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REVIEW

The Green Approach of Arabic Gum-Based Adsorbent in Wastewater Treatment

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ABSTRACT

The natural polysaccharide Arabic gum is a multifunctional, sustainable material used widely in wastewater treatment technology. Its active functional groups such as hydroxyl, carboxyl, and amino groups facilitate the efficient removal of heavy metals, dyes, pesticides, pharmaceuticals, and persistent organic pollutants. The high surface area and active functional groups facilitate its modification to form various structures such as hydrogels, nanocomposites, or biochar integrated into hybrid adsorption–photocatalysis systems. This review highlights the most familiar forms of Arabic gum in wastewater treatment technology, such as hydrogels, hydrogels nanocomposite, stabilizing agents, coating agents, and bio-activated carbon derived from Arabic gum using different preparation methods. Furthermore, this review outlines the application of Arabic gum as a photocatalyst for the degradation of different pollutants.

Keywords: Arabic gum, Adsorption, Wastewater treatment, Nanocomposite, Hydrogels, Coating agent

1. Introduction

Water is known as a "universal solvent," that can dissolve more substances than any other liquid on Earth. One of the most precious possessions of nature to humanity is the freshwater found in our plants, which drives much of the global economy. Water availability is essential for many aspects of life, including agriculture, human consumption, and industry. However, the rapid growth of industrial technology has made the ongoing depletion of water resources worldwide a serious issue [1].

Unwanted items that are harmful to the environment and public health find their way into water, causing pollution. Meanwhile, human activity is the primary cause of water contamination that makes the environment get more and more polluted due to the rapid expansion of the human population, industry, and agriculture fields. Numerous activities, including oil spills, sewage leaks, and home, industrial, and agricultural wastes, can contaminate water supplies. Untreated sewage discharge into rivers causes an instantaneous decrease in the water's dissolved oxygen content, which has a detrimental effect on aquatic life. As a result, water pollution harms the health of people as well as plants and animal's nutrition [2].

There are numerous ways to manage water contamination on a better scale. This needs to begin with our obligations to the environment by regulating and treating sewage waste discharge into water bodies rather than discharging it without controlling way. By following this approach, the original toxicity can be decreased, and the water body itself can break down and render any leftover toxins harmless. Moreover, agricultural fields and sanitary systems can repurpose the water generated by the secondary treatment by using it alone or in concert with other therapeutic methods to break down hazardous dyes, metal ions, and pharmaceutically active substances.

Many treatment methods, including coagulation/flocculation, electrochemical, adsorption, ion exchange, membrane filtration, biological degradation, sedimentation, and electro-precipitation, have historically been employed. All of these techniques, however, failed to produce the intended level of purification because of a variety of issues,

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including inefficient removal rates, high power requirements, expensive chemicals and equipment, high maintenance costs, convoluted processes, and secondary pollution sources. Therefore, an economically friendly approach with a high capacity for removal had to be devised for wastewater purification [3].

Once the industrial barriers to the traditional treatment techniques have been identified, efforts are ongoing to develop more widely accepted approaches. Consequently, sophisticated Oxidation Processes (AOP) were discovered and have been thoroughly studied for their ability to destroy a variety of organic contaminants using a range of energy sources. The basic idea behind AOPs is the generation of strong oxidants called hydroxyl radicals, which are then employed to break down pollutants and produce H_2O and CO_2 as byproducts. A few instances of AOPs are electrocoagulation, Fenton's reagent, sonolysis/sonocatalyst ozonation and photocatalysis/photocatalyst, etc [4].

Nowadays, creating green environment plans using green chemistry is of utmost importance to the entire world. The tenets of green chemistry advocate using environmentally beneficial, low-cost, natural, nontoxic materials with minimal energy usage in place of dangerous and poisonous substances. Therefore, sustainable renewable technologies are a desirable substitute for conventional physical and chemical approaches [5].

Recently, natural biopolymers come from renewable resources like plants, algae, microbiological biomass, and animals. These biopolymers are made up of monomeric components that are covalently bound to form bigger molecules. The unexpected structural and physical characteristics of natural biopolymers include safety, affordability, biocompatibility, and biodegradability, all of which can improve their use as nanocatalysts and nanosorbents [6]. Numerous sustainable natural biopolymers are employed in the water treatment process. Such as chitin/chitosan [7] cellulose [8] starch [9] pectin [10], alginate [11], guar gum [12] xanthan gum [13], and Arabic gum [14].

Acacia gum, sometimes referred to as Arabic gum (Sengalia Senegal), is made mostly in Sudan from a variety of acacia tree species. Arabic gum is a sophisticated blend of polysaccharides and glycoproteins that is utilized in a variety of applications, including water treatment and food processing [15]. Moreover, Arabic gum and its modified derivatives are widely utilized in many other sectors. Numerous studies aimed at altering the structure of Arabic gum to satisfy industrial demands have been published. The most widely used chemical processes for modifying Arabic gum were grafting and cross-linking, which produced hybrid versions of raw gum that could be used in a variety of ways [16].

Arabic gum is widely used in many different applications, including the food industry, flavor encapsulations, soil conditioning, plant growth promotion, synthesis and stabilization of nanoparticles, green electrospinning, textile, cosmetic, and pharmaceutical industries, as a binder for watercolor painting, and adhesive formulations for postage stamps [17].

The objective of this review is to critically evaluate the potential of Arabic gum as a green eco-friendly biomaterial having multifunctional active groups applied in wastewater treatment processes. Specifically, it aims to (i) summarize its chemical composition and inherent physicochemical properties, (ii) highlight recent advances in its modification into diverse functional forms such as hydrogels, nanocomposites, biochar, stabilizing and coating agents, and photocatalysts, (iii) asses the effectiveness of new photocatalytic materials through the modification with Arabic gum to design superior adsorption-photocatalytic system applicable in environmental remediation.

2. Chemical composition of gum Arabic

Arabic gum or gum acacia is Natural gum obtained from acacia trees (See Fig. 1). Acacia gum has two main types i.e. Acacia senegal gum and Acacia seyal gum, that are approved for use. Both are hyper-branched polysaccharides rich in arabinose and galactose, or PRAG. They are generally composed of side chains of 3-linked alpha-L-Araf that are substituted at position 6 in chains of 3,6-linked beta-D-Galp. In spite of their similar structure, these two gums differ significantly in terms of their sugar and amino acid contents, as well as their vastly different molecular weight distributions. However, Acacia seyal gum is less rich in proteins, more compact, more unstable in solution, less charged, less surface active, and less hydrolyzable by enzymes. It is also richer in minerals and polyphenols [18]. Dauqan and Abdullah (2013) reported the international specification of Arabic gum as in Table 1.

Table 1. International properties of gum Arabic [19].

Properties			Range
Moisture content (%)			13–15
Ash content (%)			2–4
Internal energy (%)			30–39
Volatile matter (%)			51–65
Optical rotation (degrees)			–26 – –34
Nitrogen Content (%)			0.26–0.39
Cationic composition of total ash (550°C)			
Cu (ppm)	Fe (ppm)	Mg (ppm)	
52–66	730–2490	69–117	

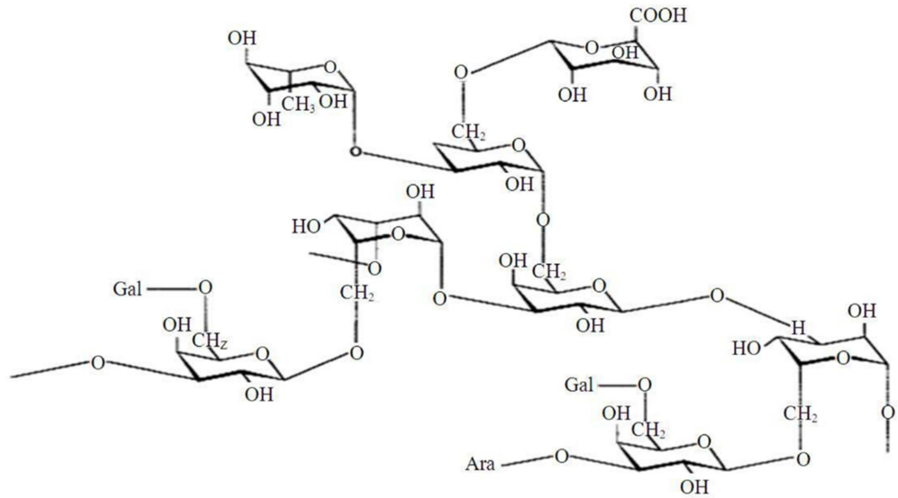

Fig. 1. Chemical structure of Arabic gum.

Arabic gum can be found in nature as a polysaccharidic acid (Arabic acid) combined with calcium, magnesium, and potassium salts. Aspartic acid was the most prevalent amino acid in Glyco Protein (GP), but hydroxyproline, serine, and proline were the amino acid groups found in the proteins of Arabino-Galactan (AG) and Arabinogalactan-Protein Complex (AGP) [19].

On the other hand, three parts of Arabic gum's molecular structure have been established via hydrophobic interaction chromatography (HIC). The first portion has no amino acids with spherically branching structure and molecular weight about 250.000. The second segment has a molecular weight of approximately 1,500,000 with around 10% of protein. Meanwhile, the five spherical carbohydrate lobes with a molecular weight of approximately 250,000 are most likely linked to a typical polypeptide chain where serine and hydroxyproline are the primary amino acids. The third segment is heavily compressed contains 20% to 50% protein with a molecular weight of roughly 200,000 [20]. Extra functional groups like COOH and -OH groups found in the monosaccharide units of Arabic gum can be added to the macromolecule's structure and characteristics to improve it for a variety of industrial applications [21].

Arabic gum is water soluble either in cold or hot water up to 50% and can create gels and emulsions because of its hydroxyl groups. It is an effective thickening and binder due to the long chain molecules. The molecular structure and biochemical content of GA can vary depending on its source, the age of the trees it was taken from, the seasons, and the soil environment. Furthermore, conditions such as storage locations, times for maturation, filtration, homogenization at high pressure, spray drying, radiation, or heat treatments were applied following the harvesting procedures [22].

There are several chemical reactions that gum Arabic can go through, such as grafting, derivatization, and cross-linking (see Fig. 2). Through these processes, gum Arabic chemical and physical characteristics can be improved, opening up new application opportunities. Gum Arabic can have its qualities improved and its applicability expanded through a variety of chemical treatments. As a result, numerous hybrid variants with distinctive qualities have been

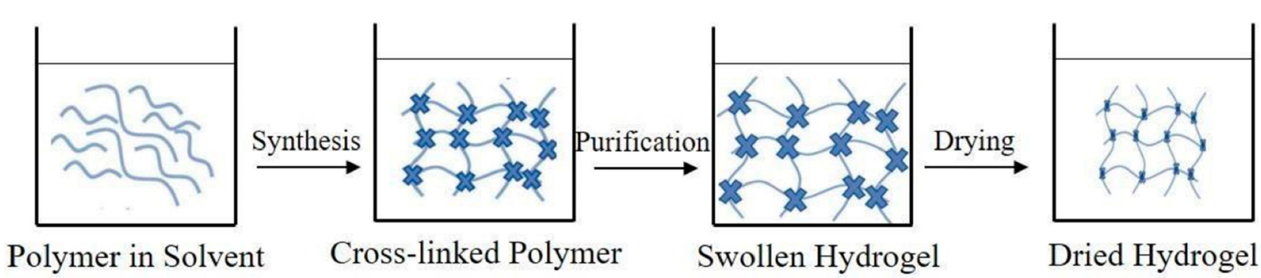

Fig. 2. Steps of hydrogel synthesis.

created and are now being used in a wide range of sectors [23].

3. Arabic gum as adsorbent

Many types of low-concentration, non-degradable organic contaminants can be removed from wastewater by the adsorption process through the purification or separation method. Numerous natural, biological, physical, and chemical systems can benefit from the use of the adsorption process since the contaminant is transferred from the liquid phase to the surface of solid matter. The adsorbent can undergo two different types of adsorption processes i.e. chemisorption and physisorption [24].

Generally, the adsorption process affected by several factors including the affinities of the pollutant towards the adsorbent, the surface characteristics of the sorbent, and the adsorption mechanism between the functional groups of the pollutant and the sorbent. Consequently, the adsorption endpoint is governed by the chemical characteristics of the adsorbent surface and the nature of the interactions between its active sites and the adsorbate [25]. Several kinds of bonds that are created between the pollutant and the adsorbent are shown in Fig. 3 which is ascribed to chemical or physical adsorption.

Arabic gum's structure can be altered by several methods, including cross-linking with other polymers, interacting with chemicals, emulsifying with proteins and polysaccharides, compositing and blending, drying and molding, nanosizing, microencapsulation, and electrospinning. The desired qualities of the finished product will determine which modification procedure is selected. For example, cross-linking might be a wise decision if the objective is to enhance the mechanical qualities of Arabic gum. Furthermore, if the objective is to produce a novel material with distinct characteristics, electrospinning or nano-sizing may be a preferable choice [26]. Another example includes the modification of Arabic gum structure to overcome the main drawbacks of its hydrophilic properties with high solubility in water up to 43–50% w/v in cold water [27]. Therefore, efforts continue to enhance the chemical structure of Arabic gum through the addition of specific compounds to the polysaccharide structure.

On the other hand, to get the intended outcomes, the operating conditions for each modification process must also be closely monitored. For instance, while cross-linking Arabic gum, the reaction's pH and temperature must be carefully regulated. Careful control over the concentration of the polymer or chemical used to alter Arabic gum is also necessary

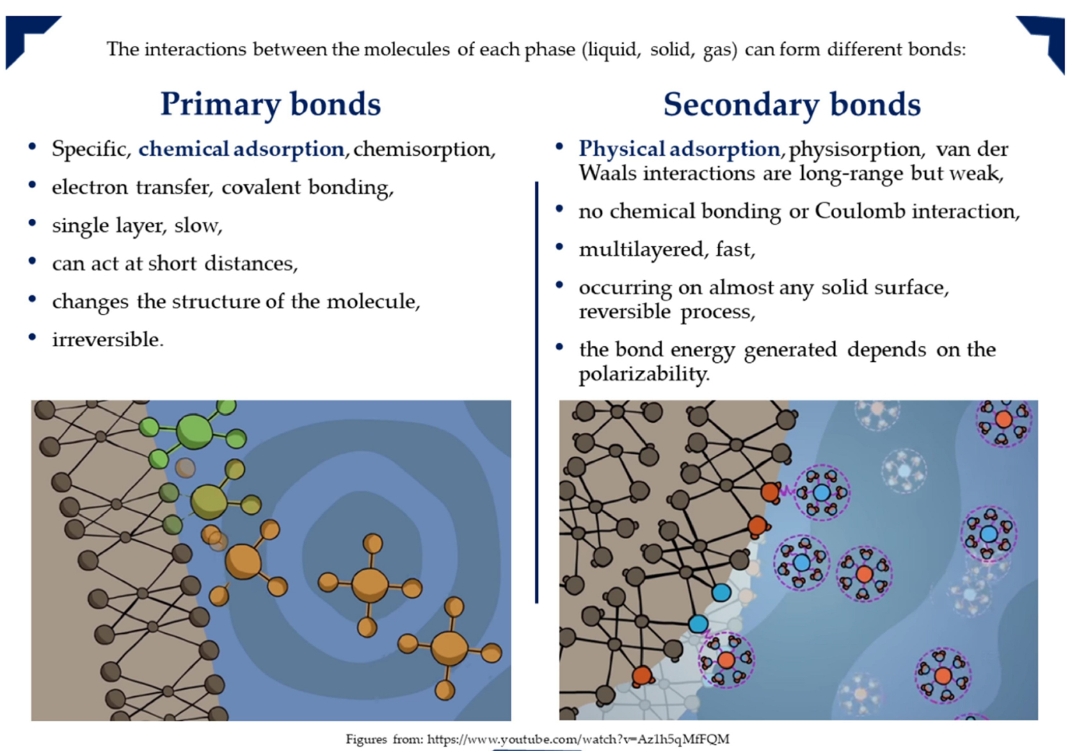

Fig. 3. Types of adsorption bonds and nature of adsorption.

[28]. Table 2 lists the potential structural changes that could be implemented for Arabic gum to increase its adsorbent capacity and improve the cost.

A study of the physicochemical characteristics of gum arabic mixed with carboxymethyl cellulose and cassava starch was published by Joseph et al. (2022). The findings demonstrated that gum arabic can be blended with carboxymethyl cellulose and cassava starch to raise its moisture content, pH, and ash content. The moisture content and certain ash content values were found to be within the WHO/FAO guidelines for gums, which state that they should not exceed 15% and 2-4%, respectively. The results also showed that swelling index and viscosity increased when gum arabic and carboxymethyl cellulose were blended, but these variables decreased when cassava starch was blended in. These findings imply that mixing gum Arabic with cassava or carboxymethyl cellulose as a modification technique can customize the characteristics of gum Arabic for particular uses, as well as lowering the cost since cassava starch and carboxymethyl cellulose are less expensive than gum Arabic [29].

On the other hand, gum arabic (GA) and magnetic nanoparticles (MNPs) were combined using the co-precipitation method by Birniwa et al. (2022) to create gum arabic magnetic nanoparticles (GA-MNPs), as an effective adsorbent for the removal of ciprofloxacin (CIP) from aqueous solution. The morphological analysis revealed that GA and GA-MNPs have smooth surfaces, this implies that after coating with GA, the agglomeration shrank. In the meantime, the FTIR data shows that GA and MNPS successfully interacted through the creation of hydrogen bonds between them. The produced adsorbent (GA-MNPs) showed high efficiency for the removal of CIP from aqueous solution and good reusability which make it easy to prepare on a large scale and financially viable for commercial production [30].

4. The functions of Arabic gum

4.1. Arabic gum as biochar

Waste biomass is now recognized as a valuable source of raw materials for the production of biochar and other products. The process of creating carbon absorption, also known as biochar, transforms the carbon in biomass sources, such as wood chips, plant remnants, manure, or other agricultural waste products, into a more stable form. The set of solid byproducts that remain after any carbon-containing material has undergone chemical or thermal conversion is referred to as “black carbon” [38].

The majority importance of biochar refers to its two primary benefits: First, the synthesis of biochar can offset greenhouse gas emissions because it stores carbon in a stable form and prevents greenhouse gases from getting released into the environment during the decomposition of biomass. Second, biochar is an economical, safe for the environment, and efficient adsorbent due to its large surface area and abundance of surface functional groups. Biochar can be added to soils to increase crop productivity and soil fertility. It can also be used to filter water, adsorb metals and metalloids, and function as a catalyst to lower greenhouse gas emissions. It can also be utilized to partially replace fossil fuels and provide sustainable energy. As a result, biochar becomes more important as a solution for various global problems [39].

The production of activated carbon from bio-natural materials produces material with high

Table 2. Arabic gum modified various materials as adsorbents for different pollutants.

Process	Finding	Ref.
Complex formation of chitosan nanoparticles with gum arabic (GA) as binding agent	The removal efficiency was evaluated as a function of NP composition and polysaccharide concentration.	[31]
Nanofiber of poly(vinyl alcohol) PVA /gums (GA, GK, and KG) via electrospinning procedure	(-OH),(-C-O) (-COOH) present in the nanofiber surfaces enhance the adsorption of nanoparticles	[32]
Gum Arabic modified with exogenous phenolic compound	The modification of the gum Arabic structure enhances its antioxidant capacity and its amphiphilic behavior.	[33]
Physical modification (plasticization of gum Arabic with ethylene glycol)followed by modification with PVC	Decrease in tensile strength as the percentage of gum increases.	[34]
Chemical modification of gum Arabic with acid hydrolysis followed by modification with PVC	Water absorption capacity was higher for ACT, PVC matrix was more supported	
Super porous gum Arabic (GA) cryogels were synthesized by crosslinking of natural GA with divinyl sulfone at cryogenic conditions	The successful fabrication of cryogel produce macro-porous structure that results in rapid adsorption of pollutant	[35]
Nanoparticles (NPs) of natural GA (NPGA) and Xanthan (NPGX) and their carboxymethylated forms (NPCMGA and NPCMGX)	The production of NPs with the commercial gums and carboxymethylated derivatives was satisfactory, with good stability due to zeta potential and low particle size,	[36]
Arabic gum-based hydrogel copolymerized with acrylamide	The adsorption capacities of potassium, phosphate, and ammonia were higher by increasing the initial concentrations due to the availability of active sites in the hydrogel network, nutrient size, and ionic charge.	[37]

porosity and large surface area (600–2000 m^2g^{-1}) [40]. Numerous methods exist for activating carbon derived from natural sources, such as gasification, hydrothermal carbonization, slow- or fast-pyrolysis, and torrefaction. The kind of activation process utilized will determine the final product's chemical and/or physical properties. For example, through the gasification around 750 to 950 °C under steam and/or CO_2 atmosphere. The activation process increases the porosity of the charcoal's surface, leading to a corresponding rise in surface area (800–2500 $m^2.g^{-1}$) [41].

The features of the biochar are influenced by various factors, such as temperature, feedstocks, heating rate, residence time, and particle size. Their surface functional groups were significantly affected by biochar produced at several temperatures. Heating biomass between 400°C and 600°C, promotes the formation of new functional groups by breaking and rearranging chemical bonds. At higher temperatures (600°C–700°C), biochar result in extremely hydrophobic material because the biomass is dehydrated and oxygenated, the amount of H- and O-containing functional groups is reduced. In contrast, because of its cellulose- and aliphatic-type structures, biochar prepared at lower temperatures (between 300 and 400 °C) exhibits a more varied organic composition. Increasing pyrolysis temperature raises both carbon and ash contents, with ash increasing by approximately 5.7%–18.7% due to the combustion of organic matter and concentration of inorganic minerals. Similarly, the carbon content rises from about 62.2% to 92.4%, indicating a higher degree of polymerization and a more compact carbon structure [42].

Shalikh and Majeed (2022) used the carbonization method to convert Arabic gum into carbon at 300 °C. The removal efficiency of charred gum arabic from industrial effluent was 80%, 68.75%, and 90.7% for lead (Pb), cobalt (Co), and cadmium (Cd), respectively [43]. On the other hand, the gum Arabic tree seed shell was chemically treated with KOH and carbonized at 750 °C by Goskula et al. (2022). The activated carbon was successfully manufactured and derived from natural gum. The interaction between KOH and gum Arabic results in a large surface area and total pore volume. Consequently, adsorption capacity was impacted by the fundamental locations of oxygen functional groups on carbon adsorbent materials [44].

Bhagawati, et al., (2024) described the pyrolysis of the stem of the Gum Arabic tree to create thermally activated carbon at 800 °C. In both continuous column systems and batch and fixed-bed reactors, activated carbon bearing the tag GAAC-800 was employed as an adsorbent to sequester fluoride. While the interparticle diffusion model provided the best explanation of the mechanism, the second-order model was determined to fit the process's kinetics the best. Furthermore, 71.93 mg/g was the greatest monolayer adsorption capacity of fluoride removal, according to the Langmuir Isotherm model [45].

Although the various industrial applications of biochar, however, few published works assisted the use of Arabic gum as biochar. This could be ascribed to its high solubility in water and the carbohydrate content that makes controlling the condition of the pyrolysis process is a challenge. Anyway, the process of modifying Arabic gum is a flexible method that may be applied to enhance the qualities of this organic substance. It is feasible to produce novel materials with a variety of properties by carefully choosing the modification technique and operating parameters.

4.2. Arabic gum as hydrogel

Hydrogels are three-dimensional polymers capable of absorbing water. They are composed of water as a filler, crosslinking, and polymer chains. Hydrogels are widely employed, for instance, in tissue engineering scaffolds, artificial cartilage, medication transporters, and bioadhesives because of their exceptional biocompatibility and functionality. The preparation techniques used by different researchers and analysts can be broadly divided into two classes: chemical and physical cross-linking techniques. In chemical approaches, the polymer chains in the hydrogel make new covalent bonds with one other, but in the physically crosslinked hydrogel, the polymer chains interact physically [46] See Fig. 4 [47].

Earlier, the main issues that polymers consistently faced were poor solubility and limited biocompatibility due to the presence of a crosslinking agent and poor three-dimensional structures. Therefore, even if the main challenge was poor mechanical strength, current researches focuses on strengthening the 3D structure of hydrogel-based copolymers by adding crosslinking agents, filler, or nonmetals to enhance their properties [48]. However, it should be kept in mind that these additives can sometimes affect the performance of the hydrogel as was reported by Dia et al. (2019) when they incorporated the graphene oxide as filler for hydrogel synthesized by graft copolymerization of acrylamide and acrylic acid onto carboxymethyl cellulose. However, the prepared hydrogel showed an increment in the adsorption capacity of MB from 80 mg/g to 130 mg/g. While, the swelling ability was decreased from 75 g/g to 55 due to the reduction in the pore size of hydrogel which could be ascribed to the addition of graphene oxide [49].

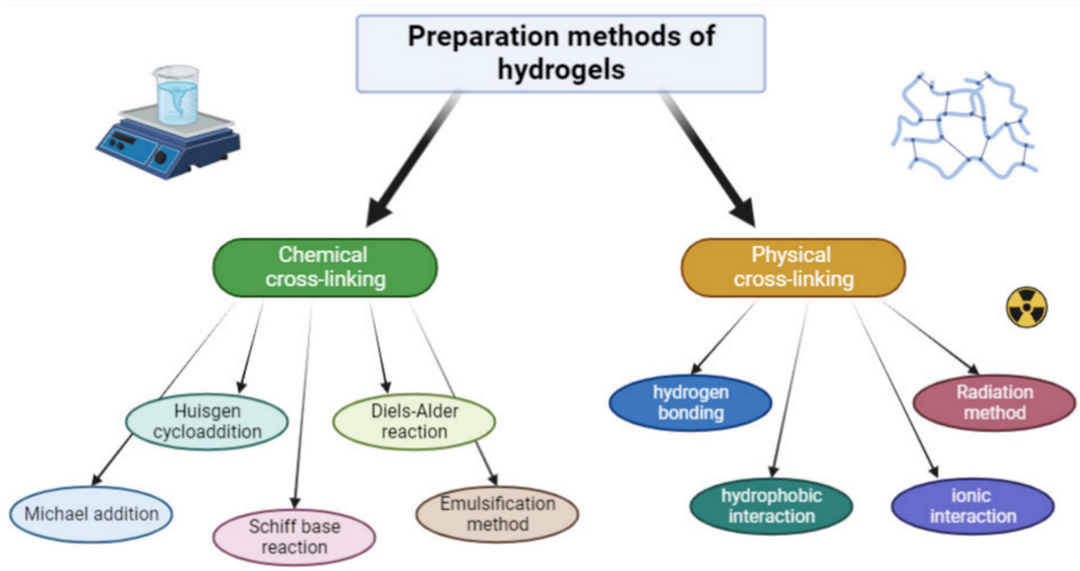

Fig. 4. Common techniques for crosslinking hydrogels include chemical and physical methods.

The production of polymer hydrogel can involve the combination of natural, synthetic, and composite polymers. The nanocomposite polymers are either formed by mixing both natural and synthetic polymers into one mixture or by the incorporation of inorganic materials into the polymer matrix as shown in Fig. 5 [50]. The produced hydrogel is designed to possess qualities that are superabsorbent, biocompatible, and switchable with customizable properties. Due to hydrogel flexibility, it can be easily molded into a variety of shapes, including sheets, blocks, films, tubes, rods, and spheres. Additionally, the kind and amount of the counterparts of the materials selected during preparation method had a significant impact on the characteristics of these nanocomposite hydrogels [51].

Hasssan zadah- Afruzi et al. (2023) describe the synthesis of the Arabic gum-grafted-hydrolyzed polyacrylonitrile/$ZnFe_2O_4$ (AG-g-HPAN@$ZnFe_2O_4$) as an organic/inorganic nanocomposite adsorbent for the removal of levofloxacin. The addition of zinc ferrite nanospheres to AG-g-HPAN enhanced both the surface area and the crystallinity with 6.86 m^2/g consequently enhancing the adsorption capacity with (Q_{max}) of 1428.57 mg/g (at 298 k). This high efficiency was ascribed to the efficient synthesis of AG-g-HPAN@$ZnFe_2O_4$ and the presence of hydrogen bonding and electrostatic interaction [52]. Elwakeel et al., (2023) reported the modification of gum Arabic (GA) with alginate (Alg) in the presence or absence of magnetite nanoparticles to create beads that were used to absorb Cu(II), Cd(II), and Pb(II) from aqueous solution. The magnetic beads (MAlg/GA) showed better adsorption than the beads manufactured without magnetite (Alg/GA). When the adsorbent is dosed at 2.5 g L^{-1} and the pH is 6.0, at 25 °C, the maximum uptake capabilities that have been observed for the MAlg/GA beads were: for

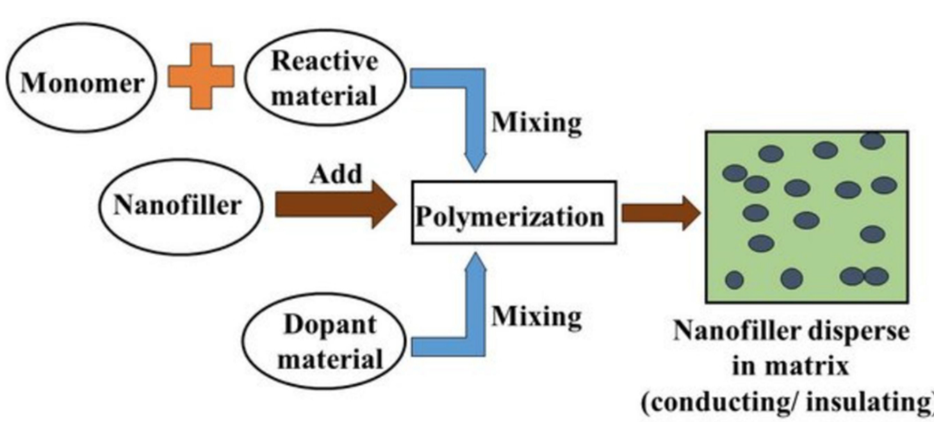

Fig. 5. In-situ polymerization method of preparation of conductive and insulating polymers.

Cu(II), 1.33 mmol g^{-1}; Cd(II), 1.59 mmol g^{-1}; and for Pb(II), 1.43 mmol g^{-1} [53].

Elbedwehy and Atta (2020) presented a comparative study between hydrogel preparations utilizing graft copolymer adsorption with AG-g-PAM/PAA prepared in emulsion against traditional crosslinking using ECH in an alkaline condition. The modification of Arabic gum with both polyacrylamide (PAM) and polyacrylic acid (PAA) improves the biodegradability and non-toxicity of the natural polymer (AG). The high adsorption capacity for MB was ascribed to the modification of AG structure with its sponge-like interconnecting micro- and macropores structure The enhancement in adsorption capacity was ascribed to the variety of pore sizes and shapes formed during the emulsification inversion process as the oil droplets' coalescence could be caused by the high shear rate of mixing resulting in a variety of droplet forms and sizes [54].

Motta and Fajardo (2021) reported synthesizing Arabic gum (GA) grafted with poly(acrylic acid) based on hydrogel (GA-g-PAAc) for the removal of DZP. The results demonstrated that the morphology of the GA-g-PAAc hydrogel owing to rough surface and porous distributed heterogeneously. Meanwhile, the internal structure showed tighter, denser, and irregular surfaces due to the polymer chain crosslinking. Furthermore, the swelling tests indicate that the material has a superabsorbent quality with a degree of swelling of more than 600%. In mild experimental circumstances (pH 7, 25°C, 150 mg of DZP), batch studies revealed that the elimination of DZP reached exceptional percentages (>80%) before 300 min [55].

Table 3. Arabic gum hydrogel-based adsorbents for the removal of dyes of heavy metals pharmaceuticals and pesticides from water.

S No.	Adsorbent	Contaminate	Maximum adsorption capacity	Cross linker	Ref.
1	Gum Arabic cross-linked pectin/O-carboxymethyl chitosan hydrogels (OGA-Pc-O-CMCS)	Levofloxacin(LVX) Delafloxacin (DLX)	66.3'–87.5% (45'–53%) for pH 3.9	Oxidized Arabic Gum OGA	[56]
2	acacia gum phthalate/pectin hydrogel (AGP/PEC)	MFA acid	93.45%,	N, N'-methylene bisacrylamide (MBA)	[57]
3	Acrylic amide-co-3-Allyloxy-2-hydroxy-1-Propanesulfonic acid Sodium salt/Gum Arabic semi-IPN hydrogel	Methylene blue	655.2 mg. g^{-1}	N, N-methylene-bisacrylamide (MBA)	[58]
4	Gum Arabic/Acrylamide	Cationic, Safranin toluidine dyes	833 mg.g^{-1} 526 mg.g^{-1}	N,N-methylenebisacrylamide (MBA)	[59]
5	Polyacrylamide/gum Arabic (pAAm/GA)composite hydrogel	Basic blue-3 (BB3) eradication	-	-	[60]
6	The gum Arabic-crosslinked-poly (acrylamide)/zinc oxide nanocomposites	Malachite green (MG)	99%	N,N-methylenebisacrylamide (MBA)	[61]
7	Macro-porous Gum Arabic-based Cryogel	Different dyes	-	No cross-linking	[62]
8	Arabic-cl-Poly(acrylamide)	Crystal violet	90.90 mg/g	N, N-methylene-bisacrylamide	[63]
9	Chitosan-gum Arabic-coated liposome 5ID nanoparticles (CS-GA-5ID-LP-NPs)	Congo red	71.23%	No cross-linking	[64]
10	Polyaniline-based nanocomposite hydrogel with Arabic gum	MB	89%	N,N' -methylene-bisacrylamide (MBA)	[65]
11	Arabic gum-grafted-poly amidoxime (AG-g-PAO/$CuFe_2O_4$)	Organophosphorus pesticide(OPP) (chlorpyrifos)	769.23 mg/g	*N*, *N*'-methylenebisacrylamide	[66]
12	Acacia Senegal Gum hydrogel (HASG)	As(V),Cr(VI), Cr(III)	69.8, 99.3, and 40.00%	DS crosslinking	[67]
13	Magnetic hydrogel based on gum acacia	MB, rhodamine 6G, Cu(II) and Hg(II)	265.2, 344.4, 307.5 and 292.8 mg.g^{-1}	N, N-methylenebisacrylamide (MBA)	[21]
14	Arabic gum-g- Polyacrylonitrile/$CuFe_2O_4$ (AG-g-PAN/$CuFe_2O_4$) nanocomposite hydrogel	Pb (II)	192.3 mg/g	N,N-methylenebisacrylamide	[68]
15	Graft copolymers of(PAN) onto Arabic gum (AG)	Pb^{2+}, Cd^{2+}, and Cu^{2+}	1017, 413, 396 mg/g	No cross-linking	[69]
16	GA-g-PAAM	Fe^{+3}	86.93%–99.86%.	No cross-linking	[70]

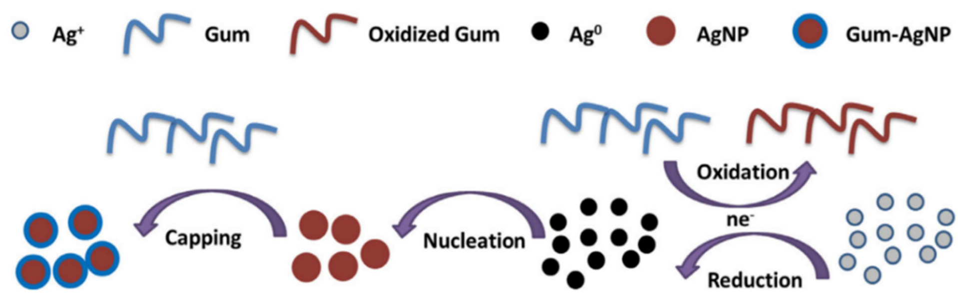

Fig. 6. Proposed mechanism of synthesizing gum Arabic-silver nanoparticles (AgNPs).

While polymer hydrogels are considered a promising material, there are still issues to be resolved, like regulating the rate of degradation, guaranteeing long-term stability, and increasing production volume to make them more affordable. As such, the preparation method and the kind of polymer they comprise are a few of the key factors in modifying the morphological characteristics of the Arabic gum. By recognizing these relationships, materials with the desired properties can be created for a variety of applications, including engineering, biomedical research, and nanotechnology. Enhancing the variety of applications and creating new functional hydrogels are the main objectives of future research. Table 3 summarizes a few more studies on different kinds of Arabic gum hydrogel-based adsorbents applied in wastewater treatment including the removal of dyes, heavy metals pharmaceuticals, and pesticides.

4.3. Arabic gum as a stabilizing agent

Green nanoparticle synthesis is a phenomenon that successfully lowers environmental risk by removing potentially dangerous elements that are detrimental to human health. Because the stabilizer's surface charge is crucial for preserving the steric hindrance and electrostatic interactions between monodispersed nanoparticles and the aqueous system, gum arabic's polyanionic character is also crucial for preserving the monodispersed nature of the nanoparticles. Metal nanoparticles are being explored extensively as a potential solution to various inorganic and biologically-toxic contaminants [71].

Arabic gum has been utilized, for instance, in the creation and modification of metallic nanoparticles (NPs) like gold NPs and metal oxide NPs like Al_2O_3 and magnetic NPs. These nanocomposites are created by covalently coupling gum Arabic through its free carboxylate groups to the surface of NPs. Zahran et al., (2021) describe the use of gum Arabic as a reducing and capping agent in a direct chemical reduction process to create gum Arabic-AgNPs with an average size diameter of 25 nm. As illustrated in Fig. 6, the abundance of hydroxyl groups organized along the gum structure's backbone is the primary factor responsible for gum Arabic's capacity to reduce Ag^+ [72].

On the other hand, Yang et al. (2022) reported the fabrication of silver-gum Arabic (Ag-GA) nanostructure synthesized by electrochemical deposition for the detection of 2,4-D herbicide. This process produced an Ag-GA nanostructure that measured between 50 and 70 nm. Various preparation techniques could result in varying sizes. Even so, the author listed the advantages of the electrochemical deposition method, which include controllability (changing the parameters of the electrochemical deposition process to modify the size and morphology of Ag-GA nanoclusters), ease of use, and building a substrate takes less than 10 seconds. Additionally, it is more scalable due to its ease of modification, which can provide enormous quantities of substrates and a high 2,4-D herbicide detection limit of as low as 1 pM without sample preparation. Using Arabic gum as a reducing agent to assist Ag ions in forming a compound with Ag atoms was the key to this method. Consequently, Ag-GA nanocluster formation and deposition on the chip surface may be controlled [73].

The frequent use of capping agents in colloidal dispersions to regulate nanoparticles controls the growth, agglomeration, and physicochemical characteristics in a precise way. The capping agent is an amphiphilic molecule comprising a polar head group and a non-polar hydrocarbon tail. Owing to the amphiphilic nature of capping agents, they confer functionality and enhance the compatibility with another phase. The non-polar tail interacts with the surrounding medium while the polar head interacts with the metal atom of the nano system. Different types of capping agents have been used in nanoparticle synthesis including surfactants, small ligands, polymers, dendrimers, cyclodextrins, and polysaccharides such as Arabic gum. All of these have been successfully utilized as capping agents having the capability to induce indirect changes in nanoparticles elucidating tremendous therapeutic and environmental cleansing effects [74].

When selecting capping agents for nanoparticle modification, factors such as biocompatibility, biodegradability, bioavailability, and solubility are key considerations. Activating the nanoparticle surface enables binding with other molecules, while also improving stability, extending storage life, and protecting against unwanted chemical reactions, such as moisture uptake. This approach can also address some concerns related to the safety of nanomaterials. In chemical and physical synthesis routes, reducing agents and capping agents are often introduced as separate components, whereas in many cases, the capping material is incorporated during particle formation. Examples of widely used capping agents include polymers such as polyethylene glycol (PEG), polyvinylpyrrolidone (PVP), and polyvinyl alcohol (PVA); proteins like bovine serum albumin (BSA); chelating agents such as ethylenediaminetetraacetic acid (EDTA); and natural biopolymers including chitosan and gum arabic, which have shown particular promise in nanotechnology applications [75].

The impact of varying gum arabic concentrations (0.5–3%) on the size, optical characteristics, and stability of ZnO was documented by Pauzi et al. ZnO nanofluids were created using a precipitating technique aided by microwave heating. ZnO nanofluids were found to have an average size of 200–350 nm, while unstabilized ZnO nanofluids had an average size of 1020 nm. Because of the Arabic gum, which has the steric effect of slowing down the growth and agglomeration of nanofluids, these ZnO nanofluids remained rather stable for at least six months. On the other hand, the quick increase in nanofluid size at gum arabic concentrations above 1.5% demonstrated that the mean nanofluid size was dependent on gum arabic concentration. The concentration of the stabilizer, which directly influences the size of nanoparticles, determines the steric action of gum arabic as a stabilizer. Another potential cause of the growing size of the agglomerated ZnO nanofluid is gum Arabic's self-association and aggregation characteristics over a wide concentration range [76].

In summary, Arabic gum presents a viable and sustainable option for the environmentally friendly synthesis of diverse metals and metal oxide nanoparticles, which exhibit high efficiency across a range of applications see Table 4. The useful functional groups (-OH, -COO-, -CO, and CH_3CO-) of Arabic gum, along with its low cost, non-toxicity, and biodegradability, contribute to its significance as a stabilizing agent for nanoparticles. The main determinants of which capping agents should be utilized are the intended size and form of the nanoparticles as well as their potential utility. Other considerations include the type of functional groups, their hydrophilicity or hydrophobicity, and the concentration of charge capping agents.

4.4. Arabic gum as coating agent

GA's structure has a major role in determining its beneficial properties, such as its viscosity, degree of cooperation with oil and water in an emulsion, solubility, and ability to microencapsulate, among other attributes. Gum Arabic is a commonly used coating chemical in the food business, used to coat candies, fruits, vegetables, and nuts. It replaces natural protective waxy coatings on edible products by forming thin, protective layers. The products are shielded from grease, oxygen, moisture, and other environmental factors by this thin film. Additionally, Arabic

Table 4. Arabic gum as a reducing/stabilizing agent for various nanoparticles applied in different applications.

Bio material	Np Size	Reducing agent	Capping agent	Application	Ref.
Gum Arabic capped copper nanoparticles	25.6 nm	GA	GA	Wound healing and antibactrial application	[77]
Fe_3O_4 nanoparticle	13–67 nm	NH_4OH	GA	Environmental(removal of Cu(II)	[78]
GA-MNPs Magnetic nanoparticles	-	NH_4OH	GA	Environmental (removal of ciprofloxacin)	[30]
GA-Ag	5 nm	GA	GA	-	[79]
GA-Ag	2–20 nm	GA	GA	Medical	[80]
GA-Ag	16nm	GA	GA	Environmental (removalof4-Nitrophenols)	[81]
GA-Au	6.52nm 4.045nm	GA $NaBH_4$	GA GA	Antioxidant activity	[82]
GA-Cu	3–9 nm	hydrazine hydrate	GA	-	[83]
GA-ZnO	16nm	GA	GA	Biomedical	[84]
GA-Se NPs	34.9 nm	GA	GA	Antioxidant activity	[85]

gum's coating properties were utilized by the pharmaceutical industry for tablets and pellets. Gum Arabic has been utilized in wastewater treatment as a coating agent for metals and metal oxide nanoparticles. This has significant effects on pollutant removals in terms of metal immobilization, pollutant selectivity, and non-toxic material, providing a desirable choice for treating wastewater.

Alzahrani (2014) investigated the addition of Arabic gum functional groups to the surface of magnetic nanoparticles. The mean diameters of the modified Fe_3O_4 and GA MNPs nanoparticles were 33 and 38 nm, respectively, and their estimated surface areas were 9.05 and 12.36 $m^2.g^{-1}$. This enhancement in surface area improves the adsorption capability within just five minutes, making it an efficient adsorbent to remove dangerous dyes from wastewater [86].

By using the co-precipitation technique, Mustafa et al. (2020) produced $Ni0.31Mg_{0.15}Ag_{0.04}Fe_{2.5}O_4$ magnetite NPs." The average crystallite size was found to be 28.57 nm which was nearly identical to the FE-SEM measurement. The presence of the distinctive peaks of GA after coating was ascribed to the OH stretching, carboxylic ion, and C-O-O band in addition to the polysaccharide's –OH groups stretch allowing for the coating process to be completed. The nanoparticles revealed a sphere-like form with a crystallite size of 25.93 nm as was predicted by FE-SEM analysis. The concentration of Pb ions dropped from 25 ppm to 6.6 ppm, reaching 1.1 ppm at 25 min only, as demonstrated by the AAS analysis of the adsorption of Pb ions by GA-magnetite NPs. The carboxyl groups in GA and the NPs' porosity both had a significant role in the adsorption process [87].

Banerjee, et al., (2007) described the ability of Gum arabic to coat Fe_3O_4 nanoparticles to produce a new magnetic nano-adsorbent that was used to extract copper ions from aqueous solutions. Gum Arabic's carboxylic groups interacted with Fe_3O_4 surface hydroxyl groups to attach gum Arabic to the latter. Secondary particles with a diameter ranging from 13 to 67 nm were formed as a result of the surface modification, although the phase transition of Fe_3O_4 was avoided. The adsorption of copper ions can be achieved by the use of both bare magnetic nanoparticles (MNP) and gum arabic modified magnetic nanoparticles (GA-MNP), which bind to the amine groups of gum arabic and the surface hydroxyl groups of Fe_3O_4. Due to the absence of internal diffusion resistance, the adsorption rate was so rapid that equilibrium was reached in about two minutes, and the adsorption capacities of both MNP and GA-MNP increased when the pH of the solution increased [88].

5. Applications and mechanisms of Arabic gum in environmental remediation

For many years, great efforts have been made to develop powerful approaches for the simultaneous removal of organic pollutants from contaminated water. Green chemistry has emerged as a dominant solution, driven by the need for low-cost, easily applicable, biodegradable, naturally abundant, non-toxic and reasonably efficient technologies through the successful synthesizing of new efficient materials applicable in wastewater treatment process. Such precursors altering the treatment methods by combining adsorption and photocatalysis process into a single process and elimination the drawback that each technique suffer from individually, achieving enhanced overall performance.

By integrating adsorption and photocatalysis within a hybrid reactor or composite material, secondary pollution can be avoided, as the catalyst concentrates pollutants on its surface and simultaneously generates reactive radicals in situ to degrade organic compounds that might otherwise block adsorption sites. This combined action not only extends the operational lifespan of the catalyst media but also reduces overall treatment costs [89].

In recent years, natural biopolymer-based photocatalysts—derived from renewable sources such as animal bones, fungi, insects, and green algae—have attracted considerable attention. They are divided into three categories: polynucleotides, polypeptides, and polysaccharides [90].

These biopolymers have a high surface area and good adsorption capacity made them a viable substrate for metallic photocatalysts. These biopolymers help in reducing the amount of intermediates generated during photocatalytic processes due to their ability to scavenge reactive oxygen. Biopolymers also facilitate the quick and simple recovery of the photocatalyst. When a photon strikes a photocatalyst, the electron is induced to move from the valence band to the conduction band. Depending on the type of photocatalyst, this electron can then be employed to decrease organic contaminants or oxidize water molecules [91].

Moreover, these biopolymers such as gums has demonstrated an effect in stabilizing nanoparticles, improving the general properties of semiconductor oxides, and their applications in environmental remediation [92].

Fardood et al., (2017) reported the preparation of zinc oxide nanoparticles derived arabic gum using sol-gel process as an inexpensive and environmentally beneficial way to work with nature. ZnO-NPs' photocatalytic activity has been assessed for their ability to degrade direct blue 129 (DB129) with 95% catalytic activity in a reasonably short amount of time when exposed to visible light without the need for hydrogen peroxide [93].

Lopes, et al (2023) successfully used gum arabic to synthesis TiO_2 nanoparticle with nano size of 100 nm, surface area 50.5 $m^2.g^{-1}$ and mesoporous structure. The catalyst was applied to degrade two types of pollutants i.e methylene blue dye and CIP under UV light. The produced catalyst showed efficient activity due to the synergetic effect of adsorption with about 10% for MB and 30% for CIP followed by photocatalytic activity of 98% and 93% for MB and CIP respectively [94].

Now a day, the trends in current work indicate a significant and growing interest in developing hydrogel nanocomposite materials for various biological and environmental applications [95].

Sharma et al., (2022) created a hydrogel heterostructure as a support for C_3N_4/BiOI, modified with gum acacia crosslinked with poly(acrylamide). The generated hydrogel was thought to be the structural element that started the surface adsorption process. In the meantime, the polymeric matrix was connected with C_3N_4/BiOI, preventing its agglomeration. Overall, it improves the elimination of harmful Crystal violet dye by increasing the effectiveness of the nanocomposite hydrogel as an adsorptional-photocatalyst [96].

Base on the special characteristic of arabic gum represented by its active functional groups including the hydroxylic, carboxylic, and amino groups. These active groups have the tendency to remove metals ions efficiently by forming a chelating agent with the metal cation M^+ (M=Mo, Ti, Cu, Zn, Fe, etc.). The first step of metal cation linkage to polysaccharides is a very complex process that involves a variety of physicochemical interactions, including complexation, ion exchange, electrostatic interactions, acid–base interactions, hydrogen bonding, hydrophobic interactions, and physical adsorption [97].

Nowroozi et al. (2022) describe the adsorption mechanism of $MgFe_2O_4$ – Gum Arabic composite for the removal of Hg ions using ultrasound-assisted precipitation method. L-cysteine was added as a thiol resource to enhance its adsorption characteristics meanwhile GA serves as a stabilizer to prevent the direct magnetic between the particles. The adsorption mechanism of the $MgFe_2O_4$-Gum Arabic was involving complexation reactions, ion exchange, and electrostatic attraction. The Ion exchange between H^+ and Hg^{2+} plays a major role in mercury adsorption at highly acidic conditions, while magnetic GA includes oxy/hydroxy groups due to the electrostatic attraction between the mercury ion and the deprotonated oxy-hydroxy groups. Ion exchange and the hard-soft acid-base interaction between sulfur and mercury ions are the primary mechanisms in this work since mercury adsorption on the surface of thiol-functionalized sorbent occurs in an acidic media [98].

Table 5 presents more successful modification of Arabic gum with different nano-metals and/or biopolymers as photocatalysts for the degradation of pollutants. According to the special properties of arabic gum many integrated approach improves pollutant removal efficiency, prevents secondary

Table 5. Arabic gum modified inorganic nano metals and/or biopolymers as photocatalysts for the degradation of pollutants.

Photocatalyst	Pollutant	Ref.
GA-Ni Micro-gel GA-Cu Micro-gel	4-nitrophenol, (4-NP) t	[99]
GA-PVA Hydrogel	Folic acid	[100]
Gum acacia–activated carbon-CaO/NiO nanocomposite	Methylene blue, Methyl orange Methyl red, Rhodamine B	[101]
TiO_2@Gum Arabic-Carbon Paste	Pb^{2+} Ions in Plastic Toys	[102]
GA–mediated greener synthesis of MoS_2 (NPs)	Methylene blue	[103]
GA-Sch-Pd nanocatalyst	o-nitroaniline, p-nitrophenol p-nitro-o-phenylenediamine, p-nitroaniline,Congo red Methylene blue, Methyl orange	[104]
α-Fe_2O_3 (hematite) nanoparticles/Arabic gum (AG) as a biotemplate	DB 129	[105]
ZnO-GA	Methylene blue dye	[106]

pollution, and extends the functional lifespan of the catalyst.

6. Conclusion

Biomaterials have been extensively used in wastewater treatment technology due to their inexpensive cost, great surface area, strong efficiency, and biodegradable abilities. A variety of biomaterials, including bio-waste, bio-composite, and biopolymers such as starch, cellulose, carrageenan, alginate, chitin, chitosan, and gums, were employed to create a viable adsorbent photocatlyst catalyst system. Arabic gum with its unique properties can have different forms such as biochar, hydrogel, hydrogel nanocomposite, arabic gum-coated metals/metals oxide, bio-template, photocatalyst, etc. These forms of Arabic gum can be chemically modified through some common methods such as grafting, cross-linking, and depolymerization to enhance its properties such as gum solubility, viscosity, gelation, film forming ability which make it a good choice for a wide range of applications. These adaptable characteristics make Arabic gum a strong candidate for diverse environmental applications. Furthermore, gum arabic can be modified physically through fractionation, encapsulation, and nanosizing. Finally, it appears that there is an opportunity for the advancement of biopolymers to explore the use of other natural polymers and conduct additional systematic review Research.

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