iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL
FOR RESEARCH
IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 12 **Issue:** V **Month of publication:** May 2024

DOI: https://doi.org/10.22214/ijraset.2024.62091

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 12 Issue V May 2024- Available at www.ijraset.com

Investigating Natural Polymer Nanocomposites in Relation with Eco-Friendly Potential in Environmental Contexts

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Abstract: The escalating global waste crisis and precipitous decline in biodiversity have emerged as two of the most pressing environmental challenges of our time. These interconnected issues pose grave threats to the delicate balance of ecosystems and the myriad species that inhabit them. This research Endeavor seeks to harmonize these critical spheres by proposing an integrated approach to waste reduction and wildlife preservation, recognizing their inextricable linkages within the intricate web of life. This research explores the synergistic potential of integrating waste reduction strategies with targeted wildlife preservation efforts. By promoting circular economies, sustainable production and consumption practices, and innovative recycling technologies, the influx of harmful pollutants into ecosystems can be mitigated, alleviating the burden on vulnerable species and habitats. Complementarily, robust conservation measures, ecosystem restoration initiatives, and the engagement of local communities can safeguard biodiversity, thereby maintaining the ecological integrity that underpins sustainable waste management.

Keywords: Heavy metals (HMs); organic pollutants; polymer; nanocomposites; PM;

I. INTRODUCTION

Polymers have been extensively investigated and effectively employed as sustainable products to enhance the quality of life for decades. These well-established polymer findings, utilized in biomedical and pharmaceutical approaches, have proven successful in monitoring drugs released and innovative approaches to polymer-based pharmaceuticals [1]. Polymers play a genuine and pivotal stand in contemporary society. Furthermore, modern advancements in nanotechnology provide fresh and newer avenues to the development of small and nano-sized products that exert a significant influence on biomedicine, food, and environmental applications. Notably, polymeric nanocomposites establish a mutually beneficial relationship between the matrix and reinforcing materials, leading to numerous advantages through this scientific methodology. In essence, the production of polymeric nanocomposites is an integral component of polymer nanotechnology.[2]

One crucial factor to consider is the harmonious interaction between two phases, which are the continuous matrix and the discontinuous reinforcement. When it comes to dispersing nanoparticles, it is imperative to prevent the clustering and aggregation of reinforcements within the polymeric matrix. Naturally, the selection of nanoparticle varieties is closely tied to the intended uses and intended characteristics of thermoplastic nanocomposites. There are several well-established synthetic techniques for creating polymeric nanocomposites, including as mixed precipitation and the technique known as sol-gel. Several methods are adopted in the formation of polymers, including Several well-established synthetic techniques are employed for creating polymeric nanocomposites, including precipitation methods, sol-gel processes, thermochemical treatments like hydrothermal synthesis and laser pyrolysis, as well as advanced techniques such as reverse micellar synthesis, microemulsion, and laser ablation [3]. Nowadays polymer manufacturing innovations are more and more concentrated on using natural polymers as environmentally friendly remedies for a greener world. Cosmetic goods are increasingly using polymers like cellulose, starch, and poly (lactic acid) (PLA), whose biodegradability helps to minimize the amount of space needed for waste disposal. Nevertheless, outstanding features require chemical modification of naturally generated polymers because of their poor stability and restricted solubility. For example, cellulose acetates showed biodegradability in simulated compost environments, with degrees of substitution exceeding, Natural polymers, often referred to as biopolymers, originate from the metabolic processes of Monomer compounds that bind together via covalent interactions make up living things. They play important functions in the maintenance and transfer of biological data as well as the energy storage of cells in the natural world. These biopolymers' biodegradability is one of its main advantages since the emitted CO2 is quickly and readily assimilated by soil and agricultural crops [4].

Most of these biopolymers are classified as polysaccharides, which includes well-known substances including starch, lignin, chitin/chitosan, and cellulose, which makes up about 33% of all plant components [6, 8]. As shown in Figure 1, this work provides a brief introduction to the aforementioned polymers and their nanocomposites, emphasizing the natural origins of these cutting-edge materials and their various uses.

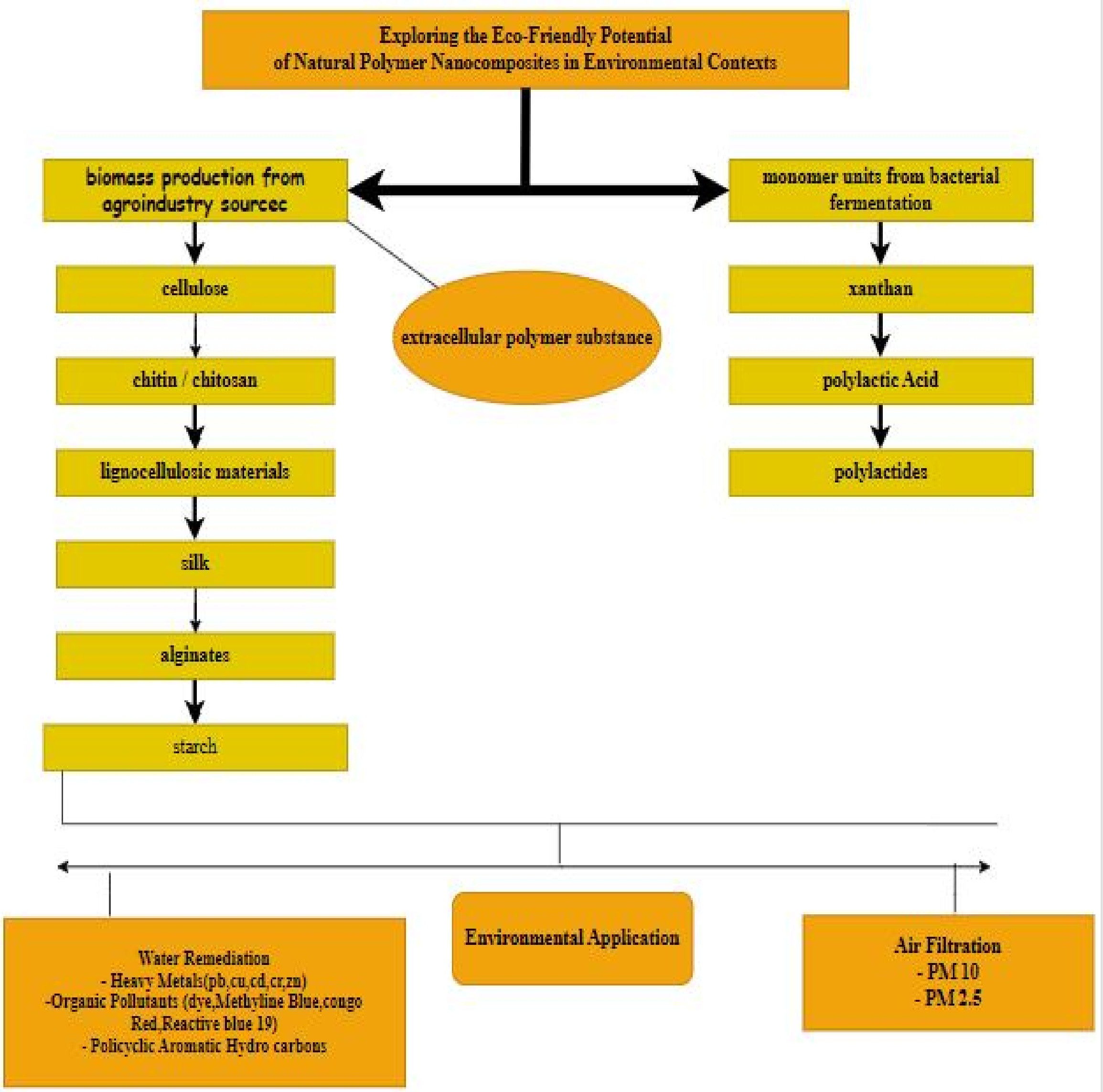

Figure 1. Polymers made from natural materials and nanocomposites for use in ecological settings.

Common polymers, such as polypropylene (PP) and polyethylene (PE), deteriorate over years and show sustained stability. The use of synthetic polymers has the potential to exacerbate environmental contamination. Making use of these organic polymers can provide a useful remedy.

This investigation is novel because it concentrates on the noteworthy progress made when raw materials are used as a basis for the creation of sophisticated nanocomposites meant to be used in environmental restoration [5]. Thus, in order to address the decontamination issues in air, soil, and water systems, the study introduces the most widely utilized natural polymers that are obtained from natural sources, either as freestanding materials or in composite forms. The extraction of harmful elements like heavy metals, both inorganic and organic substances, and microbes is the goal of these applications. The most potentially useful and often mentioned natural polymers, either on their own or when mixed with other cutting-edge materials, include chitosan, cellulose, lignocellulose, and starch, according to the results of the literature review. The biopolymers in question have a number of important characteristics that make them appropriate for use as adsorbents or filter membranes in environmental settings.

A significant ability to absorb into the air or water-related pollutants, good thermal and mechanical characteristics, strong resistance to changing pH levels, biodegradability, enlargement capacity, low modification needs to improve adhesion, and most importantly, affordability are some of these attributes [6].

Certain characteristics of biopolymers, such as sufficient solubility and the compatibility in water solvents, a set molecular mass, and the appropriate surface morphology for attracting positive (+) or negative (-) ions, are required in the context of electrospinning techniques for the synthesis of fiber. These requirements facilitate the production of nanoscale fibers with regulated diameters, free of flaws in the beads, and with an exact surface area. Regardless the fact that artificial substances are more durable than genuine ones, it is important to recognize the environmental risks posed by the toxic compounds found in synthetic materials. A new study has demonstrated that environmental protection can be strengthened without sacrificing the intrinsic qualities of materials by replacing at least one synthetic element with one that is organic [7]. Our creative method encourages the usage of these plant-based polymers in this situation as a workable substitute to support a healthier and more secure environment. Our findings indicate that the majority of research conducted in the past twenty A significant portion of research conducted over the past two decades has concentrated on utilizing natural polymers and their derived nanocomposites as effective adsorbents, membranes, hydrogel matrices, coatings, and metal-organic frameworks for the removal and immobilization of heavy metal contaminants from water bodies and soil environments.structures. Regarding air quality, the majority of the literature offers strategies to retain particulate matter (PM), with little focus on biological pollutants elimination. We have arranged the material in this evaluation according to its value, as determined by the data analysis. Although the majority of the articles in this review have been released in the previous 20 years, it also includes more historical yet relevant information about polymers made from plants.

II. PAGE LAYOUT

1) Mother Nature Polymers as Advanced Green Materials to Preserve the Environment

A plentiful supply of natural and monomeric feedstock polymers can be found in the complicated molecular makeup of glucose, plant-based substances, and biomass from bacteria [8]. The most often used biopolymers among these naturally occurring polymers are complex sugars, which are also used in healthcare fields and are ecologically beneficial. Furthermore, lignin and cellulose make up the majority of the natural polymers found in Earth's biggest numbers. Usually obtained from plants, polysaccharides are made up of two or more monosaccharides permanently joined by glycosidic linkages. They are widely used in both the pharmaceutical and food sectors and, because of their hydrophilic functional groups, have high water-absorption capacities even though they are impermeable to their native pH. The flexibility of the polymer structure, wettability, and cross-linking density are all important aspects that affect how well polymer nanocomposites absorb water. Because both chitosan and chitin may be easily shaped into distinct forms, sophisticated nanostructures with large particular porosity as well as surface area can be created [9]. Because of this, large amounts of heavy metals can be retained more easily than micron-sized particles, which makes them useful for collecting pollutants from contaminated soil and water. With an annual production of over 1 billion tonnes, chitin—the second most prevalent polymer found in the nature after the cellulose—is industrially taken from the marine sources. A wide range of fungal organisms, arthropods, crustaceans, algae, aquatic creatures, and some plant species are sources of chitin. It is the main source of many plastics that degrade over time and is essential to the development of products used in the food and pharmaceutical industries, the medical field, the cosmetics industry, and environmental cleanup. Chitin is a good adsorbent and ion converter because to its notable antioxidant, anti-inflammatory, and skin-regenerating capabilities [10]. It is especially useful when employed in nanometric dimensions with a crystalline structure. Conversely, chitosan is made from biomass and materials that are left over from fishing. One potent option for eliminating heavy metals from water is chitosan. It comes from chitin that has been deacetylated. Issues with gelation and aggregation are addressed by combining chitosan with nanoparticles. For instance, chitosan is frequently combined with two clay-based minerals that are frequently employed, montmorillonite and bentonite, to remove or extract heavy metals such as (Cr), (Ni), and (Pb) from contaminated soil and water. The pore shape, pH, and dimension are some few the elements that affect how effective certain combinations are. Chitosan is a compostable biopolymer with a degree of deacetylation ≥70% that is derived from waste sources such as shellfish and fungal biomass. It is antibiotics, biologically compatible, safe for use around people, and friendly towards the environment. Chitosan is widely used in heavy metal biosorption, cosmetics, and medicine [11]. Green synthesis techniques have been developed to cap nanoparticles into chitosan substrates because of its broad application. Chitosan can hold and immobilize heavy metals in tainted systems because of its amino and hydroxyl functional groups. Chitosan and its derivatives, when in solid form, can be used as soil amendments and to immobilize metals, especially in damp soil. This can greatly lessen the toxicity of heavy metals to living things. It is a part of the exterior of plant cells and, when paired with pectin, creates a chain of cross-linking fibers. Hydragels in three dimensions can be made by mixing alginate with ions such as calcium.

It is composed of two block structures: β-(1→4) connected D-mannuronic acid (block M) and α (1→4) linked L-type guluronic acid (block G). This allows it to bind additional ions through block M, resulting in flexible gels with fast diffusion rates, or through block G, yielding resistant and hard gels [12]. Ca alginate has a preference for retaining heavy metals due to functional groups such as amine, phosphate, Sulphate, and hydroxyl. Lactic acid is an acid and its oligomers that dissolve in water as a result of abiotic hydrolytic dissolution of PLA accompanied by microbial disintegration, mostly by bacteria and fungus. The silk that is obtained from B. Mori's silk cocoons is a distinctive kind of natural resource that has superior strength and biological compatibility, particularly cytocompatibility in vitro. Because of these characteristics, it is a favored biomaterial for use in regenerative medicine and the medical device sector. Due to its adjustable qualities, it can also be used in materials for air filtration, including face masks. Extracellular polymer substances (EPSs) are an important category of extracellular microbial substances that are used in environmental cleanup, in addition to these naturally occurring polymer elements. Microorganisms release polymers known as extracellular polymeric substances (EPSs) that are either soluble or bound [13]. For a variety of contaminants, EPSs demonstrate potential as flocculants and adsorbents.

2) Eco-Friendly Cutting-Edge Nanocomposite Materials for Safeguarding the Environment

Polymeric nanocomposites are substances that have enhanced properties due to the addition of modest amounts of nanoparticles to reinforce the polymers. When it comes to high-quality applications in modern society, such as thermoplastics, thermosets and rubber, these materials provide sustainable substitutes for traditional polymers.

Generally speaking, composites consist of three main matrix types: polymers, metals, and ceramics mixed with different reinforcement additives (such fibres, fillers, flakes, or particles). dimensional linear nanocomposites (like carbon tubing), two-dimensional laminated surfaces (like this mineral), or three-dimensional granules (like silver particle nanoparticles). The resulting nanocomposite as a whole has a variety of functionalities as a result of these geometric changes [14]. However, there is a growing demand for the manufacture of environmentally friendly materials with low negative environmental effects. Switching to natural sources from synthetic ones is one way to solve the problem.

As shown in Figure 2, the chitosan/silver nanocomposite, for instance, has much stronger antimicrobial activity than chitosan alone, which makes it useful for treating effluent and decolorizing chemicals including methyl orange (MO).

Figure 2 illustrates the environmentally conscious application of a chitosan/silver nanocomposite for eliminating colours from water for consumption. This text has been adapted from with authorization. Copyright Elsevier 2022.

In his study, Zaferani clarified the characteristics and difficulties of nanocomposites and provided a thorough classification of them [15]. This classification consists of two main types, each with unique important features: (i) polymer-nonmetallic and (ii) polymer-metal nanocomposites. Important molecules in the first group are polymer graphene, polymer-carbon nanotubes, and polymer clays.

Nano-clays, in particular, are environmentally friendly and cost-effective, with the ability to enhance mechanical and permeability properties through cross-linking. To achieve the desired performance, nano-clay layers must be properly dispersed and intercalated. Metal nanoparticles operate as support in the second type of polymer-metal nanocomposites; their large surface area increases reactivity as particle size decreases. Because of their antibacterial qualities, silver nanoparticles are widely used in healthful and ecological tasks. Other noteworthy nanoparticles that are integrated into the polymer matrix including palladium and Gold.

However, because nanocomposites made from polymers having metallic nanoparticles may have unfavorable impacts on living things, it is imperative to evaluate their toxicity [16]. Composites of zeolite treated with chitosan exhibit potential for use in environmental engineering.

These frameworks draw inspiration from natural zeolites. The outstanding thermal and chemical resistivity, extensive porousness, significant adsorption capacity, excellent chemical equilibrium, vast internal surface area, and non-toxicity of MOFs are what set them apart [17] An interesting advancement concerns nanocellulose-based sorting materials made by introducing ZIF nanocrystals into the cellulose microfiber network; Figure 3 illustrates this process with particular reference to the MOF HKUST-1.

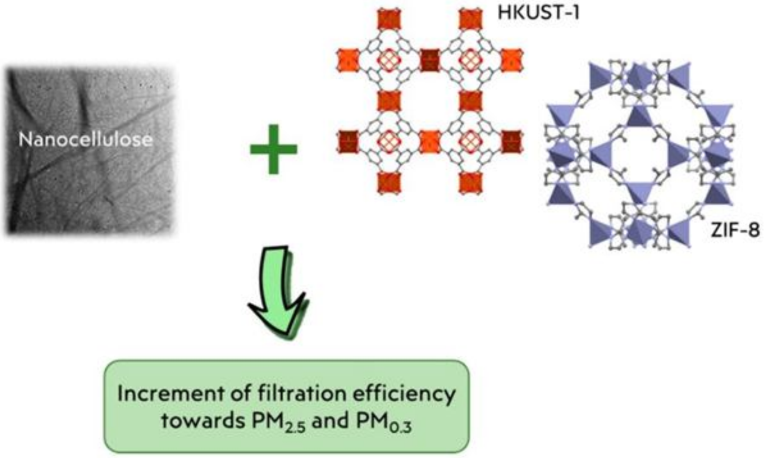

Figure 3 shows how well MOFs work with a medium for air filtration [9].

The incorporation of ZIF-8 nanocrystals significantly enhanced the surface area of cellulose microfibers, increasing the BET surface area from 6.66 to 620.80 m2/g, resulting in improved filtration efficiency of 99.9% against PM 0.3 particles compared to 99.5% without modification [18]. In a separate study, coating chitosan/polyvinyl alcohol electrospun nanofibers (CS/PVA-ENF) with ZIF-8 crystals demonstrated a high adsorption capacity of 1000 mg/g for dye removal from wastewater during the second cycle. Moreover, the ZIF-67@Fe3O4@ESM composite, formed by incorporating ZIF-67 crystals onto the Fe3O4@ESM magnetic eggshell membrane, exhibited a substantial surface area of 1263.9 m2/g and maximum adsorption capacities of 344.82 mg/g for Cu(II) and 250.81 mg/g for Basic Red 18 (BR18) dye. The presence of magnetite in this adsorbent facilitated straightforward separation from aqueous media. Additionally, the potential of Materials Institute Lavoisier frameworks (MILs) to capture heavy metals from sewage has garnered significant research attention. to capture heavy metals from sewage has recently attracted a lot of academic attention [19].

Table 1. Polymers made from natural resources and their nanocomposites are employed in the elimination of water pollutants.

III. PAGE STYLE

POLYMER OR NANOCOMPOSITE	Water Pollutants and Performances	References
Clay and Chitosan nanocomposite created by A dip-coat method with the smallest pore size at 13 nm	Achieved complete removal of 500 µg/L 1000 µg/L As (III) and Hg (II)	[95]
Chitosan hollow fibers with nanosized Fe3O4 as Fenton-like catalysts	Demonstrated Reactive Blue 19 (RB 19) dye clearance rate of 89.4% in a continuous system, and 74.4% for the reused catalyst	[92]
Nanocomposite of Graphite oxide and poly (acrylic acid) grafted onto chitosan	Successfully removed dorzolamide (a pharmaceutical industry compound) at a rate of 447 mg/g	[92,96]
Beads containing chitosan, gum arabic, and carbon nanotubes (CNT) membranes with a BET area ranging from 78 to 198 cm²/g	Utilized for the removal of solids from water	[97]
Chitosan–montmorillonite membrane with montmorillonite content ranging from 10% to 50%	Functioned as an adsorbent for Bezactiv orange V-3R dye at 80 mg/L, achieving a	[98]

POLYMER OR NANOCOMPOSITE	Water Pollutants and Performances	References
by mass	maximum adsorption capacity (Qmax) of 279.3 mg per g	
Magnetic mesoporous carbon/β-cyclodextrinechitosan nanocomposite	Demonstrated extraction efficiency of fluoroquinolones ranging from 90.6% to 99.7%, with adsorption capacities ranging from 130 to 165 mg/g	[99]
Glutaraldehyde cross-linked chitosan-coated Fe_3O_4 nanocomposites	Achieved removal efficiency of Methylene Blue (MB) in the range of 96% to 98%, with an adsorption capacity of 758 mg per g	[100]
Nanocomposite using chitosan, polyvinyl alcohol (PVA), and zeolite	Successfully removed Red Congo is a colour that is effective of 94% and an adsorption capacity of 5.33 mg/g	[92,101]
Chitosane quaternized organic rectorite intercalated composites	Demonstrated efficiency of up to 90% for E. Coli removal	[102]
Chitosane–zinc oxide nanocomposite	Achieved a 99% efficiency in removing permethrin	[103]
(PEG) Polyethylene glycol / chitosan nanocomposite	Successfully removed nitrate from the water at a rate of 50.58 mg per g	[92,104]
Chitosan/ Al_2O_3 / Fe_3O_4 nanofiber	Efficiently removed phosphates at a rate of 135.1 mg per g	[105]
Nano-SiO_2-Cross-linked Chitosan-Nano-TiO_2 nanocomposite	Achieved removal efficiency of Hg in the range of 98% to 99.5%, with an adsorption capacity of 1515.2 mg/g	[92,106]
EPSs (bioflocculant and bio-adsorbent with bacterial cells and natural polysaccharides, lignins, proteins)	Demonstrated the removal of various pollutants, including heavy metals, from water using different strains of bacteria and EPSs	[55,57,107–111]
Novel (SA) sodium alginate supported tetrasodium thiacalix [4] arene tetrasulfonate (TSTC[4]AS-s-SA) nanogel and superparamagnetic nanocomposite	Displayed varying adsorption capacities and removal percentages for several heavy metals	[112]
Novel magnetic nanocomposite alginate beads with a 3:4:1 aspect ratio	Showed removal percentages and adsorption capacities for phosphate, copper, and toluene, along with information on isothermal and kinetic studies	[114]
PVA/SA beads formed by blending PVA with SA and incorporating zeolite nanoparticles (Zeo NPs)	Achieved high removal percentages for various heavy metals at different pH levels in both synthetic and natural wastewater samples	[115]
PVA/graphene oxide (GO)-SA nanocomposite hydrogel beads with an average size of 0.15–0.2 µm	Demonstrated an adsorption capacity of 279.43 mg/g for Pb(II) using the second-order kinetic model and Langmuir adsorption isotherm	[117]

Polymer or Nanocomposite	Water Pollutants and Performances	References
Alginate/Ag hydrogel with Ag nanoparticles of 19 nm size	Displayed a high adsorption capacity of 213.7 mg/g for Methylene Blue (MB) using the Langmuir adsorption model	[120]
Cellulose/CuO nanoparticles	Exhibited antibacterial activity against (Gram-positive and Gram-negative) bacteria for microbial disinfection of water	[121]

Bacterial polymers derived from microorganisms such as Bacterial polymers derived from microorganisms such as Pseudomonas, Halomonas, Paenibacillus, Bacillus, and Herbaspirillum have shown promising potential as flocculating agents for the removal of heavy metals like lead (Pb), mercury (Hg), cadmium (Cd), nickel (Ni), zinc (Zn), iron (Fe), and aluminum (Al), particularly from industrial effluents. These polymers can be extracted from various sources, including wastewater, activated sludge, and other materials [20]. Significantly, high nitrogen effluents can facilitate the formation of substantial amounts of microbial polymers, leading to enhanced immobilization efficiency for heavy metal contaminants.

Specific examples of different bacterial species producing microbial polymers that act as adsorbents for heavy metal removal include Bacillus licheniformis for chromium (Cr (VI)), Bacillus mucilaginosus for iron and lead, Herbaspirillium sp for arsenic (As), zinc (Zn), manganese (Mn), lead (Pb), aluminum (Al), iron (Fe), and chromium (Cr), Cloacibacterium normanense NK6 for iron (Fe), aluminum (Al), copper (Cu), zinc (Zn), and nickel (Ni), Rhizobium radiobacter and Bacillus sphaericus for copper (Cu) and nickel (Ni), among others. These microbial polymers have demonstrated the ability to address not only heavy metal contamination but also other water quality parameters such as turbidity and chemical oxygen demand (COD).

Furthermore, studies have revealed that a higher protein content in bacterial polymers can enhance their flocculation capacity, while a lower concentration of humic substances is associated with a higher total number of bacterial polymers. This is because each of these polymers plays a role in improving the overall efficiency of the flocculation process [21]. The interplay between the composition and concentrations of bacterial polymers and other water constituents significantly influences their performance in heavy metal removal and water treatment applications.

Air Decontamination

Air or atmospheric pollution is a significant environmental concern, particularly in growing nations. The most effective and readily applicable method for air decontamination remains air filtration. While the respiratory system can filter out most particulate matter (PM) when we breathe, PM 2.5, due to the variation in size, can penetrate the respiratory system, posing significant health risks. Its elevated surface area, a consequence of its size, makes it capable of adsorbing other harmful substances [22]. This looks into One (1) of the vital most widely recognized air pollutant is the black carbon (BC), with diameters ranging from 50 up to 80 nm, primarily produced during burning processes, especially when burning fossil fuels (such as coal, petroleum products, and gasoline) and the biomass. Its presence in the atmosphere significantly impacts the carbon balance, affecting climate change and overall air quality. Additionally, recent public health concerns have been raised due to the release of viral droplets, with sizes between 50 to 200 nm, contributing to atmospheric pollution during the current pandemic. More effective filtration methods, including those integrated into air conditioning systems, are required. Additionally, microorganisms are included in the PM 2.5 category along with hazardous gases, heavy metal atoms, and other organic pollutants like benzene, aerosols, and polycyclic aromatic hydrocarbons. category, significantly impacting the environment [23]. Conventional filters are characterized by low porosity (typically <30%) and are constructed from porous materials with small pore sizes. The utilization of nanofibers significantly increases material porosity and surface area, leading to enhanced efficiency in capturing atmospheric pollutants. The automotive and aerospace industries, as major contributors to air pollution, are actively seeking efficient solutions to reduce emissions. The pursuit of sustainability in filters through the use of fibres, nanotubes, or various foamy materials has sparked study and development in this area. Of these, electrospun nanofibers have shown to be one of the most effective and versatile materials. The electrospinning method uses both synthetic and natural polymers. In contrast to synthetic options, the literature suggests that polysaccharides, collagen, silk, and cellulose are promising natural polymers for this application [24].

These different kinds of polymers can be combined into filters for air by electrospinning them. Advanced qualities appropriate for pollutant removal must be present in the materials used in order to obtain best performance in pollutant filtering and separation. Figure 4 shows how the sizes of PM are directly related to the removal processes on the material's surface.

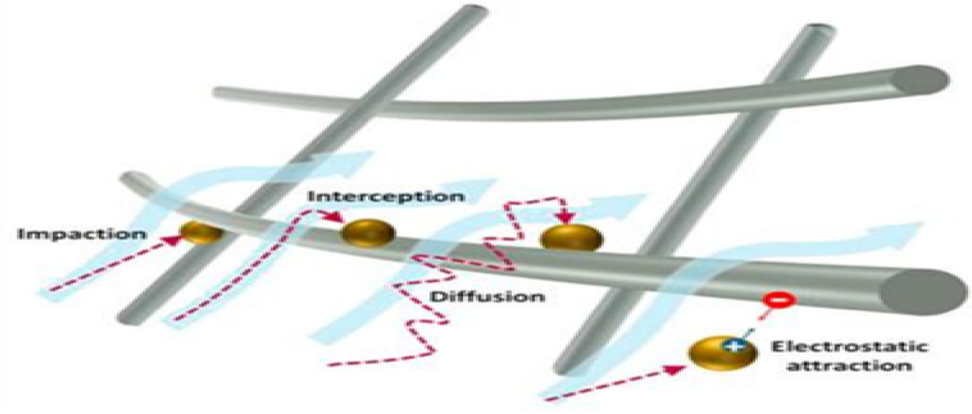

Figure 4. Impingement, spying, dissemination, and magnetic attraction are the four main categories of particle filtering methods. These processes are primarily mediated by diffusion, electrostatic attraction, impaction, and interception. In an equally significant concern is the reusability of filters and their environmental sustainability. Developing new materials remains a challenge, but nanofibers and nanocomposites exhibit great promise as structures with exceptional filtration capabilities.

Conventional air filtration membranes, typically constructed from materials like glass, consist of fibers at the micrometer scale [24]. Such membranes have relatively large pores, allowing ultra-fine particles (PM 2.5) and bacteria to pass through, thus affecting air quality In contrast, electrospun nanofiber membranes exhibit an interconnected pore structure that results in pores of manageable size with substantial surface area and porosity. An important aspect of air filtration membrane design relates to the methods used for their synthesis. Often, the preparation steps involve the use of toxic organic solvents, which can have adverse environmental implications. Moreover, these solvents might pose a safety hazard due to flammability. Another challenge lies in achieving multifunctionality, where the membrane needs to simultaneously filter inorganic, organic, and bacterial materials. Various For the successful creation of nanofibrous barriers for cleaning, basic synthetic polymers like polyimide (PI) [25], PU, PAN, polyamide, and polysulfone have been used. purposes. The environmental impact of membrane fabrication extends beyond air filtration efficiency. Therefore, the development of eco-friendly materials through green synthesis methods is essential for overall membrane efficiency. As a result, green electrospun materials have been engineered to produce fibrous membranes[26]. To achieve this, specific Polymers that are natural and biocompatible—that is, soluble in non-toxic solvents like ethanol, water, or acetic acid—have been developed and examination.

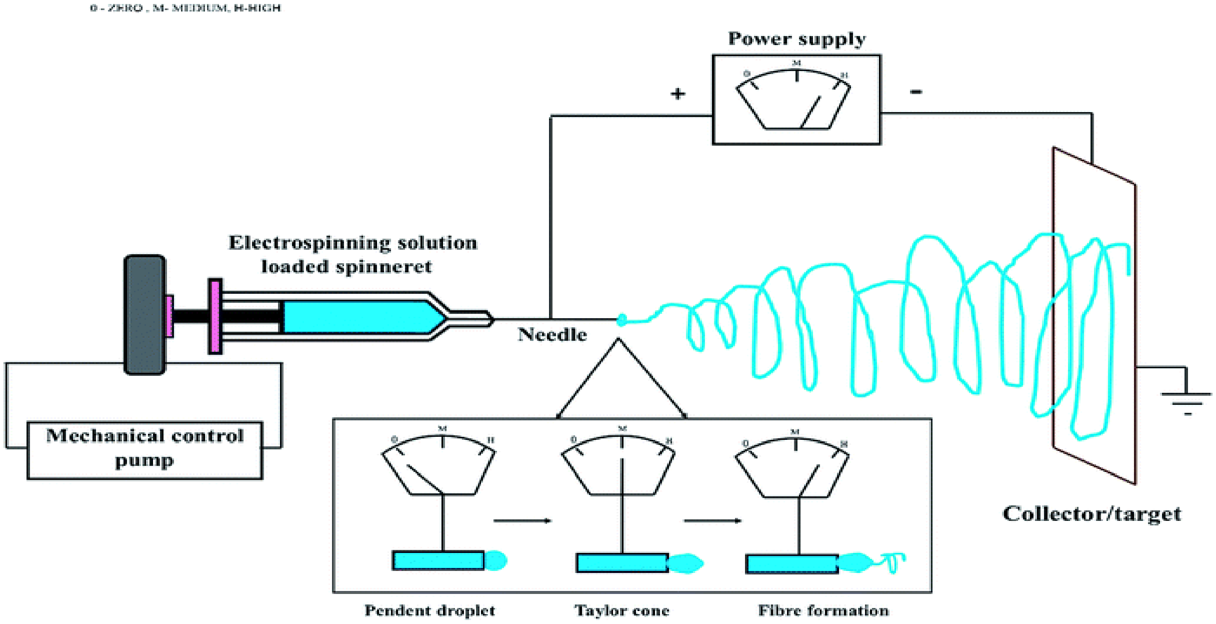

Figure 5 illustrates an environmentally friendly electrospinning technique integrated with UV treatment.

It showcases the production procedure for CS-PVA nanofibrous films with antibacterial and hierarchical properties that include one-step (UV) reduction, healing, and electrospinning (a). Additionally, the picture illustrates (b) the CS-PVA@SiO2 NPs-Ag NPs filter the air films' filtering process and (c) the chemical arrangement of CS/PVA/TEGDMA/1173.

A primary obstacle associated with this environmentally sustainable electrospinning technique is the restricted stability of the fibres, namely the nanofibers. UV reduction and thermal cross-linking techniques are used to overcome this problem. Ag nanoparticles are incorporated into the nanofibrous membrane to provide not only antibacterial but also enhances the efficiency of removing both non-oil and oil aerosol particles. Furthermore, the ongoing pandemic has necessitated approaches for reducing pathogens, particularly in the manufacturing of face masks. The majority of conventional masks for the face are made of artificial substances that are not biodegradable, and their widespread use has an adverse effect on the environment. In order to address this issue, a unique substance that exhibits antibacterial action against Staphylococcus aureus and Escherichia coli, In fact, SARS-CoV2 has been created by adding SiO2-Ag composite materials to a polymeric matrix made of ethyl vinyl acetate. Alternative approaches have been investigated to address these issues, such as using biodegradable and environmentally friendly supplies as face mask substrates. For example, hybrid composite nanofibrous layers have been created using renewable nanofibers. TiO2 nanotubes were used as spacers into electrospun nanofibers composed of chitosan/PVA and silk / PVA to create these nanofibrous layers. The face mask filters were designed with chitosan/PVA and silk/PVA as the middle and inner composite layers, respectively, to control protection and prevent contamination.

Significant health concerns arise when unstable organic matter are coupled with air pollution. As a result, attempts have been undertaken to create improved ocular and multifunctional air filters that are both economical and ecologically benign. Because of their optical characteristics, silk protein nanofibers produced by electrospinning have outperformed traditional semi-HEPA filters in terms of efficiency. Furthermore, when their useful lives are coming to an end, these nanofibers spontaneously disintegrate. Additionally, biodegradable poly (l-lactic acid) (PLLA) polymer has been utilised in the production of electrospun nanofibers for air filters, a product of biotechnologies. PLLA nanofibers have outperformed a commercial 3M filtering system, with a success rate of over 99% for PM 2.5. As a result, PLLA biodegradable nanofibers provide industrial air equipment developers with new opportunities and filtering capabilities at a reasonable price. The key attributes of polymer substrates for air purification are summarized in Table 2.

Table 2. Principal functions of natural polymers as air decontamination filtering substrates.

Pollutants	Polymer Type	Performance and Mechanism	References
PM 2.5 and 10 µm	Electrospun silk protein nanofibers	Achieved air filtration 90% efficiency for PM 2.5 and 97% efficiency for PM 10 exceed the capabilities of semi-high-efficiency particulate air (semi-HEPA) systems seen in business settings. filters. These nanofibers naturally degrade over time.	[217]
PM 10 µm (including DEHS and NaCl aerosol particles)	Chitosan/PVA nanofibers with SiO2/Ag nanoparticles	Demonstrated a filtration efficiency of 96% for particles ranging from 300 nm to particles at the micron level, 1 µm and 100%. The weights of the composite barrier varied from 1.48 to 6.2 g/m³, and the matching filtering efficiency for NaCl particles varied from 42.97% to to 96.60% and for DEHS particles ranging from 51.01% to 99.12%.	[178]
PM 2.5 and 10 µm	Biodegradable electrospun PLLA polymer nanofibers	Achieved a filtration efficiency of 93.3%. The PLLA filtration layer outperformed the 3M ventilator in terms of PM 2.5 particle quality factor despite 6 hours of filtration. It also showed great porosity of (91.9%), 4.5 m²/g of particular surface space, and an ability to store dust of 7.36 g/m².	[219]

Pollutants	Polymer Type	Performance and Mechanism	References
PM 2.5	Electrospun nanofibers with an average diameter of 239 nm	These nanofibers displayed good permeability (10–11 m^2) & and great-efficiency filtration for aerosol nanoparticles, including Black Carbon (BC) and the new coronavirus, with a pressure drop of 1.8 kPa at 1.6 cm/s. They also retained BC particles from the air, with an efficiency of about 90% for 375 nm and about 60% for 880 nm wavelengths. The nanofiber retention organization for the atmospheric PM 2.5 and BC were analysed.	[43]
PM 0.3 and PM 10	ZnO@PVA/konjac glucomannan membranes and gelatin nanofiber	Achieved great filtration with the accuracy of 99.99% for ultrafine particulates with a size of 300nm for ZnO@PVA/KGM, and a filtration efficiency of 99.3% for PM 0.3 and 100% for PM 2.5 for gelatin nanofiber.	[189,219]
PM 2.5 and Escherichia coli	Soy protein isolate (SPI)/PVA electrospinning membrane	Demonstrated an efficient filtration of 99.99% for PM particles that are smaller than (2.5 μm) and exhibited an inhibiting effect on Escherichia coli.	[220]

The combination of (CA) nanofibers with the cationic surfactant (CPB) through electrospinning presents an effective solution for the removal of aerosol nanoparticles & PM 2.5 in the air. These aerosols can include black carbon (BC) or even coronaviruses, and the system achieves a 100% removal efficiency. These results suggest the potential for designing future Face masks and ventilation filters made of biodegradable and ecological polymers. Moreover, chitosan, an organic polymeric foundation, was combined with PVA to form multifunctional membranes. Additionally, this kind of membrane demonstrated biological and antimicrobial qualities. High filtering efficiency was also shown by electrospun nanofibrous films that included hydrophobic nanoparticles of silica in a PVA-citric acid matrix. Testing a natural polymer called KGM in conjunction with electrospun PVA nanofibers for the purpose of filtering harmful aerosols was the focus of another strategy.

IV. CONCLUSIONS AND FUTURE PERSPECTIVES

In conclusion, this review highlights recent developments in the usage of polymeric nanocomposites and natural polymers, especially with regard to the extraction and suspension of heavy metals (HMs) and related organic compounds from water and the environment. A good standard of living is dependent on sustainable solutions to address major environmental issues like waste management, carbon emissions, and air and water quality. The implementation of concepts such as sustainable development and the circular bio-economy is vital in order to protect biodiversity and ensure a stable and clean environment for future generations.

The enormous potential of existing natural resources, especially industrial biomass made from natural materials like polymers. The use of organic polymers in industries such as biomedicine, pharmaceuticals, and food production is already well-established. Recent research in environmental remediation, particularly in soil treatment, has shown promising outcomes with natural polymers, especially chitosan, either individually or as nanocomposites. This paper compiles the most pertinent findings in the context of Natural polymers and their nanocomposites are used as remediation materials in air, soil, and water ecosystems. Based on our research, novel materials with significant potential for removing target contaminants from integrated soil, water, and other systems can be created by fusing a natural component with a nanoscale element. Based on the first findings, these results confirm the efficacy of heavy metal removal and present new opportunities for tackling organic pollutants. The work highlights the benefits of using nanocomposites by leveraging the complementary functions of both of its constituents—nanoparticles as well as polymers—which result in improved characteristics like stability, reactivity, and a certain size. Additionally, the availability and affordability of natural polymers as environmentally conscious components are benefits. With an increasing emphasis on environmental rules and a more thorough perspective for the future, the focus should be on scaling up these advancements for industrial and business uses, building on the shown laboratory efficiency.

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