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Exploring The Potential of 3D-Printed Antibacterial Membrane From Waste-Derived Graphene Oxide

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There has been a notable expansion of research addressing technological limitations and critical challenges of conventional membranes such as biofouling, energy consumption, and low flux. The inherent advantages of additive manufacturing (AM) or 3D printing (3DP) have led to significant breakthroughs in water filtration membranes in terms of material selection and prototype design to create innovative membranes, while the growing demand for efficient, sustainable, and multifunctional membranes has driven interest in advanced materials such as graphene oxide (GO). This review explores the potential of 3D-printed antibacterial membranes derived from waste-derived GO for liquid-phase separation processes. Graphene oxide (GO), renowned for its exceptional antibacterial properties, high surface area and hydrophilicity, has emerged as a promising material for membrane technology. This review highlights the integration of waste-derived GO into 3D-printed membranes, and the enhancement of their antibacterial activity for applications in water filtration. The paper also discusses the challenges faced in combining 3D printing with GO and provides an overview of recent advancements in the field, identifies existing gaps, and suggests future research directions for the development of sustainable, high-performance membranes. By combining the environmental benefits of waste-derived GO with the versatility of 3D printing, this technology presents a promising solution to address global water and sanitation challenges

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With the ongoing advancement and enhancement of membrane technology, some of these membranes still did not possess the necessary performance capabilities to fulfil specific industrial needs in separation processes. Membrane fouling is a substantial obstacle that hinders the widespread use of membranes in aqueous separation, particularly for intricate aqueous solutions [1]. Membranes used in wastewater treatment processes are susceptible to biofouling [2], where microorganisms accumulate on the membrane surface, reducing filtration efficiency [3] and potentially causing contamination issues.

Three-dimensional (3D) printing, also known as additive manufacturing (AM), has become a transformative technology, particularly in engineering and manufacturing. Recent advancements have enabled the production of intricate and functional objects with high precision, facilitating breakthroughs across diverse industries. 3D printing is already widely used in

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aerospace for lightweight components, in tissue engineering for implant development, and in energy storage for creating supercapacitors [4] and fast-charging batteries [5]. AM works by creating 3D objects layer by layer, offering significant benefits such as cost reduction, faster production times, and enhanced design flexibility [6]. Various materials, including metals, ceramics, and polymers, can be used in 3D printing [7], which allows for the creation of complex structures tailored to specific needs [8, 9].

Among the materials of interest, graphene has emerged as a promising candidate due to its exceptional mechanical [10], thermal [10], electrical [10], and physicochemical properties. Graphene is approximately 100 times stronger than conventional steel, making it an ideal nanofiller for enhancing polymer composites. Even small amounts of graphene can significantly improve the mechanical properties of composites, including strength, stiffness, and flexibility [11], which are essential for a wide range of applications [12]. Graphene oxide (GO), a derivative of graphene, provides extra functional groups that can enhance dispersibility and bonding within the polymer matrix. The incorporation of GO into polymer resins used in 3D printing has shown substantial improvements in tensile, flexural, and impact properties.

The cost and uses of membrane-based structures are also primarily determined by the selection of material. For established membrane processes like such as gas separation and desalination, is typically determined by two primary variables – permeability or water flux and selectivity [8, 13]. Challenges in additive manufacturing of graphene-based separation membranes include ensuring uniform dispersion of graphene within the membrane matrix, controlling the membrane thickness, and optimizing the pore size distribution for separation applications [9, 14]. The incorporation of graphene oxide in a polymer matrix may results in an increase in viscosity due to the aggregation and agglomeration of the nanoparticles. This aggregation results from the Van der Waals interactions that bind the nanoparticles together [10]. Ganesh et al. introduced graphene oxide into their study and discovered that the incorporation of graphene oxide resulted in increased flux and rejection [15]. However, they also noted that the graphene oxide exhibited a folded and agglomerated shape [15].

To maximize its potential, AM for membrane fabrication must address several gaps and challenges. Therefore, this review focuses on exploring future developing novel graphene-functionalization to enhance membrane performance and achieve precise control over membrane structure. It specifically examines the use of 3D printing, specifically vat photopolymerization, for incorporating GO as a nanofiller into polymer-based resins. The integration of GO in this way offers the potential for optimizing mechanical properties and expanding the functionality of 3D-printed materials, especially for applications requiring enhanced strength and durability.

1. Relevance of Waste-Derived Graphene Oxide

The conversion of plastic waste into GO provides an attractive option for upcycling polymers like polyethylene (PE), polypropylene (PP) and polystyrene (PS) into valuable nanomaterials. This carbon-rich plastic undergo pyrolysis, a process that uses high temperatures that decays the polymers into nanoscale carbon structures. Chemical exfoliation integrates oxygen-containing groups onto the carbon layers, turning them to GO. This process, typically assisted by catalysts that involve bentonite, enhances yield and reduces reaction duration and improves GO quality, leaving it appropriate for environmental and industrial applications [16–18].

Waste-derived GO made from plastic waste possesses distinctive characteristics, including increased hydrophilicity due to its abundant oxygen functional groups (–OH, –COOH, C—O) [19, 20], which enhance its dispersibility in water and efficacy in water filtration, energy storage, and catalysis applications. The afore-mentioned qualities, together with its extensive surface area and antibacterial capabilities, render GO suitable for filtration and adsorption applications [21]. Additionally, GO synthesis from waste materials addresses critical environmental challenges by reducing plastic pollution and supporting sustainable waste management practices [19]. Plastic production is energy-intensive, generating approximately 4% of global oil and gas use. Despite representing a substantial portion of municipal solid waste (11% in China and the UK, 13% in the United States, and 8% in the European Union), only 14-18 % of plastic waste is recycled [22]. The remainder is either used for energy recovery (24%) or discarded in landfills or open areas (58-62%), contributing significantly to global pollution. Repurposing plastic waste into GO offers a sustainable solution by diverting it from landfills and marine environments, mitigating pollution, and supporting circular economy principles [16, 23]. For example, innovative methods such as flash Joule heating have demonstrated the rapid and energy-efficient synthesis of graphene from mixed plastic waste, addressing both environmental and economic challenges [24]. Methods have been developed to convert polyethylene microplastics from discarded dropper bottles into graphene, thereby mitigating the introduction of microplastics into marine ecosystems [25].

Similarly, waste cooking oil (WCO) presents another viable carbon source for GO production. WCO primarily comprises triglycerides, diglycerides, monoglycerides, fatty acids, and various compounds formed during the cooking process [17, 26, 27] , such as carbon chains with hydrogen, oxygen, and trace impurities. The specific composition can vary depending on the type of oil used and the duration of its use. The high carbon content and presence of hydrogen make WCO an excellent precursor for synthesizing carbon-based materials. These characteristics enable effective conversion into carbon-rich compounds that serve as the basis for GO production. However, the direct conversion of WCO into GO is not straightforward. WCO often contains impurities and contaminants that can interfere with the GO synthesis [28]. Therefore, pretreatment steps are often necessary to remove these impurities and obtain a suitable carbon source. Several methods have been explored to convert WCO into valuable carbon-based products such as pyrolysis [12], chemical vapor deposition (CVD) [17], and hydrothermal carbonization (HTC) [29]. Pyrolysis involves heating WCO at high temperatures in an oxygen-free environment, breaking down complex organic molecules into simpler compounds, including carbon-rich gases and bio-oil. The process involves catalytic temperatures ranging from 350-550°C and the use of metal oxides like CoO, NiO, ZrO_2, SrO, CeO_2, and CaO [12]. A study demonstrated that pyrolysis at 425°C with activated carbon as a catalyst yielded 81.7 wt.% bio-oil, which can be further processed into diesel-like fuel [30]. CVD involves the decomposition of gaseous precursors such as methane or acetylene, on a catalyst surface to form carbon-based materials [31]. WCO is vaporized and introduced into a high-temperature reaction chamber, where carbon atoms deposit onto a substrate to form graphene or GO layers. The synthesis of carbon quantum dots and GO via one-pot pyrolysis of citric acid suggests that similar methods could be adapted for WCO [31-32]. HTC involves heating WCO under high pressure and temperature in the presence of water to produce hydrochar, a carbon-rich solid material. Hydrochar can be further processed to produce graphene oxide or other carbon-based materials [33].

Recycling WCO into GO and other valuable products has significant environmental benefits. It reduces the environmental hazards associated with waste oil disposal and decreases reliance on fossil fuels. The environmental benefits of converting waste materials like plastic and WCO into GO are significant. These processes reduce the environmental burden of waste disposal, reduce pollution, and offer sustainable alternatives to traditional carbon sources. For instance, the co-pyrolysis of WCO with waste lubricating oil not only produces diesel-like fuel but also lowers the sulphur content, making it less harmful to the environment. Additionally, the use of heterogeneous catalysts derived from biochar or other renewable sources further enhances the sustainability of these processes [27]. WCO has also been utilized as a carbon source in synthesizing graphene sand composites, which demonstrate excellent performance as adsorbents for removing contaminants from water, effectively addressing waste oil disposal issues [34]. Moreover, GO derived from WCO has been employed as a catalyst in biodiesel production, enhancing reaction efficiency and contributing to renewable energy initiatives.

Economically, utilizing waste materials as feedstock for GO synthesis reduces dependency on high-purity and expensive raw materials, significantly lowering production costs. Advanced processes, such as chemical exfoliation with bentonite catalysts, enhance yield and quality while shortening reaction times, making GO production more efficient and commercially viable. The distinctive properties of waste-derived GO, including its hydrophilicity, large surface area, and antibacterial capabilities, further justify its cost-effective production and enable applications in water purification, energy storage, and catalysis [34, 35]. Additionally, processes like the transesterification of WCO using GO-based catalysts have demonstrated the potential for efficient biodiesel production, offering economic and environmental benefits [36]. For example, the pyrolysis of WCO with activated carbon has been shown to yield bio-oil, which can serve as a diesel-like fuel, reducing production costs and enhancing the overall economic value of waste-to-product conversion. Furthermore, advancements in catalyst technology, such as biochar-derived heterogeneous catalysts, have improved the efficiency of GO synthesis, further lowering costs and promoting sustainable practices [37].

GO derived from waste materials represents a sustainable and cost-effective alternative for producing antibacterial membranes, especially for uses in water filtration and healthcare. The inherent mechanisms of action, such as physical membrane disruption and reactive oxygen species generation, contribute to strong antibacterial efficacy of GO. GO is the chemically oxidised form of graphite, distinguished by notable oxygen bonding at its edges and defects on both available surfaces, which feature carboxylic (–COOH), carbonyl (–C—O), and hydroxyl (OH) groups [38]. The antibacterial properties, stemming from its inherent characteristics and possible functionalization from the bonding group, position it as an environmentally friendly and sustainable approach to addressing bacterial contamination. The primary mechanism involves the physical disruption of bacterial membranes. The nanosheets of GO feature sharp edges that effectively puncture and compromise bacterial cell walls and the lack of an intracellular process results in these groups improving interactions with biomolecules, ultimately causing bacterial death [38], [39]. This physical mechanism demonstrates efficacy against a wide variety of bacterial strains, encompassing both Gram-positive and Gram-negative bacteria, while eliminating the necessity for chemical disinfectants.

Waste-derived GO is highly relevant due to its excellent separation efficiency, high permeability, and stability in removing dyes, salts, and heavy metals from water [40]. This tunable GO nanofiltration membrane separates dyes and salts from highly saline wastewater forming clean water for environment [41]. Waste-derived GO retains the high surface area of graphene, which facilitates increased interaction with contaminants during filtration by controlling some properties such as the synthesis conditions for specific applications such as selective ion rejection, oil water separation and also removal of heavy metal contaminants [42]. This knowingly graphene derivatives are known for the high surface to volume ratio where each layer of GO interacts with contaminants through van der Waals forces, hydrogen bonding leading to efficient pollutant capture [43]. Its functional group which contains abundant of oxygen-containing functional which enables strong adsorption capacities and compatibility with various polymer matrices in membranes [44]. This hydrophilic property improves the longevity and efficiency of membranes filtration. Inducing the idea of 3D GO membranes as efficient adsorbent for removing complex pollutant especially various organic solvents from water.

2. Additive Manufacturing and Membrane Separations

Additive manufacturing (AM) and membrane separation technologies are two distinct yet potentially complementary fields that have gained significant attention in recent years. AM, also known as 3D printing, is a rising manufacturing method that has shown notable progress across various industries. It uses computer-aided designs to precisely and directly deposit material layers to form of a three-dimensional shape from a digital file [45-46]. 3D printing has undergone continuous development and enhancement to utilise both preexisting and newly developed materials [6].

In contrast, membrane separation technologies utilise semi-permeable membranes to separate components of a mixture, such as in water filtration, gas separation, and food processing. Membranes serve as the main physical barrier in membrane-based technologies. They enable the selective movement of certain components while blocking others based on their individual features and the size of the pores, which allows for molecular differentiation [47]. This selective movement makes them ideal for applications like desalination, wastewater treatment, and chemical separations.

Although AM and membrane separations are often considered separate technologies, there are growing opportunities for their integration, particularly in the areas of customized membrane design, optimization of membrane support structures, and improving filtration efficiency. Emerging techniques like 3D printing allow for exact manipulation of membrane structure and distribution of pore sizes, resulting in membranes that may be customised to have improved performance and less fouling [11, 48]. 3D printing can enable the creation of membranes with highly specialized geometries, including intricate pore structures, multi-layer configurations, and flow channels that improve the efficiency and selectivity of separation processes. Additionally, 3D printing could contribute to the development of more durable membranes with enhanced resistance to fouling, while also allowing for rapid prototyping enabling researchers and engineers to iterate new designs quickly and cost-effectively, as shown in Figure 1.

Among various AM technologies, vat photo-polymerization (VP) methods like stereolithography (SLA), digital light processing (DLP), continuous liquid interface production (CLIP), and two-photon polymerization (TPP) have transformed 3D-printed membrane fabrication. VP represents the pioneering 3D printing process, employing a light source to initiate polymerisation reactions in photosensitive materials, where liquid polymer resin is selectively cured by light source, layer by layer, to match a 3D model [11, 45]. This technique enables the creation of complex, multifunctional materials with precise control over optical properties.

Like SLA, DLP uses photopolymer resin and ultraviolet light. However, instead of a laser, it uses a digital light projector, which makes it possible to simultaneously cure a complete layer. Research work on DLP technology has mostly focused on increasing the material possibilities, decreasing the layer thickness, and enhancing the resolution. CLIP represents an advanced version of DLP, that reduces free radical photopolymerization by using oxygen diffusion to control the polymerization process and enhance printing speed [49]. It uses UV projection at the base to cure the photosensitive resin, while oxygen keeps the resin at the bottom of the vat in a stable liquid state, ensuring continuous curing. A window at the bottom allows light and oxygen to pass through [50]. Another photo curing technique utilised in VP is TPP, which requires the absorption of two photons by a single molecule. The vat filled with photopolymer resin undergoes polymerisation via a photopolymerisation process that employs a focused beam of light. This phenomenon takes place solely in the areas where the laser beam is aimed [6, 20]. The polymerization process employs long-wavelength, low-energy light to ensure deep penetration into the resin without significant single-photon absorption [33, 37]. The following table summarizes the various AM methods used in 3D-printed membrane fabrication, highlighting their benefits along with relevant references for each approach. The future of separation membranes is promising with exploration of advanced materials, such as graphene-based membranes, molecularly selective membranes, and biomimetic membranes. These materials aim to achieve unparalleled levels of selectivity, permeability, and durability.

In any fabrication of vat photopolymerization-based resin, material compatibility is one of the critical considerations that directly impacts the performance and effectiveness of the printing system. The choice of materials, specifically the selection of resin polymer matrix and additive filler must be considered to have an optimal interaction between the components. Parts printed using VP, particularly those made with acrylates, face challenges due to their high shrinkage and curling issues, resulting in weakness [52, 53]. In contrast, epoxy-based printed parts, while harder, more precise, and stronger with only 1-2% shrinkage, encounter different challenges such as brittleness, slow curing times, and sensitivity to humidity, which can impede the polymerization process [53]. Hence, a synergistic approach that combines the two resins can merge the benefits of both, which results in enhanced accuracy and increased green strength in printed parts. Presently, some commercially available resins are blends of epoxy and acrylates, allowing them to mix and tune them to achieve desired properties [54].

Table 1. Vat Photopolymerization Approaches in 3D Membrane Fabrication.

Types	Principle	Advantages	Limitations	Ref
Stereolithography (SLA)	Layer-by-layer preparation method utilising Ultraviolet (UV) laser for the curing of photopolymer resin	High resolution	Longer time production	[55]–[57]
Digital Light Processing (DLP)	Similar principle to SLA but using a UV projected light source and digital projector screen	Fast production, High-quality printing	Low resolution compared to SLA	[38],[39],[41]
Two-Photon Polymerization (TPP)	Photopolymerisation process occur by using focused beam light	Create fine-resolution product (small as 100nm)	Highly-priced, longer production and produce limited size of products.	[59]-[11]
Continuous Light Interface Production (CLIP)	A technique employing oxygen diffusion to control the polymerisation process and the rate of printing.	Speed up the process (25-100 times faster than DLP) of making areas that are very smooth and detailed.	Precursor materials are expensive and limited in availability, not suitable for graphene used.	[11], [60]

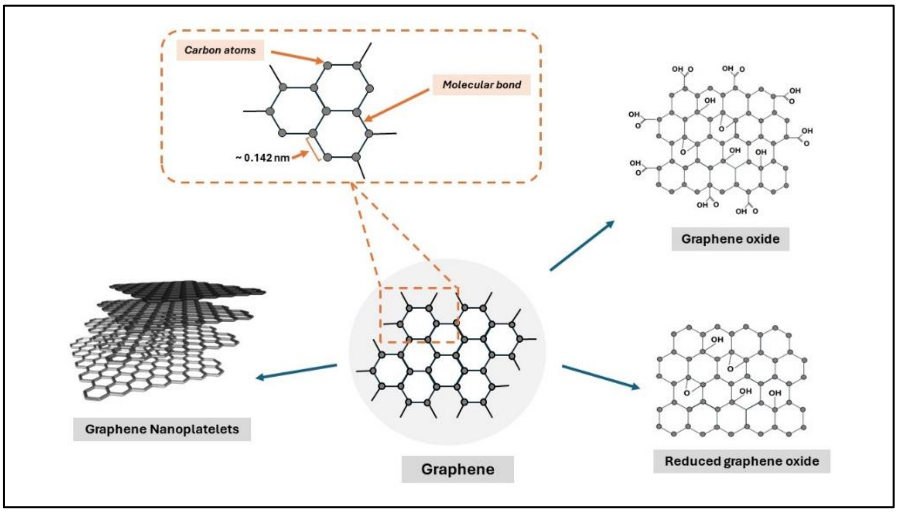

Figure 1. Structures of Graphene, Graphene Oxide, Reduced Graphene Oxide and Graphene Nanoplatelets.

3. Additive Manufacturing of Graphene-Based Materials Structures

Nanofillers offer multiple benefits for polymers used in additive manufacturing techniques. The development of composite materials in 3D printing has improved mechanical, optical, electronic, thermal, and biomedical by adding these reinforcements. Similarly, as graphene has gained significant attention among researchers due to its remarkable qualities, the addition of graphene and graphene-based materials as nanofillers to the photopolymer resin has helped in improving its mechanical properties.

The three-dimensional printed polymer products can produce intricate geometries, but they frequently lack the mechanical properties and functionality required for practical application [61]. To improve the properties of the polymer, nanofillers are used in the polymer matrix. Carbon-based nanofillers like graphene and derivatives, including graphene oxide (GO), reduce graphene oxide (rGO), graphene nanoplatelet (GNP) and functional graphene oxide (fGO) are widely used in 3D printing manufacturing. The integration of graphene into polymer-based composite offers many functionalities while also improving the processing performance and expanding the potential applications of composites. The addition of graphene types in photopolymer resin allows the vat photopolymerisation to create a very high-strength composite with outstanding or excellent properties such as electrical conductivity and durability [1]. The molecular compositions of graphene, graphene oxide, reduced graphene oxide and graphene nanoplatelets are depicted in Figure 1.

The bonding between graphene with polymer matrix can effectively improve the structural performance of the composites, while the configuration of the composites can be monitored based on the designability of 3D printing [62]. H. Zhang et al. reported that the three-dimensional graphene-based adsorbents prepared by additive manufacturing technology generally have better performance [20]. Similar observation by Valentin et al. showed that the hydrogels with GO addition prepared by light-directed 3D printing have improved mechanical properties, excellent stability in high salt solutions, and super oleophobic. Despite the complexity of graphite flakes and structural defects poses challenges in understanding detailed oxidation mechanisms for graphene-based membranes, Graphene-based membranes typically in thin film composite form, have demonstrated improved solvent permeance in water treatment processes, serving as a reference for potential utility in organic solvent nanofiltration [63].

Graphene-based membranes exhibit high solvent flux and solute rejection rates, making them effective in organic solvent nanofiltration processes. Their superior performance is attributed to the unique properties of graphene, such as high surface area, mechanical strength, and chemical stability. Due to its toxic properties towards bacteria, the membrane made of GO composites has the ability to inhibit the growth of microorganisms in membrane bioreactors. GO destroyed the integrity of bacteria cells by two primary mechanisms. Firstly, the atomically sharp edges of GO penetrated the bacterial cell. Secondly, the GO nanosheets connected to the cell membrane underwent oxidative reactivity [64]. In summary, the integration of additive manufacturing and graphene materials has significant potential for enhancing membrane separation methods.

4. Antibacterial Mechanism of Carbon and Nanostructure-Based Materials

Carbon nanomaterials, such as graphene oxide (GO), carbon nanotubes (CNTs), and fullerenes, exhibit unique and highly beneficial properties, including high surface area, exceptional electrical and mechanical strength, adjustable chemical properties, and ease of functionalisation [65]. These characteristics position them as promising candidates for antibacterial applications. Because of their distinctive and remarkable characteristics, these materials are frequently referred to as "wonder materials" [66]. The materials can be customised at the nanoscale to attain specific antibacterial properties, rendering them highly effective in inhibiting bacterial growth and making them suitable for a range of applications, including antibacterial uses in water treatment and filtration systems.

The study of antibacterial properties through carbon nanomaterials has gained significant growth, particularly studies examining how physicochemical properties affect on their antimicrobial efficacy. The two widely discussed possible mechanism of action for carbon and nanostructure-based materials, such as graphene oxide (GO), carbon nanotubes (CNTs), and fullerenes, include (a) direct action, which involves the toxicity of free metal ions that leach from the surfaces of nanoparticle, and (b) the generation of secondary active agents, specifically oxidative stress caused by the production of reactive oxygen species (ROS) on the surfaces of nanoparticles [67–69].

Direct action serves as a crucial mechanism by which carbon-based nanostructures demonstrate antimicrobial activity, taking place through the release of free metal ions from their surfaces. Carbon-based nanostructures can be functionalised with metal ions nanoparticles to enhance their antimicrobial properties. The dimensions, morphology, or form, concentration, and interactions of nanoparticles (NPs) with the target pathogens have been demonstrated to influence the mechanisms of antimicrobial action and the effectiveness of antimicrobial activities. Reports reveal that smaller nanoparticles have the strongest bactericidal effect and exhibit enhanced ability to penetrate cell surfaces, hence improving their antibacterial efficacy. Metal nanoparticles, including silver, zinc oxide, and copper oxide [61], exhibit potent antimicrobial activity due to their ability to generate reactive oxygen species (ROS), which cause stress due to oxidation and ruptures of microbial cell structures. The incorporation of metal ions nanoparticles induces oxidative stress and facilitates the penetration of metal ions toward the negatively charged bacterial cell wall, leading to the formation of reactive oxygen species (ROS) [70]. These ROS cause significant disruption of cellular components, including DNA, proteins, and lipids, effectively inhibiting microbial growth [71, 72]. These nanoparticles can also disrupt microbial cell membranes, leading to cell lysis and death. Furthermore, metal ions nanoparticles can aggregate within bacterial cells, resulting in cytoplasmic content depletion and inactivation of respiratory enzymes, ultimately causing cell death [73]. This antimicrobial mechanism alters the membrane charge and increases cell wall thickness, while nanoparticles with a high surface-to-volume ratio interact more efficiently with the bacterial cell wall, enhancing microbial damage [74]. Metal ions released from these nanoparticles can interact with microbial enzymes and proteins, disrupting their normal function and inhibiting cellular metabolism.

The generation of secondary active agents, particularly oxidative stress from reactive oxygen species (ROS) produced on nanoparticle surfaces, is another important mechanism of antimicrobial action. Similar to metal nanoparticles, GO and other carbon-based nanostructures can generate ROS, boosting their antimicrobial efficacy. Simultaneously, the formation of ROS triggers oxidative stress, causing severe cellular damage by disrupting the cell wall and plasma membrane through physical interactions, resulting in DNA disruption and protein denaturation [75]. These dual mechanisms, ion release and ROS generation work synergistically to inhibit bacterial growth by compromising the structural integrity of microbial cells and interfering with essential biomolecular functions. The oxygen-containing functional groups on GO further destabilize bacterial membranes, enhancing antimicrobial efficacy. Advanced properties, such as photocatalytic ROS generation under light irradiation, add another layer of antibacterial action. These multifaceted mechanisms make carbon-based nanostructures highly effective in addressing bacterial contamination, with applications in water treatment, antibacterial membranes, and medical devices, offering a sustainable and innovative solution to biofouling and microbial resistance challenges. Figure 2 illustrates the different possible mechanisms highlighting the processes that contribute to the antimicrobial efficacy of these nanomaterials.

Carbon-based nanostructures also demonstrate significant anti-adhesive properties, attributed to their nanoscale size and surface interactions, which effectively reduce bacterial adhesion. By preventing the initial attachment of bacteria to surfaces, these nanostructures inhibit biofilm formation and microbial colonization, thereby mitigating the risk of microbial infections [76]. This dual functionality acting as antimicrobial agents and as anti-adhesive materials makes carbon-based nanostructures highly promising for biomedical and surface-coating applications.

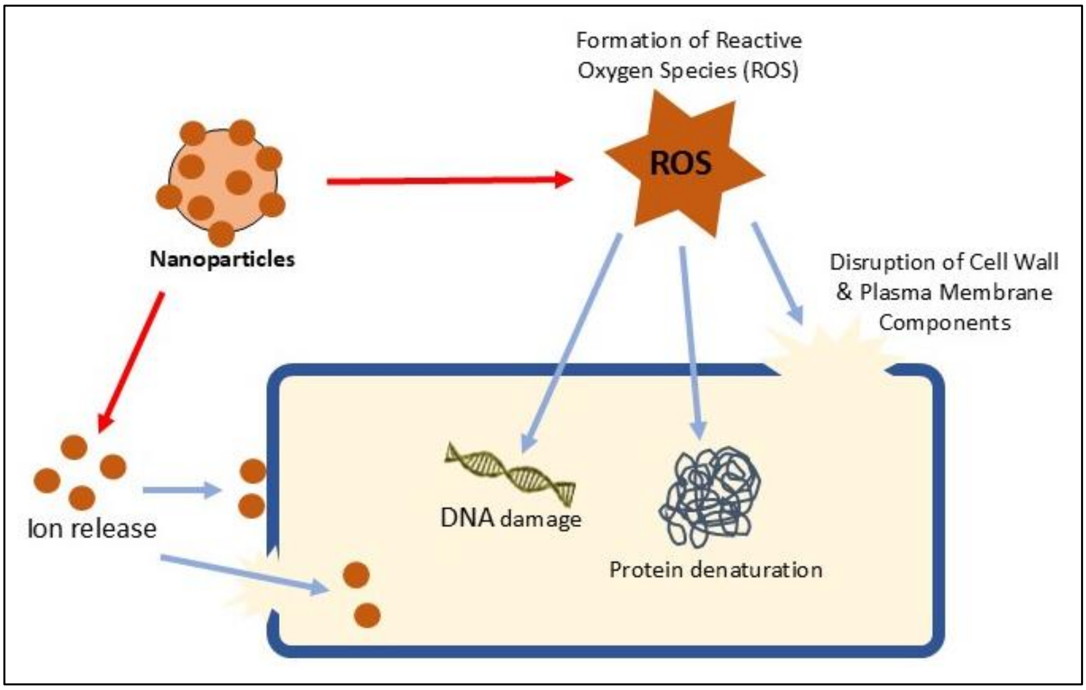

Figure 2. Representation of possible antimicrobial mechanism of carbon and nanostructure-based materials [77].

5. Future Directions for 3D-Printed Membranes: Emerging Technologies, Continuous Innovations, and Market Trends

The advancement of 3D-printed membranes has swiftly attracted interest due to their potential to transform sectors dependent on filtration, separation, and various membrane technologies. The application of 3D printing in the fabrication of membranes spans various fields, including water treatment and biomedical devices, providing exceptional flexibility [9, 78, 79], customization [80], and scalability. However, as technology advances, it is crucial to consider not only the performance and application possibilities of 3D-printed membranes but also the broader aspects such as material performance, scalability, and cost-effectiveness. These factors play a significant role in determining the long-term feasibility and sustainability of adopting 3D printing for large-scale membrane production.

One of the primary advantages of 3D printing technology is the potential for cost reductions in manufacturing [78, 79], but this comes with both challenges and opportunities that warrant thorough exploration. Traditional membrane manufacturing methods, such as casting or phase inversion, often involve expensive and complex processes that require significant labor, material, and energy inputs. Conversely, 3D printing facilitates a more efficient, on-demand production approach that minimises material waste by precisely depositing material only where it is needed. This may result in considerable cost reductions in both the procurement of raw materials and the manufacturing process, especially when developing membranes that incorporate intricate geometries or tailored characteristics [9]. However, although the decrease in material waste and the ability to customise are evident advantages, the upfront costs of 3D printing equipment and the specialized materials used in 3D printing membranes can be high. The cost associated with high-quality 3D printers, particularly those that can achieve the necessary resolution for membrane structures, poses a significant obstacle to broader acceptance, especially among small and medium-sized enterprises (SMEs).

Additionally, the cost of the materials used in 3D printing, including advanced polymers, graphene oxide, and composite resins, might exceed those of conventional membrane materials. As 3D printing technologies evolve, there will likely be cost reductions in costs associated with both hardware and materials, influenced by enhancements in printing speed, material efficiency, and competitive market dynamics. For instance, research into new, more affordable printing materials such as bio-based resins, recycled polymers, or waste-derived materials could lower the cost of production. Overall, while the upfront expenses associated with 3D printing membranes might remain high, the prospects for long-term cost savings, coupled with the potential for on-demand production and reduced material waste, present compelling financial rationale for further investment in this technology.

The environmental impact of 3D-printed membranes is an important consideration, particularly in the context of growing concerns on sustainability within industrial manufacturing. Conventional methods for producing membranes which often rely on chemical treatments, elevated temperatures, and substantial energy consumption, resulting in considerable environmental impacts. Conversely, 3D printing presents a more energy-efficient option that lessens the reliance on hazardous chemicals and minimizes waste through its additive process, which involves depositing materials layer by layer precisely only where needed. The creation of innovative materials that align with 3D printing techniques is essential for enhancing the mechanical, thermal, and chemical characteristics of 3D-printed membranes. A promising direction is the advancement of multi-material printing, which allows for the simultaneous deposition of different materials with distinct properties. This facilitates the development of membrane with integrated functionalities, such as hydrophilicity, antibacterial properties, and selective permeability. For instance, membranes could be fabricated with a combination of polymers and nanomaterials (e.g., graphene oxide, carbon nanotubes) to enhance mechanical strength and filtration efficiency.

The integration of additive manufacturing with conventional fabrication methods such as injection molding presents a fascinating domain of exploration. This approach can help optimize the production of membranes by combining the precision of 3D printing with the scalability and diverse materials offered by conventional methods. Continuous advancements in materials science play a crucial role in the development of 3D-printed membranes. The development of novel materials that are compatible with 3D printing processes is crucial for enhancing the mechanical, thermal, and chemical characteristics of 3D-printed membranes. Table 2 outlines essential domains of investigation in the development of 3D-printed membranes, including the application of nanomaterials and hybrid composites, the incorporation of sustainable and bio-based materials, the enhancement of antibacterial properties, and the design of high-performance, multi-functional membranes. The significance of each of these domains is paramount in enhancing the functionality and performance of 3D-printed membranes across diverse applications.

Table 2. Key research areas in the advancement of 3D-printed membranes.

Key Research Area	**Description**	**Key Features/Advantages**	**Ref**
Nanomaterials and Hybrid Composites	a) Incorporation of nanomaterials like graphene oxide (GO), carbon nanotubes (CNTs), and metal-organic frameworks (MOFs) in 3D printing to improve membrane performance. b) Hybrid composites combine polymers with nanoparticles or other advanced materials.	Enhanced mechanical strength, permeability, and selectivity	[48], [79], [81]
Sustainable and Bio-based Materials	Use of biodegradable or recyclable polymers such as bio-based resins, polylactic acid (PLA), polyhydroxyalkanoates (PHA), and waste-derived GO in membrane production.	Environmentally friendly materials	[82], [83]
Antibacterial Properties	Development of membranes with antibacterial and self-cleaning properties using antimicrobial agents (e.g., silver nanoparticles) or bioactive surface functionalization.	Prevention of contamination and biofouling	[84]–[86]
High-Performance and Multi-functional Membranes	Creation of membranes with the ability to perform multiple functions (e.g., filtration, desalination, resource recovery) and integrated sensing capabilities for real-time monitoring and dynamic adjustments.	Multi-tasking (e.g., filtering, desalination, resource recovery)	[79], [87]

With the ongoing technological advancements in 3D-printed membranes, market trends are starting to showcase the growing interest and demand for more efficient, sustainable, and economical filtration solutions. The escalating severity of global water scarcity and pollution issues resulted in a growing need for sophisticated filtration technologies capable of effectively eliminating pollutants and contaminants. The market for 3D-printed membranes is particularly strong in industries such as water treatment and filtration, where the demand for these membranes is driven by the need for cost-effective, tailored solutions and sustainability factors. 3D printing offers a way to create membranes with tailored properties (e.g., pore size, surface texture) [4, 65] that are optimized for specific contaminants, such as heavy metals, bacteria, or organic compounds. This customisation offers a significant advantage over traditional membrane manufacturing techniques, which frequently yield generic, one-size-fits-all solutions. The biomedical market demonstrates significant potential for 3D-printed membranes, especially in applications such as drug delivery systems, wound healing, tissue engineering and various biomedical products like implants and prosthetics [78]. As the demand for personalized healthcare solutions grows, 3D-printed membranes are expected to play a crucial role in this evolution. Another emerging market is in energy storage systems, where membranes are used in batteries, fuel cells, and supercapacitors. The utilisation of 3D printing enables the design of advanced electrodes and separators that improve energy efficiency and overall performance. Moreover, the utilisation of 3D-printed membranes in environ-mental cleanup initiatives, such as addressing oil spills, removing toxins from water, and recovering rare metals from industrial waste, is expected to grow as regulatory frameworks promote more sustainable approaches.

While the potential is vast, the path to commercialising 3D-printed membranes still faces challenges. The cost of high-end 3D printing equipment, the need for specialised materials, and the lack of standardised processes for large-scale production remain significant barriers. However, as efforts continue to drive down costs and improve the efficiency and scalability of 3D printing techniques, it is anticipated that these barriers are expected to decrease. Partnerships among academic institutions, industry leaders, and public sector organisations will play a critical role in accelerating the adoption of 3D-printed membranes by fostering innovation, lowering manufacturing expenses and creating supportive regulatory frameworks.

CONCLUSION

This paper explores the potential of 3D-printed antibacterial membranes using waste-derived graphene oxide (GO), highlighting their superior performance and sustainability benefits. By incorporating GO into 3D printing, these membranes offer enhanced mechanical strength, antibacterial properties, and filtration efficiency, addressing the need for more effective and sustainable filtration solutions. Using waste-derived GO is environmentally and economically beneficial, reducing reliance on virgin materials and promoting a circular economy. This aligns with the growing focus on sustainability in industries like water filtration, biomedical applications, and environmental remediation. 3D printing provides cost advantages over traditional methods through on-demand production, material waste reduction, and rapid prototyping. Although initial costs may be high, long-term efficiency gains make it a promising alternative for scalable membrane production. The antibacterial properties of these membranes are particularly valuable in preventing biofouling and microbial contamination in water treatment and healthcare. As research advances, integrating graphene oxide with other antimicrobial agents will expand their applications and performance. In conclusion, 3D-printed antibacterial membranes made from waste-derived graphene oxide offer cost-effective, sustainable, and high-performance solutions for a range of applications. With ongoing advancements, these membranes hold the potential to transform filtration technologies, driving more efficient and innovative solutions in the future.

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