Current Water Purification Technology and Role of Materials Modification: A Review

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***Abstract*—Water scarcity and water pollution are core global environmental problems. This paper introduced the current water resource shortage and water environment problems worldwide, exploring various purification methods and water pollution treatment materials. Given such circumstances, purification technology is the primary way to address these two problems. The primary technical methods for water environmental pollution and the corresponding water purification materials were further delved into, with detailed introductions of adsorption, membrane separation, and precipitation technologies. Additionally, nanomaterials and activated carbon materials were discussed, identifying them as promising and worthy of further development for water purification in the future. The results of this research are of significant importance in providing foundational information for further future water purification research.**

***Keywords*—water purification technology, purification materials, material modification, nana materials**

I. Introduction

With the escalating development of worldwide industry and increasing human population, the problem of water scarcity and pollution has attracted long-term public concern. Fresh water only takes up 3% of the whole water body on earth. Lakes and rivers only make up 0.3% of all. Furthermore, approximately 30.1% of fresh water is stored underground, and the overuse of groundwater has become an environmental issue. Over the past 40 years, global water usage has continued to increase at the rate of 1% per year. Currently, there are about 2 to 3 billion people worldwide face water scarcity [1]. Moreover, approximately 2 billion people need more chances to access safe drinking water. Consequently, it assumes paramount importance to ensure people's secure access to fresh water and keep them away from pollution.

In addition to the water resource shortage, people also face the increasingly severe global water pollution problem. At present, water pollution has become a universal global environmental problem. The accumulation and transport of pollutants in water threaten the health of humans and wildlife. Despite the general release of elements and organic substances into aquatic environments from natural origins, human activities, particularly in industry and agriculture, are the dominant causes of water pollution. In many countries, due to the sewage treatment system and the lack of management and supervision awareness, untreated sewage will be directly discharged into nearby lakes or rivers, and accumulating pollutants. In addition, the use of pesticides and fertilizers in farmland will also lead to water pollution. There are various kinds of pollutants in the water, including organic contaminants such as plasticizers and pesticides and inorganic pollutants such as heavy metals and acid-base substances. The increasing concentration of various contaminants in water adversely affects the health of organisms and humans. Due to the urgent need to protect water resources, and improve usage efficiency as well as safeguard the environment, we must address the severe water environment problem.

Water purification treatment is an essential way to solve the problem of water scarcity and pollution. Various biological and synthetically produced materials are usually used in water purification. For example, natural materials, such as algae, bacteria, and other aquatic organisms, can adsorb and convert organic substances into water. Furthermore, artificially synthesized materials such as active carbon and nanomaterials exhibit predominant adsorption properties and can adsorb organic substances and heavy metal ions in water. However, vast differences in purification efficiency were often observed among different materials due to variations in the physical and chemical properties. For instance, an experiment based on algal cathode photosynthetic microbial fuel cells and a novel device called a Rotating Algal Bacterial biofilm (RAB) was conducted by Zhang *et al.* [2]. The ammonia removal efficiencies of the anode and cathode chambers were $91.1 \pm 1.3\%$ and $98.0 \pm 0.6\%$. Biological carbon and algae are effective materials in purifying water pollution, but their removal capacities are relatively low. As for active carbon, the ammonia removal efficiency in wastewater purification was $73.9 \pm 24.4\%$ [3]. The purification efficiency of activated carbon reactors can be affected by various factors such as flow rate, temperature, and pH value. Algal materials have energy recovery properties, but their purification efficiency can be affected by changes in the community structure of algae-loving organisms. Thus, the modification and optimizations of materials are necessary to improve water bodies' purification efficiency.

Based on the research background, the research objectives of this paper are listed below:

1) Summarize the dominant water purification technologies.
2) Elucidate the classification and function of materials in water purification.
3) Analyze different effects of material modification on water purification efficiency.

II. Major Pollutants in Water

Contaminants in aquatic environments can generally be categorized into organic and inorganic pollutants. Inorganic pollutants can be divided into heavy metals such as lead, mercury, arsenic, and acidic/alkaline substances. Heavy metals may harm the growth and reproduction of organisms in the water, and through biological amplification, more advanced microorganisms may also be poisoned. Moreover, acidic and alkaline substances, including sulfuric acid and nitric acid, could cause damage to water quality. These pollutants originating from industrial production will affect the pH of the water body and mar the balance of the aquatic ecosystem. Moreover, the nitrogen and phosphorus compounds that arise from chemical compounds and organic matter in agricultural fertilizers will cause eutrophication of the water body [4], which will lead to a considerable population of algae in the water body, and cause a significant consumption of oxygen in the water body. Additionally, organisms ingest water contaminated with radioactive substances, mainly from nuclear power plant accidents, could increase the risk of cancer gene mutations. Even if people do not consume it, they can be exposed to radiation from outside highly radioactive water sources after prolonged exposure. Lastly, common gaseous pollutants, such as sulfur dioxide and carbon monoxide, predominantly originate from fuel combustion, and motor vehicle emissions contribute to environmental issues like acid rain and atmospheric precipitation. This process, directly or indirectly, leads to the acidification of water bodies and other significant harmful environmental impacts. Organic pollutants can be classified into two categories: easily degradable and non-degradable. The easily decomposable contaminants include proteins, sugars, and fats, which are usually produced by the metabolism and decomposition of organisms. The less decomposable organic substances include persistent organic pollutants such as Polychlorinated Biphenyls (PCBs), Polychlorinated Dibenzo-P-Dioxins (PCDDs), and high molecular weight organic substances such as plastics and synthetic rubber. The variety of pollutants emphasizes the research of water purification technology.

III. Current Water Purification Methods

Due to the diversity of pollutants in water bodies, specific optimal purification methods are tailored for each type of pollutant. Among them, biological treatment techniques are often used to remove inorganic contaminants such as heavy metals from decomposed sewage. For example, the high adsorption properties of proteins are used to adsorb heavy metal ions in water. Moreover, oxidation treatment can also treat industrial wastewater rich in various inorganic substances. In the treatment of pulp wastewater, a 70.5% COD reduction and an 80% TSS reduction were achieved using an optimal 0.75 g/L TiO_2 dosage at pH 6.5, significantly lowering the initial concentrations from 2075 mg/L for COD and 1165 mg/L for TSS [5]. Besides, distillation, adsorption, precipitation, and filtration are physical methods usually used in the first step of the preliminary sewage treatment. To remove inorganic compounds from the water, chemical treatment is commonly used to remediate water pollution. Chemical treatment converts or breaks down organic contaminants in water to produce a more stable, simpler substance. For instance, by utilizing electrochemistry and sedimentation Electro-Flocculation (EC), a study on model wastewater with an iron electrode showcased a 43% reduction in organic matter (as indicated by the COD index), a 62% decrease in turbidity, an 81% reduction in suspension concentration, and a 51–58% decrease in phosphorus concentration [6]. Additionally, when applying membrane separation technologies like Nanofiltration (NF) and Reverse Osmosis (RO) for sewage treatment, organic matter such as Fluoxetine (FLX) can be effectively removed. Specifically, NF can eliminate 50–60% of FLX, whereas RO can remove up to 98.8% of FLX [7]. In the following section, we will provide a brief introduction to various common techniques and methods used for water purification.

A. *Adsorption*

Among all the treatment methods, adsorption is the most frequent way to remove aquatic pollutants. Adsorption is a physicochemical separation technique for dissolved contaminants. Adsorption can be divided into physical adsorption and chemical adsorption. Physical adsorption, caused by electrostatic interaction, is a relatively weak and multilayer phenomenon. The surface area, temperature, pressure, and properties of the adsorbate affect the efficiency of physical adsorption. Chemical adsorption is caused by the Chemical bond Van der Waals' force, which is a more robust process and is almost a monolayer phenomenon. Chemical adsorption usually occurs at the centre of the reactant due to its characteristics. Similarly, the surface area, temperature, and the properties of adsorbate also affect the efficiency of chemical adsorption. In the role of physical adsorption, it often acts to remove organic substances and heavy metal ions in water. In previous studies, active carbon is the most used adsorbent in physical adsorption. [8] The Langmuir monolayer adsorption capacity of activated carbon from reed grass activated with H3PO4 is 56.82 mg/g. The adsorption energies calculated by the Dubinin-Radushkevich (EDR) model before and after activation are 0.50 and 2.24 kJ/mol, respectively. When used to purify humic acid, an organic substance in water, the increased adsorption energy means an increase in the physical affinity of humic acid to the active sites of the adsorbent. As a result, active carbon exhibits strong adsorption capacity. In the study of high surface area active carbon prepared from walnuts, the concentration of methylene blue decreased from 6 ppm to 0.184 ppm after three applications and the removal rate of methylene blue reached 96.93%. The result reveals the high efficiency and environmental friendliness of the physical adsorption method. Physical adsorption can use renewable resources as the preparation materials for adsorbents. However, physical adsorption may be affected by conditions such as pressure and pH value. In applying the chemical adsorption method for wastewater purification [9], the polyamide covalent polymer CPCMERI-2 demonstrated notable hydrophilicity due to its wealthy electronic groups, and its primary secondary amine (-NH) groups show a strong affinity for certain acidic gases. It exhibited a CO_2 absorption capacity of 11.5 cm^3/g under a high-pressure (1 bar) environment and 20.7 cm^3/g under a low-pressure (0.3 bar) environment.

The chemical adsorption method has the advantage of solid adsorption because chemical adsorption involves forming chemical bonds, making the adsorption process more stable and the adsorption energy considerable. Furthermore, because chemical adsorption involves chemical reactions, the reaction has a more robust selectivity for adsorbates so that chemical adsorption can remove specific pollutants. We cannot control whether a substance is a chemical or physical adsorption. Still, after comparing these materials, we need to combine the physical and chemical enhancement of these materials. After reaching these materials, it is essential to recognize that while active carbon is a prominent adsorbent, its efficiency can be limited by factors such as flow rate, temperature, and pH value. Therefore, considering the physical and chemical enhancement of these materials, a nuanced approach involving the specific nature of the contaminants and the water source in material selection and application is necessary.

B. Membrane Separation Technology

Membrane separation technology is a method used in water purification that involves the use of specially manufactured membranes with selective transmission functions to separate, purify, and concentrate pollutants in mixtures. This technology operates by selectively separating mixtures of molecules of different sizes at the molecular level as they pass through a semi-permeable membrane. Notably, membrane separation can be used to separate various types of gas mixtures, as well as to separate liquid components into gas in two-phase separation and to isolate solids from liquids or dilute solutions [10]. There are six main types of membrane separation technology, including microfiltration, ultrafiltration, nanofiltration, reverse osmosis, electrodialysis, and pervaporation. Microfiltration, which sorts particles with diameters ranging from 0.1 to 0.2 μm, is typically applied in the final processing of ultra-pure water. Nanofiltration, on the other hand, is commonly utilized for water softening and wastewater decolorization. Besides these specific applications, ultrafiltration is recognized for its high retention performance for organic substances with molecular weights between 200 and 1000, as well as both high and low-valued inorganic substances.

The membrane separation techniques commonly used in various industries are reverse osmosis, ultrafiltration, electrodialysis, and pervaporation. Reverse osmosis is a method used when only the solvent needs to pass through. It employs a semi-permeable membrane for separation. Ultrafiltration, with a separation fraction diameter of 0.005~10 μm, can achieve membrane separation processes ranging from ions to particles when used in conjunction with reverse osmosis and microfiltration, positioning it between the two methods. Electrodialysis operates by using ion-exchange membranes to separate electrolytes in a solution under a direct current, forming a potential difference. On the other hand, pervaporation relies on differences in solubility and diffusion coefficients in liquids, achieving separation through permeation and evaporation. These membrane separation techniques are widely used in the food industry, pharmaceuticals, and other fields, bringing substantial convenience to modern industry and daily life [11].

Membrane filtration technology has emerged as the most widely utilized method due to its chemical and thermal inertness, as well as its regeneration techniques. This technology is commonly applied in the treatment of industrial wastewater, facilitating the physical separation of larger and smaller volume substances. In the case of treating Palm Oil Mill Effluent (POME), membrane technology offers significant advantages over traditional aerobic and anaerobic methods, with a much shorter processing time of three days, compared to the 27 to 40 times longer duration required by conventional methods. Notably, hollow fiber membranes with molecular weights ranging between 30k–100k have demonstrated remarkable potential in treating POME, achieving a substantial reduction in COD, TSS, TKN, and ammonia nitrogen levels by 97.66%, 98.00%, 53.85%, and 61.91%, respectively. The efficiency of membrane separation technology is further underscored by the high mechanical performance of rubber-based membranes, which can be augmented by incorporating natural fibers as fillers and pore formers. Despite these advantages, a prevalent limitation in the application of membrane separation is the inevitable contamination caused by the sedimentation of pollutants which adversely impacts its lifespan. Moreover, the need for self-cleaning and the challenges associated with regular cleaning and membrane replacement present additional obstacles. [12] Furthermore, the adaptable nature of membrane separation technology and the potential of Thermoplastic Elastomers (TPE) in enhancing water separation performance is evident in the research conducted by Gao (2016) [13].

C. Precipitation

Precipitation plays a significant role in water pollutant treatment, with two main categories: physical and chemical. Physical precipitation uses gravity and porous media to separate the solid sediment, employing filtration, sedimentation, or flotation methods that utilize the physical properties of contaminants to separate them. On the other hand, chemical precipitation aims to change the form of pollutants dissolved in water into solid particles, primarily targeting the removal of metal ions and phosphates from the water. Both physical and chemical precipitation are of significance in sewage treatment.

In the treatment of heavy metal wastewater, chemical precipitation is a valuable and straightforward technique. This method involves the addition of reagents to convert the soluble heavy metal ions into insoluble hydroxide and carbonate, thereby precipitating them. For instance, when using magnesium hydroxyl carbonate to treat heavy metal wastewater, the initial concentrations of various heavy metal ions are as follows: VO2+: 0.21 g/L, Cr3+: 0.04 g/L, Fe3+: 1.04 g/L, Mg2+: 0.21 g/L, and TiO2: 0.01 g/L. Upon the addition of 0.30 g of magnesium hydroxyl carbonate, the reaction efficiency notably increased, leading to complete precipitation within 20 minutes. After treatment, the concentrations of VO2+, Cr3+, and Fe3+ in the wastewater were reduced to 0.01, 0.05, and 1.12 mg/L, respectively, with a pH value of 7.1. The composition analysis of the precipitate indicated that 53.98% of it comprised Fe_2O_3, demonstrating effective precipitation of Fe during treatment. Furthermore, the presence of seven other substances in the precipitate underscores the effectiveness of hydroxy-magnesium carbonate as a precipitant.

Chemical precipitation is widely recognized as one of the most effective methods for treating industrial wastewater. Particularly, the aluminum-calcium sulfate precipitation method is relatively cost-effective and boasts a high removal efficiency of ions in water, making it an undeniable benefit. However, it is important to note that in some cases, certain chemical reactions used in this process may result in lower output. Therefore, although chemical precipitation remains an effective method, its application and outcomes should be carefully considered based on the specific industrial wastewater composition and treatment goals.

IV. Materials for Water Purification

The efficiency and effectiveness of water purification can be significantly influenced by the materials utilized, with a prime example of activated carbon, the most commonly used material in water purification processes. The adsorption capacity of activated carbon is primarily dependent on the size of its pores that give activated carbon a large surface area. This large surface area enhances the material's ability to adsorb organic matter, thus contributing to the improved efficiency of sewage purification. Therefore, the choice of materials in water purification processes plays a crucial role in determining the overall effectiveness of the purification process.

Water purification involves a wide range of materials that can be tailored to target different pollutants and treatment goals. The materials can be classified into different categories based on their physical and chemical properties. Porous materials, which function with a porous structure can absorb pollutants and remove pollutants from water. In addition, biological materials constitute another category, utilizing microorganisms to decompose pollutants. Furthermore, photosensitive materials also play a role in leveraging their optical properties to eliminate microorganisms in water, with ultraviolet light being a commonly used example. Each category of materials serves a specific purpose in water purification, making the selection of appropriate materials crucial for effective treatment.

Materials for water purification can be classified into various categories based on their chemical reaction capacity, mineralization capacity, and ion exchange capacity, in addition to their primary origin rather than their physical and chemical properties. The two primary categories of water purification materials include synthetic materials, which are manufactured artificially, and biomaterials, such as algae, microorganisms, and biological enzymes. Some well-known biomaterials used in water purification are chitosan and alginate, whereas activated carbon, polyether sulfone, and titanium dioxide are examples of synthetic materials.

A. *Biomaterials*

The application of biomaterials in water purification primarily entails the utilization of the biological treatment method. This method highlights the biodegradation capabilities of microorganisms and chemical activities to decompose both organic and inorganic pollutants in water, thereby achieving the goal of water purification. Common biological materials used in this process include activated sludge, biofilm, biofilter material, and microbial bacteriological agents. This approach is recognized as an environmentally friendly and highly efficient means of water purification. Various extraction methods are employed to retrieve active substances and microorganisms from different biomaterials. For instance, yeast biomass, present in beer waste, provides a robust resistance to acidity and osmotic pressure. Yeast exhibits versatility in applications, being suitable for organic wastewater treatment, metal adsorption, and conversion of organic matter into non-toxic proteins. Extraction of yeast-derived preparations from beer waste involves centrifugation of the yeast biomass from beer production, followed by freezing the sediment at −18 ℃. Subsequently, a preparation based on yeast biomass autolysis procedure is obtained through graded extraction using aqueous, alkaline, and acidic solutions, along with filtration, precipitation, purification, and drying steps. Furthermore, two types of mannoproteins, namely mannoproteins-LB-MP, and β-glucan-LB-GL, are extracted from the remaining solid residues [14].

In summary, the oxidative decomposition of organic pollutants dissolved in water can be facilitated by leveraging the biochemical properties of yeast preparations. This method harnesses materials that can be derived from waste, highlighting the inherent value of this approach and the potential for biomaterials to be effectively employed in water purification. The practical significance of this application underscores its promise for addressing water pollution challenges.

B. *Synthetic Materials*

The ability of synthetic materials to tailor their chemical structure, mechanical properties, and thermal properties allows for customization to meet specific needs, resulting in products with a range of properties controlled by the synthesis process. For instance, activated carbon, known for its porous structure that enables pollutant adsorption, can be modified by adjusting pore size and surface properties, leading to the creation of various porous activated carbon materials optimized for efficient adsorption and filtration of different pollutants. Furthermore, aside from physical manipulation of pore size, synthetic materials can also modify their chemical properties by incorporating diverse chemical components during the synthesis process, ultimately producing materials with designated adsorption capacity or catalytic activity.

Synthetic materials, such as volcanic rock filters, granular activated carbon, Metal-Organic Frameworks (MOFs) materials like MOF-5, and nanocomposites like CMC/M-nGOX, are widely utilized in water purification due to their versatility, high porosity, and environmental benefits. The preparation of these materials reflects their advantageous properties. For instance, the synthesis of Nitrogen-doped Porous Carbon (NPC) material through Zn-MOF to produce NPC800 illustrates the varied properties exhibited by synthetic materials at different carbonization temperatures. It is worth noting that NPC800 retains the original MOF morphology and pore size after carbonization at a specific temperature and exhibits a high CO_2 absorption of 4.71 mmol/g at 273 K and 1 bar [15]. Synthetic materials are indispensable in water purification due to their ability to be tailored to specific pollutants. However, they also pose inevitable challenges. For example, some synthetic materials such as nanosilver (Ag) particles may lead to secondary pollution by releasing silver ions during usage, potentially harming aquatic organisms. Moreover, the preparation of certain complex materials like Multi-Walled Carbon

Nanotubes (MWCNTs) through methods such as Chemical Vapor Deposition (CVD), Arc Discharge, and Laser evaporation can be economically burdensome. Notably, each method incurs high costs and high-power lasers. Therefore, although synthetic materials have unique advantages and potential in water purification, it is crucial to address the associated challenges in research and application. The synthesis of synthetic materials, particularly MOFs, often requires precise and sometimes costly conditions, incurring high costs and the usage of high-power lasers. This complexity and cost could limit the widespread application of these materials in water purification, especially in resource-limited settings.

Additionally, the long-term environmental impact of disposing of these synthetic materials, which may contain novel chemicals, must be fully understood and pose a potential risk. Notably, each method incurs high costs and high-power lasers. Therefore, it is crucial to address the associated challenges in research and application, despite synthetic materials' unique advantages and potential in water purification.

C. Nanomaterials

Nanotechnology encompasses the manipulation of matter at the scale of atoms, molecules, and supramolecules, typically ranging from 1 to 100 nanometers. This field encompasses various types of nanomaterials, which can be categorized into natural and manufactured nanomaterials. Natural nanomaterials, such as volcanic ash, occur in nature, while manufactured nanomaterials, like car exhaust, are created by human activity. Over the past few decades, nanomaterials have been increasingly used in environmental protection, particularly in water treatment applications, owing to their capacity to effectively remove metal ions and organic pollutants. Consequently, nanotechnology has garnered significant attention, leading to the development of numerous nanomaterials for sewage purification and treatment. This has resulted in the production of filtration membranes, adsorbents, and photocatalysts for wastewater treatment. One significant advantage of nanomaterials is demonstrated by the use of algal synthetic nanoparticles in sewage treatment. For instance, before the application of nanoparticles, levels of Cr, Cd, and Pb in leather wastewater were recorded at 310.1, 210.5, and 75.5 mg/L, respectively. However, by following a 41-day treatment with 1 mg of nanoparticles, the removal efficiency of Cr, Cd, and Pb increased by 54%, 57.6%, and 59.3%, respectively [16], illustrating the high reactivity and strong adsorption capacity of nanomaterials. This exemplifies the cost-effectiveness and sustainability of algal synthesis. The small size and high surface-area-to-volume ratio of nanomaterials contribute to their enhanced reactivity and strong adsorption capacity. Furthermore, their precise reaction surface area and increased surface reactivity to themselves and other systems amplify these characteristics. However, these advantageous features can lead to increased instability of nanomaterials and potential health risks during the manufacturing process. Due to their small size, the risk of inhalation must be carefully considered, especially in the case of materials like carbon nanofibers and nanotubes, which can induce pulmonary fibrosis. Additionally, nanoparticles can enter the body through the intestines and skin of the lungs, potentially resulting in lung inflammation and heart problems. Hence, although acknowledging the advantages of nanotechnology, it is essential to consider the potential risks and ensure the safe handling and disposal of nanomaterials.

V. Modification of Materials for Improving Purification Efficiency

In water purification processes, materials play a crucial role as the central component. The chemical modification of materials can be employed to optimize the performance of water purification materials, thereby improving purification efficiency and making the materials more environmentally friendly and sustainable. A material modification is a technique used to alter the structure and properties of a material through physical or chemical processes, which can occur internally or externally to the material. For instance, physical modification can enhance the adsorption capacity and selectivity of pollutants for activated carbon in water purification materials. On the other hand, chemical modification can alter the surface properties of membrane materials to improve their filtration efficiency and antimicrobial features. In the realm of materials science, material modification is a commonly employed strategy to achieve specific chemical or physical properties, and water purification materials are no exception. Group modification is a widely used technique involving the addition or alteration of specific groups of molecules with distinct chemical properties or combinations of atoms. This type of material modification can impart new physicochemical properties to the material, making it more suitable for various applications. For example, MOFs with open metal sites and functional groups have been found to efficiently remove heavy metals, dyes, and pharmaceuticals. Nevertheless, the use of MOFs for pollutant removal has only gained traction in recent years because early synthesized MOF materials were unsuitable for practical applications; subsequent chemical modifications improved their applicability. Specific group modifications on MOFs can be categorized into four types: pre-synthesis modification, post-synthesis modification, hybridization/carbonization, and pore size adjustment, all of which serve to enhance the adsorption capacity and functional groups of MOFs [17].

Another material modification technique involves adjusting the molecular arrangement on the material's surface, which can be achieved through physical and chemical processes. Unlike group modification, adjusting surface molecular arrangement does not necessarily involve adding new chemical groups; instead, it can entail changing the structure and orientation of existing surface molecules. An example of this is the use of perfluoroacrylate coating on glass substrates to enhance resistance to bacterial adhesion and the antifouling properties of membranes. Another simple and widely used chemical modification method involves adjusting the pH (acid-base) of the material by adding acids or bases, such as sodium hydroxide or potassium hydroxide. This type of chemical modification is crucial for optimizing the efficiency of chemical cleaning and is particularly applicable to water purification methods such as coagulation and flocculation. Additionally, in micelle-enhanced ultrafiltration, surface activation, a material modification technique, is used to enhance the retention of metals in the filtration process and confer a bactericidal effect on the filtration technology. In conclusion, material modification significantly contributes to improving water purification efficiency and enhancing the utility of materials.

While group modification and surface molecular arrangement adjustment offer precise control over material interactions, pH adjustment is a cost-effective and straightforward technique. Each technique has specific advantages and limitations, but they collectively play a crucial role in boosting the performance and efficiency of water purification materials, ultimately improving water quality and safety.

VI. Evaluation of Modification Technology

A. *Evaluation of Modification Technology of Nanomaterials*

After understanding the behaviors of various materials and material optimization techniques in water pollution control, we can see that the optimal purification materials and techniques vary for different contaminants. To achieve better purification efficiency, water purification technology modification and the use of the most suitable materials are the two directions. This is due to the complexity of the water treatment technology selection and optimization process, which relies on the specific water contamination to be treated, the desired treatment outcome, and environmental considerations. Before an optimal choice of materials and technology can be made, we need to consider the type of pollutant, technology competitiveness, and sustainability, the impact on the environment, and even the technology integration. Membrane technology and nanomaterials are frequently used to treat water contaminants, and these materials' physical and chemical properties are often modified to enhance their absorption capacity, removal efficiency, and selective removal of specific contaminants. For instance, after TEMPO-mediated (2,2,6,6-Tetramethylpiperidine-1-oxyl-mediated) oxidation and maleic anhydride esterification of the surface hydroxyl groups, the carbonylated nano cellulose showed higher absorption of methylene blue and cationic dyes similar to crystalline violet, which indicates that organic molecules with different functional groups have different adsorption capacities, i.e., cellulose nanomaterials with ionic and nonionic surface groups can be affected by different functionalized modifications. Different functionalizations can modify the cellulose nanomaterials with ionic and nonionic surface groups to change their surface shape, promoting their adsorption capacity for organic pollutants in water. For heavy metal pollutants in water, the adsorption of metal cations by nanomaterials can be increased largely by changing their surface chemical properties. For C6, carboxylate groups can be formed on the surface of cellulose nanofibers after TEMPO-mediated oxidation (TOCNF). As a function of the amount of metal adsorbed, TOCNF can also adsorb up to 167 mg/g of UO22+ at pH=6.5. Generally, nanofiber materials can show excellent purification performance for organic and inorganic pollutants using different material modifications. Therefore, the nanofiber-material membrane can show adequate adsorption capacity when dealing with organic and biological pollution. Unlike the more popular materials, MF membranes based on nanomaterials showed 16 times higher adsorption capacity than commercial nitrocellulose-based MF membranes when treating positively charged pigments. [18] According to its wide range of application characteristics and the technical comparison with existing technologies, the nanofiber materials were usually applied to various water treatment scenarios after modification and made into a variety of forms, such as membranes and powders. As a new type of water purification material, it shows a new and efficient method of purification, and its potential as a water purification material is demonstrated by the possibility of converting non-potable water into potable water in the future due to the deterioration of the global climate, such as drought-induced water scarcity problems. In addition, since the superior performance of this material has been proved through experiments, how to make it more widely used needs extensive publicity so that the public understands the advantages and potential risks. In addition, among the materials used in nanotechnology, carbon is one of the main elements used as the basis for water purification materials, such as 3D graphene (GBMs), which has an excellent adsorption capacity for both organic and inorganic pollutants. 3D GBMs can be used for various water purification applications. 3D reduced graphene oxide nanosheets prepared by Advanced Oxidation Processes (AOPs) show high catalytic activity in Fenton and photo-Fenton reactions, especially after H_2O_2 activation. The adsorption capacity of the material and the multiphase catalytically active sites were strengthened, and excellent purification results were demonstrated. In addition, the potential application of this material lies in its high efficiency and low cost. For example, the operating cost of 3D sponge@MoS2@GO (SMG) is only $0.33 for treating one ton of antibiotic wastewater by removing 120 mg L 97.87%–1 of antibiotic wastewater [19]. Compared to membrane technology, which generally costs $2.50 per cubic meter (1,000 liters) of water produced, it can be seen that GBMs have a more significant economic effect and more far-reaching commercial value, and the economy in large-scale production and application is very high compared with other materials, especially membrane technology, which requires advanced technology for modification and a shorter life cycle that requires frequent replacement of the material. GBMs can provide a cost-effective and efficient method for water treatment in developing nations, improving water quality for millions. However, the modification of nanomaterials is not without limitations. The safety and potential toxicity of modified nanomaterials, particularly in terms of their interaction with the aquatic environment and human health, remain areas of concern. The complexity of these modifications may not only increase production costs but also raise questions about the long-term environmental impact of these altered materials.

B. *Evaluation of Modification Technology of Activated Carbon Materials*

Activated Carbon (AC), as the most widely used material, has been the subject of several studies demonstrating that chemical and physical modifications can effectively enhance its adsorption properties. Chemical modification stands out as one of the methods that can significantly improve the adsorption capacity of activated carbon. In addition to its wide range of applications, AC is recognized as an environmentally friendly water purification material, prepared from renewable carbon-rich organic materials such as coconut shells, bamboo, fruit shells, and petroleum crumbles. By utilizing these renewable organic materials to prepare activated carbon, the process helps to reduce waste and minimizes resource depletion. Furthermore, the source material used for the preparation of activated carbon influences its characteristics, thus allowing for a wide range of applications tailored to specific needs. The different pore structures and surface chemistry resulting from the use of varied source materials are crucial in determining the efficiency of water purification and the removal of targeted pollutants. Additionally, AC exhibits economic and sustainability advantages over other materials due to its preparation from renewable organic materials, ensuring a more stable supply. In some less developed countries, such as in Africa, the abundance of coconut trees offers the advantage of local resources, further reducing the cost of preparing activated carbon from coconut shells that would otherwise be discarded. In addition to the cost of preparation and sustainability advantages, modifications made to activated carbon can also have significant economic implications. For instance, in a study by Kharrazi *et al.* [20], the thermal tension of powdered activated carbon obtained from lignocellulosic wastes showed a 133% increase in the BET surface area, leading to a substantial improvement in adsorption performance, with a 51.14% and 160.48% increase observed in the adsorption of Cr and Pb, after modification. Notably, chemical modification has been found to considerably enhance the performance of activated carbon. In a study by Sultana *et al.* [21], the treatment of commercial coconut shell-based activated carbon with 35 wt.% HCl for 24 hrs. resulted in the formation of oxygenated complexes on the surface, leading to a 1.7-fold increase in the adsorption of chromium (VI). This demonstrates the significant effect of modifying functional groups on the water purification efficiency of activated carbon. In conclusion, despite the availability of various materials for water purification, the popularity and extensive use of AC persist. Furthermore, the significant enhancement of its water purification efficiency through various modification methods further underscores the importance of activated carbon in the field of water treatment. Considering the chemical modification of activated carbon is important, as it can affect its stability and regeneration capacity. While chemical modifications can be effective, they may also compromise the carbon's ability to be regenerated, potentially impacting its long-term usability and cost-effectiveness. This aspect is especially pertinent in large-scale water treatment applications, where the durability and cost of the material are key considerations.

C. Comprehensive Comparative Evaluation

A comprehensive comparison of Activated Carbon (AC) and nanomaterials reveals their respective advantages and limitations. In terms of preparation and source, AC materials have a simple preparation process that utilizes raw materials from a wide range of sources, with the carbonization and activation steps being relatively straightforward. Conversely, the preparation of nanomaterials necessitates advanced technology and equipment to control size and structure. For instance, graphene can be manufactured through chemical vapor deposition and mechanical exfoliation, requiring specialized raw materials and precursors, and limiting availability. Both materials have demonstrated promise in material modification, as both AC and nanomaterials can be surface modified to increase functional groups or alter pore structure, thereby improving water purification efficiency. When considering sustainability, AC materials can be easily regenerated by heat treatment, while the regeneration of nanomaterials is challenging due to their small size, resulting in the need for immobilization in purification systems, reducing reusability. Economically, AC has an advantage in terms of low cost, as it can be prepared from relatively inexpensive waste materials, while nanomaterials tend to be more costly to prepare. Furthermore, AC is generally considered to be safe, whereas nanomaterials pose health and environmental risks due to their size, potentially leading to secondary contamination of the environment during water purification. Activated carbon is a well-established and widely used technology with proven adsorption capacity, particularly for inorganic substances. On the other hand, nanomaterials, a relatively new field, show great potential for water purification, especially when surface control at the nanoscale allows for greater customization. Considering practical application, the weight of removal efficiency and processing speed largely determines material utilization, and the removal efficiency of specific pollutants in specific cases is crucial. However, enhancing removal efficiency may compromise other properties, such as the permeability of polymer membranes when increasing selectivity or even vulnerability to contamination and low chemical stability of defects. Additionally, the economics of the material, including technology cost, equipment replacement, and maintenance, must be considered. For instance, although membrane materials display high purification efficiency, frequent replacement due to bacterial growth increases maintenance costs, hindering their widespread application. The complex modification technology of membrane materials further restricts scalability and adaptability to diverse needs. As a result, a comprehensive evaluation of water purification technology and material modification must consider multiple factors to assess their effectiveness for practical applications and sustainability.

VII. CONCLUSION

This manuscript introduced the types of pollutants found in water, including heavy metals, acidic and alkaline substances, nitrogen and phosphorus compounds, radioactive materials, gaseous pollutants, and both easily decomposable and resilient organic substances. These pollutants are significant in light of the global scarcity of water resources and the challenges posed by water pollution. This work also discussed prevailing water purification technologies, encompassing adsorption, membrane separation, and precipitation. Furthermore, adsorption and precipitation are categorized into two primary types: physical and chemical processes. Membrane separation is further subdivided into microfiltration, ultrafiltration, nanofiltration, reverse osmosis, electrodialysis, and pervaporation. Additionally, the materials employed in water purification are broadly classified into biological and synthetic materials. To enhance the efficiency of water purification, this article evaluated modification techniques for various materials, especially focused on surface molecular arrangement adjustment and the addition of supporting groups. It specifically assesses the modifications of nanomaterials and activated carbon. This article estimated different methods in terms of water purification efficiency, economic viability, and the complexity of the modification techniques, and concluded by suggesting that nanomaterials and activated carbon hold the most promise for future advancements in water purification technology. The results of this research are of significant importance in providing foundational information for further research on water purification in the future.

In conclusion, it is imperative to recognize the significant promise demonstrated by nanomaterials and activated carbon in water purification. However, rigorous evaluation of their scalability, cost-effectiveness, and long-term environmental impacts is essential. Moreover, future advancements in water purification technology should take into account the evolving nature of water pollutants, which are influenced by industrial advances and climate change. This consideration is crucial for ensuring the continued relevance and effectiveness of these technologies.

Conflict of Interest

The author claims that no conflict of interest exists.

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