in laboratory and pilot-scale studies, there is still a need to demonstrate the effectiveness of the technology at larger scales.

Another challenge is the potential environmental impact of the nanoparticles used in the treatment process. While many studies have shown that these nanoparticles can be effective at removing pollutants from wastewater, there is a concern that they may also have negative impacts on the environment and human health.

Furthermore, there is a need for more research to understand the long-term effects of using MGN in wastewater treatment. This includes not only the impact on the environment and human health, but also the economic feasibility of the technology and its potential to be integrated into existing wastewater treatment systems.

Despite these challenges, there is a great deal of optimism regarding the future of MGN in wastewater treatment. As research continues to progress, it is expected that the technology will become more efficient, effective, and scalable, allowing wider adoption in both developed and developing countries.

One potential future direction for the technology is the use of nanotechnology-enabled sensors to monitor water quality in real time. This could help to prevent pollution and improve the efficiency of wastewater treatment systems. Additionally, the use of nanotechnology in wastewater treatment could also help to address global water scarcity by enabling the safe reuse of treated wastewater for irrigation, industrial processes, and other applications.

5.11 CONCLUSION

In conclusion, marine green nanotechnology (MGN) offers a promising solution for the remediation of wastewater due to its eco-friendliness, low cost, and high efficiency. The use of nanoparticles derived from marine organisms, such as algae and seaweed, in combination with traditional wastewater treatment methods, has been shown to enhance the performance of treatment systems and reduce their energy consumption. MGN presents significant potential for sustainable and effective wastewater remediation, which is essential for the preservation of aquatic ecosystems and the provision of clean water resources. Its implementation can contribute to achieving access to clean water and sanitation. Overall, MGN is a promising approach that requires further research and development to unlock its full potential in environmental remediation.

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