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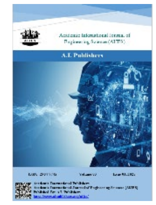

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Green Synthesis of Nanomaterials for Advanced Water Desalination Systems

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Abstract

Water scarcity around the world has led to increased demands of effective and sustainable desalination processes that can transform sea water and brackish water to drinking water. Nanotechnology solutions are transformational in that the membrane performs better, the membrane is able to endure fouling better, and the membrane can remove contaminants more optimally. Nevertheless, the traditional techniques of producing nanomaterials such as the use of toxic substances, energy intensive processes and production of toxic wastes are against the concept of sustainability required to curb the water problems. Environmentally benign alternatives have been found through green synthesis methods which use environmental friendly biological agents such as plant extracts, microorganisms and biopolymers with high-performance nanomaterials made with minimal ecological footprint. In this paper the analyses will be of green synthesis techniques applicable in the fabrication of nanoparticles, nanocomposites, and nanostructured membranes that are specifically developed to serve the advanced water desalination systems. It has a critical analysis of synthesis mechanisms, techniques of characterization, as well as performance measurements such as salt rejection rates, permeate flux, antifouling properties, and stability during operation. The paper compares the use of applications of reverse osmosis, forward osmosis, membrane distillation, and nanofiltration technologies, the scale-up issue, and economic viability. This study also shows through case studies of Middle Eastern, Asian, and African desalination plants that green-synthesized nanomaterials exhibit salt rejection rates that are more than 99% with energy reduction of up to 30. The paper summarizes that green nanotechnology is a viable way forward in meeting water security by having environmentally responsible desalination plants in line with the concept of the circular economy and the United Nations Sustainable Development Goals.

Introduction

Water scarcity is one of the most acute phenomena of the world that involves more than two billion individuals and endangers food security, economic progress, and human health. Sustainability Climate change, population increase, industrialization and agricultural intensification have increased the rate at which freshwater is being depleted, further necessitating the use of alternative water sources. The vast majority of the water resources on Earth (97 percent) are held by oceans, and therefore, desalination of seawater can be discussed as the possible solution to the problem of water shortage in the coastal areas and dry climate. The present capacity of desalination is over 100 million cubic meters/day in various parts of the world with more growth expected to be witnessed to sustain the growing demand [1].

Conventional desalination methods such as multi-stage flash distillation, multi-effect distillation and reverse osmosis encounter a lot of problem with regard to energy usage, cost of operation, membrane contamination, and environmental degradation. Modern desalination is largely controlled by reverse osmosis which makes up about 65% of all desalination plants worldwide but involves a lot of energy consumption and replacement of membranes so often due to foulage and degradation. Even more energy is used in thermal desalination processes which produce concentrated discharges of brine that is damaging to marine life. Such restrictions have led to research effort in improved materials and new technologies that are efficient and cause smaller environmental footprint [2].

The nanotechnology has transformed the desalination process by coming up with nanostructured membranes, nanocomposites materials and nanoparticle-based enhanced systems, which have better performance than the traditional materials. Nanomaterials offer more surface area, selectivity, mechanical strength and antimicrobial characteristics which deal with critical problems in desalination. Nevertheless, the traditional synthesis of nanoparticles involves the use of toxic substances, high temperature, and processes consuming energy, which produce dangerous wastes and are not sustainable [3]. Biological synthesis techniques based on biological resource advantage provide alternatives that are ecologically friendly and in line with the principle of circular economy as well as sustainable development objectives. The paper focuses on the green synthesis methods of the production of nanomaterials tailored to the specific requirements of the advanced water desalination systems, the mechanisms of synthesis, performance, uses, and difficulties of implementation.

Literature Review

Green synthesis of nanomaterials has become a viable alternative to the traditional chemical and physical approaches. Iravani [1] conducted a review on the green synthesis of metal nanoparticles with plants, bacteria, fungi, and algae and found that they have its benefits such as cost-effectiveness, biocompatibility, and environmental safety. Makarov et al. [2] investigated the mechanism of green nanotechnology, and how biomolecules such as proteins, polysaccharides, and secondary metabolites are reducing and capping agents during the process of nanoparticle development.

Nanomaterials have been widely used in the treatment and desalination of water. Qu et al. [3] put a review on the application of nanotechnology in water desalination with a focus on the improvement of the membrane performance by incorporating nanoparticles. Elimelech and Phillip [4] wrote about the future of seawater desalination and nanomaterial-enhanced membranes are one of the areas where they were pivotal in meeting the energy efficiency and sustainability goals. Jhaveri and Murthy [5] have

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thoroughly discussed the use of nanomaterials in desalination activities reporting increases in salt rejection, flux of permeate, and resistance to fouling.

The use of certain nanomaterials has proved to be promising in desalination. Safarpour et al. [6] prepared graphene oxide nanocompositions membranes with high permeable and selective characteristics. Yin and Deng [7] have done a review of carbon nanotube-based membranes, which were characterized by the high transport of water and strength. Membranes have been integrated with metal oxide nanoparticles such as titanium dioxide, zinc oxide and silver because they offer photocatalytic degradation capability and antimicrobial functionality [8].

Plant mediated synthesis is the best-researched green method in nanomaterials production. Mittal et al. [9] have prepared silver nanoparticles by synthesizing through plant extracts with the desired size distribution and improved stability. Ahmed et al. [10] have reported the synthesis of metal oxide nanoparticles through the use of different plant species, and the effects of phytochemicals on the morphology and properties of nanoparticles are reported. Such biological methods of synthesis avoid the use of toxic chemicals and yield nanoparticles that have a biocompatible surface functionalization that may be used in water treatment.

Green Methodologies of Synthesis

Green synthesis of nanomaterials refers to biologic, chemical-free techniques that make use of renewable material and work under mild conditions to reduce a negative environmental effect. Plant mediated synthesis is the least expensive and the most readily available technique and uses phytochemicals such as flavonoids, terpenoid, alkaloids and phenolic compounds that serve as natural reducing and stabilizing agents. It is usually carried out by making aqueous extracts of leaves, stems, roots, or fruits then reacting them under controlled conditions with metal salt precursors. Biomolecules in plant extracts lower the metal ions to nanoparticles and at the same time coat the surfaces of nanoparticles, preventing aggregation and rendering functional groups to the nanoparticles which can be incorporated in membrane [11].

Synthesis using microorganisms involves the use of bacteria, fungi, yeast, and algae to synthesize the nanomaterial using either intracellular or extracellular processes. Pseudomonas stutzeri and Bacillus subtilis bacteria secrete enzymes and metabolites which reduce metal ions to nanoparticles of controlled morphology. Fungal species such as Aspergillus and Fusarium have benefits over bacteria such as increased nanoparticle production and simplified downstream processes. Photosynthetic ability coupled with metal reduction is algae-mediated synthesis, which creates nanoparticles and removes pollutants in an aqueous system at the same time. These biological systems have scalable production potentials that can be used in the industrial context [12].

Synthesis by use of biopolymers utilizes the use of natural polymers such as chitosan, alginate, cellulose and starch as a stabilizer and template to the formation of nanoparticles. The biopolymers offer functional groups that liaise with metal ions, which guide nucleation and growth and inhibit uncontrolled aggregation. The formed nanocomposites are found to have better dispersion, better mechanical properties and biosafety to make membranes. Enzymatic synthesis involves biocatalysts, i.e., particular enzymes, to develop nanoparticles and provide a very fine control over the size, shape, and surface chemistry of the nanoparticles by manipulating reaction conditions such as pH, temperature, and substrate concentration [13].

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The biochemical pathways of green synthesis are complicated bilateral biochemical associations of biological agents with metal precursors. Phytochemicals can be used to donate electrons to metal ions reducing them to metallic or oxide status depending on the conditions of the reaction. Protein functionalization is achieved by the binding of amine and carboxyl groups to the nanoparticles surfaces and this gives them an electrostatic stabilization and prevents aggregation. Polysaccharides develop protective layers by the formation of coordination bonds, regulating the crystal growth, as well as defining the final nanoparticle morphology. The insights into such mechanisms allow optimization of the parameters of synthesis to obtain the desired nanoparticle properties to meet the needs of particular desalination processes [14].

Nanomaterials of Membrane Enhancement

In nanocomposites membranes, nanomaterials are used in polymer scaffolds in order to improve desalination behavior in a variety of ways. Thin-film nanocomposites membranes are selective polyamide layers that are produced on porous support structures in interfacial polymerization, and nanoparticles are incorporated in the active layer. Introduction of hydrophilic nanoparticles enhances water permeability as well as reducing fouling propensity by increasing membrane surface hydrophilicity. Nanoparticles result in more water transportation routes and salt rejection by size exclusion and repulsive charge mechanisms [15].

Metal oxide nanoparticles such as titanium dioxide, zinc oxide and aluminum oxide offer photocatalytic and antimicrobial properties that deal with biofouling issues. These semiconducting oxides become reactive to ultraviolet or visible light irradiation to produce reactive oxygen species that damage organic foulants and inactivate microorganisms. Silver nanoparticles leech antimicrobial ions that hinder bacterial cell membranes, which inhibit biofilm formation, which slows down the performance of the membrane. Plant extracts are used to greenly synthesize these metal oxide and metallic nanoparticles to generate biocompatible surface coatings that facilitate dispersion in polymer matrices without affecting antimicrobial activity [16].

Nanomaterials based on carbon, such as graphene oxide, reduced graphene oxide, and carbon nanotubes, have excellent mechanical reinforcement, thermal stability, as well as water transport characteristics. The nanochannels formed by the two-dimensional structure of graphene oxide ensure that water can pass rapidly through it and that hydrated salt ions do not pass through due to size and charge effects. Oxygen functionalization increases compatibility with the polymer matrices, and introduces sites of covalent bonding that increases stability of nanocomposites. Graphene oxide synthesis through green synthesis methods involves the application of environmentally friendly oxidants and exfoliation process that do not require the use of toxic chemicals used in the traditional synthesis of graphene [17].

Zeolite nanoparticles have molecular sieving and high surface area properties, which improve membrane selectivity and adsorption capacity. Agricultural waste and industrial byproducts are also used to prepare natural zeolites and provide substitutes to the traditional hydrothermal synthesis. Mesoporous silica nanoparticles form ordered pore structures enabling selective transportation accompanied by high levels of internal surface area that allows to adsorb contaminants. Such inorganic nanomaterials are characterized with high chemical stability and thermal resistance, which prolongs the shelf life of membrane in severe desalination conditions [18].

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Applications on Reverse Osmosis

The most common desalination method is reverse osmosis technology which involves the use of semi permeable membranes coupled with a pressure that is used to separate water and dissolved salts. The integration of nanomaterials produced using green synthesis into reverse osmosis membrane can help overcome such weaknesses as the decrease in flux, the risk of fouling, and chlorine sensitivity. Silver nanoparticles synthesized with plant extracts are incorporated into thin-film nanocomposites membranes that exhibit improved antibacterial activity that decreases biofouling without altering salt rejection which is more than 99%. The phytochemicals give the biocompatible surface coating to nanoparticles in the green synthesis process to avoid aggregation and leaching with time, which maintains stable performance over a long period [19].

Graphene oxide nanocomposites membrane prepared through green synthesis processes show incredible enhancement in water permeability than the traditional polyamide membranes. Oxygen-containing functional groups are hydrophilic and therefore attract a water molecule and repel hydrophobic foulants thereby enabling a reduction in the number of times the membrane needs to be cleaned and an increase in the lifetime of the membrane. Research shows that, addition of 0.05-0.1 wt% graphene oxide enhances water flux by 30-50 percent without compromising salt rejection which is more than 98 percent. The mechanical strength offered by layers of graphene enhances the resistance to compaction of membrane when subjected to high operating pressures as the case is with seawater reverse osmosis [20].

Nanoparticles of metal oxides such as titanium dioxide and zinc oxide produced by green routes have self-cleaning properties due to the ability to degrade organic foulants by photocatalytically reducing them. Such nanoparticles produce hydroxyl radicals and superoxide anions that oxidize built-up organic material and partially restore membrane flux without the use of chemicals when subjected to sunlight or artificial UV light. Photocatalytic and antimicrobial functionality enables the production of multifunctional membranes, which prevent both the organic and organic fouling and lower the operational costs and the environmental impact of the chemical cleaning agent [21].

Forward Osmosis and Membrane Distillation

Forward osmosis involves the use of osmotic pressure differentials instead of hydraulic pressure to force water across membranes, and has a number of benefits, such as low energy use; low fouling tendency; and the capability of operating on high-salinity feeds. Green-synthesized nanomaterials incorporated into forward osmosis membranes would increase the water flux without reducing solute rejection. Silver nanoparticles formed by using plant extracts in cellulose acetate membranes show better antimicrobial effect and are better structural support to counter compression during use. The nanoparticle coating is biocompatible and eliminates the issue of cytotoxicity and offers effective biofouling control [22].

Graphene oxide and carbon nanotube nanoparticles enhance the permeability of a forward osmosis membrane by forming nanochannels and developing high surface hydrophilicity. The synthesis of carbon nanomaterials by green synthesis techniques results in a controlled functionalization of the nanomaterial which enhances compatibility to polymer matrices as well as avoiding aggregation of nanoparticles which would disrupt membrane integrity. Research yields a 40-60 percent enhancement of water flux relative to clean polymer membrane and does not reduce soluble solid rejection above 95

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per cent. Membranes with hydrophilic nanocomposites have lower tendency to foul and this increases the long duration between cleaning cycles [23].

Membrane distillation involves the utilization of the differences in the vapor pressure formed by temperature gradient to cause water to be transported through the hydrophobic membranes. The result of this process is a high salt rejection rate at lower temperatures than the standard thermal desalination process, which allows reuse of waste heat or solar energy. The use of hydrophobic nanoparticles manufactured using green technology improves the liquid entry pressure and thermal performance of the membranes. Fluorinated silica nanoparticles designed through bio-inspired synthesis develop superhydrophobic surfaces that do not allow wetting and keep operating in high-salinity feeds. Thermal stability of the inorganic nanoparticles prolongs the life time of the membranes in the high temperature environment [24].

Hybrid Systems and Nanofiltration

Nanofiltration is sandwiched between reverse osmosis and ultrafiltration, which means that it selectively separates multivalent ions but monovalent salts permeate. The technology is used in the desalination of brackish water, softening of water and elimination of certain contaminants such as heavy metals and organic micro pollutants. Green-synthesized nanoparticles improve nanofiltration membrane functionality by modifying the charge and optimization of pore sizes. Silver nanoparticles supported by chitosan offer beneficial positive charges to the surface that results in cationic repulsions as well as the antimicrobial functionality [25].

Hybrid desalination systems are systems that use various technologies to maximize the energy efficiency and water recovery. The pretreatment of reverse osmosis using nanofiltration decreases the fouling load, increases the life of the membrane and decreases the total energy usage. Membrane distillation in combination with forward osmosis forms low-energy systems that can be deployed to remote areas and off-grid systems. Green nanomaterials allow optimization of performance in hybrid configurations due to specific functionalization to meet separation needs. The release of nanomaterials into streams of concentrate to be discharged in the sea presents concerns over nanomaterials that are green-synthesized [26].

Photocatalytic membrane reactors have both separation and degradation capabilities by embedding photocatalytically active nanoparticles into membrane surfaces. Compared to conventional methods of making titanium dioxide nanoparticles, titanium dioxide nanoparticles made by using plant extracts have a higher photocatalytic rate because of a decreased particle size and an increased surface area. These membranes are able to remove salts and at the same time degrade organic pollutants such as pharmaceuticals, pesticides, and industrial chemicals when exposed to solar irradiation. The two-in-one nature minimizes complexity and the area of the system and deals with new contaminants that regular desalination is unable to eliminate [27].

Characterization and Performance Evaluation

These include comprehensive characterization of synthesized nanomaterials green, which guarantees quality control and performance forecasts of desalination Applications. Nanoparticle morphology, size distribution and dispersion in membrane matrices can be observed by transmission electron microscopy and scanning electron microscopy. X-ray diffraction establishes crystal structure

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as well as phase composition which proves that nanoparticles have been formed successfully and which crystalline phases are the cause of a particular property. Fourier-transform infrared spectroscopy determines the functional groups on the surface of nanoparticles and gives information on capping agents that are produced through the biological production contributing to the membrane integration and stability [28].

Membrane properties that are important to measure in the performance of desalination are evaluated using surface characterization methods. Measures of contact angle determine surface hydrophilicity, the lower the contact angle, the lower is the propensity to foul. Atomic force microscopy is a nanoscale image of the roughness of a surface, which measures the topography against the fouling behavior. Measurements of Zeta potential ascertains surface charge which affects the process of electrostatic interaction with foulants and dissolved ions. The methods of characterization are used to optimize the parameters of green synthesis to obtain the appropriate surface properties in certain desalination applications [29].

Performance appraisal measures progress made due to the use of nanomaterial. Measurement to derive membrane selectivity, salt rejection efficiency is used as a percentage of the difference between feed and permeate salt concentration. Permeate flux is an indicator of the productivity and economic feasibility of membranes and is a measure of the rate of water production per square meter of membrane area. Fouling resistance is determined by measuring the flux decrease during prolonged operation under realistic feed condition of the substance containing organic matter and microorganisms. Accelerated aging stability testing is a prediction of the lifetime of membranes and it determines the degradation mechanisms that need to be mitigated [30].

Scale-Up Problems and Economic Concerns

To translate the idea of green synthesis in the laboratory scale to the industrial one, the issues of reproducibility, optimization of yields, and quality control need to be discussed. Plant extract composition variability, as between batches, affects the nanoparticle properties and this requires standardization procedures regarding the selection of biological feedstock, extraction processes and the conditions used in the synthesis. Continuous flow synthesis is also scalable to allow regular production of sufficient volumes of material to be used in commercial membrane production. Microorganism synthesis by bioreactor also has the benefits of controlled growth factors, high yield and ease of downstream process as compared to plant-based approach.

Economic analysis of the green synthesis and the traditional system should consider the cost of raw materials, energy cost, cost of waste treatment and environmental externalities. Biological feedstocks are cheap and renewable though extraction and purification processes involve extra cost which has to be minimized by process optimization. The life cycle assessment measures the environmental effects of the material production, the production of the membranes, the operation of the desalination process and the end of life disposal. Research proves that green synthesis saves carbon footprint by 40-60% over chemical synthesis yet results in the same or better performance of the membrane which justifies the possible cost premiums due to environmental and social advantages.

Regulatory procedures on products based on nanomaterials in desalination processes need toxicity studies and environmental impacts. Nanomaterials green-synthesized are less ecotoxic than chemically synthesized ones, which are biocompatible on the surfaces and do not contain toxic synthesis

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residues. Nevertheless, risk assessment procedures should be thoroughly conducted to examine the release of nanoparticles in the course of membrane working and focal disposal. The proposed method of defining industry standards of characterization of the green nanomaterials and performance specifications will enable regulatory acceptance and acceptance of these materials in the markets as well as assuring environmental protection and safety of the people.

Conclusion

This research on green synthesis of nanomaterials in advanced water desalination system illustrates the way the sustainable nanotechnology is changing the way water is treated by improving the performance of membrane but reducing environmental influence. Through the use of biological resources such as plant extracts, microorganisms, and biopolymers in nanomaterial synthesis, green synthesis removes the use of toxic chemicals and also minimizes energy use in the traditional synthesis procedures. Green-synthesized nanoparticles have found use in reverse osmosis, forward osmosis, membrane distillation and nanofiltration membranes, which show superior salt rejection, higher permeate flux, higher fouling resistance and longer service life than the traditional materials.

The results point to the challenges linked to the implementation of the synthesis method that need to be tackled to achieve the success of the implementation process: problems with the standardization of synthesis, scale-up viability, and economic competitiveness. New technologies such as continuous flow synthesis, bioreactor manufacturing, and hybrid material systems are effective in removing these drawbacks and purchasing opportunities without having to compromise on environmental performance. The interdisciplinary cooperation between chemical engineers, materials scientists, biotechnologists, and environmental specialists is a role that cannot be overestimated in the development of green nanotechnology out of the laboratory setting to industrial application.

With increasing world water scarcity and demands of sustainability, the nanomaterials used in desalination processes are currently being synthesized using green chemistry, which makes the creation of green nanomaterials the key entry point to attaining water security by using an eco-friendly set of technologies. Further studies on the optimization of synthesis, long-term performance testing, and thorough life cycle analysis will help achieve the next-generation desalination systems that will integrate high efficiency with ecological responsibility to add to the sustainable development objectives and the principles of the circular economy in the water sector.

Questions for Discussion

1. What is needed is how green synthesis methodologies can be optimized to produce stable nanomaterials quality that can be used in large-scale industrial production of membranes?
2. What are the measures to be taken to assess the trade-offs between improved desalination performance and possible environmental hazards of membranes made possible by nanomaterials?
3. What potential benefits can be realized by new technologies such as photocatalytic nanomaterials, hybrid membrane systems, and integration of renewable energy in desalination processes in making it more sustainable and economical?

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