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Immobilization of silver nanoparticles on solid materials and their applications: A Review

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ABSTRACT

Nanotechnology is a rapidly developing interdisciplinary field of science. Its emergence is due to the potential for revolutionary breakthroughs in various fields of human endeavor, such as medicine, agriculture, the food industry, biosensors, electronic devices, biotechnology, water purification, environmental remediation, and robotic systems. The colloidal AgNP is synthesized and used for many applications, but agglomeration and instability are leading problems associated with their synthesis. Hence, the use of solid carriers seems to address such problems. The immobilization of silver nanoparticles (AgNP) on the carrier mainly occurs based on the charge differences between the carrier and the silver ion (Ag^+), which form a strong bond. The reduction of Ag+ to AgNP during the formation of nanocomposites (NCs) occurs by chemical, physical, or biological processes. The NCs formed with solid supports can prevent agglomeration and exhibit high thermal, mechanical, and chemical stabilities. Due to these unique properties, many NCs can be synthesized using nanotechnological processes, developing innovative techniques that improve human life. This review focuses on various methods used in immobilizing AgNP on different solid substrates as supports and their applications, such as in biomedical, food industries, and water treatment, among other areas. Several methods for immobilizing AgNPs could be used to produce NCs for other important applications.

Keywords: *Nanocomposites, silver nanoparticles, immobilization, solid carriers*

1. INTRODUCTION

Nanotechnology has tremendous potential applications owing to the unique size-dependent properties of nanoscale materials, which have significantly influenced all domains of human existence. This technology has enabled the development of numerous innovative nanomaterials with useful applications [1]. Over the years, metal nanoparticles (NPs) such as silver have drawn considerable attention due to their exceptional optical, electrical, and antibacterial capabilities [2].

In contemporary scientific discourse, silver nanoparticles (AgNP) have emerged as one of the most extensively researched materials, particularly within the field of nanotechnology and its resulting nanostructures over the past few decades. AgNPs are defined as nanoscale entities composed of elemental silver (Ag), exhibiting diameters ranging from 1 to 100 nm. A variety of methods have been used for the synthesis of AgNP, including chemical reduction [3], laser ablation [4], [5], [6], thermal decomposition [7], [8], and sonochemical methods [9], [10]. Due to their special properties and increasing use in various biomedical applications, AgNPs have attracted considerable attention as novel nano products [11], [12]. Among the various synthetic routes, chemical reduction techniques and laser ablation have emerged as the two most popular options [2], [6], [13]. On the other hand, plants and microorganisms can be used to synthesize NPs similar to the methods previously described. The plant entity contains protective capping agents, including proteins, flavonoids, polyphenols, esters, sugars, alkaloids, and organic acid groups that occur naturally. These substances limit the amount of the metal and mitigate its harmful effects [14], [15]. Such agents affect the physicochemical properties of AgNP, such as particle size, size distribution, shape, dispersion, and stability, which are crucial for their outstanding efficiency [16]. Despite the effectiveness of AgNPs produced by both methods, the agglomeration of these NPs limits their effectiveness due to their bonding nature to each other, preventing direct access to the target substrate. Therefore, there is a need for solid materials that can be used to immobilize NPs and serve as carriers, which can improve their efficiency and control their release into the environment. The incorporation of NPs such as AgNP on the solid particulates is a new alternative way to improve their usage owing to less toxic effects and environmental friendliness, which is termed as a nanocomposite (NC). For example, AgNP exhibits remarkable antibacterial properties, possesses anti-inflammatory effects, and functions effectively as a drug carrier; thus, their incorporation into solid matrices to form NCs renders them a promising candidate for applications in wound healing.

Nanocomposites (NCs) are classified as multiphase materials wherein at least one constituent exhibits dimension within the nanometer scale (10–100 nm). The probability of interaction between the matrix and the reinforcing nanoparticles in NCs is significantly high due to the pronounced surface-to-volume ratio. The enhancement of properties in any NC is contingent upon the characteristics of the component materials as well as the overall geometry of the NCs. Distinct materials possess unique properties, which, when amalgamated, yield a novel material endowed with supplementary advantages pertinent to various domains of research. These materials exhibit exceptional thermal and mechanical stability, multifunctional capabilities, and opportunities for chemical functionalization, among other attributes [16], [17]. NCs can be produced with individual carriers or in combination for specific applications. NCs consisting of biopolymers or inorganic solids are widely used in regenerative medicine, drug delivery, tissue engineering, electronics, and food packaging [18]. Applying synthesized nanocatalysts on a combined solid of silica and carbon maximizes their catalytic activity, selectivity, and stability [19]. NCs made from biopolymers have advantages when used as tissue scaffolds in healthcare due to their improved properties, such as biodegradability (BD) and biocompatibility (BC). Once NCs are incorporated, packaged, or covered in various materials, they can be used as antibacterial agents in medical and surgical equipment or artificial antimicrobial fabrics [20]. NCs can be formulated by various methods, such as mixing techniques (melt mixing, ultrasonication, melt shear mixing), chemical methods (functionalization of NPs, addition of surfactants, photoinitiated polymerization, in situ polymerization) [21], [22], and physical methods (coprecipitation, solution casting, electrospinning) [23], [24]. The immobilization of silver nanoparticles (AgNP) can be accomplished through either an in-situ or ex-situ methodology. In instances where the immobilization occurs after the independent synthesis of AgNP, followed by a stirring or shearing process and ultimately centrifugation, this method is classified as ex-situ. Conversely, when the Ag^+ derived from the precursor $AgNO_3$ is affixed to the surface, potentially influenced by charge disparities similar to those in clay minerals, and is subsequently sheared within a liquid medium to facilitate the reduction of Ag^+ to AgNP, followed by centrifugation to segregate the solid phase from the reaction medium—typically an aqueous environment or alternative processes—this approach is referred to as the in-situ technique.

The immobilization of individual NPs on solid supports not only overcomes the inherent limitations of NPs but also expands their range of applications. Further surface modifications are required to enable specific interactions between the NPs or their precursors and the substrate. This is paramount to ensure that the incorporation of nanoscale materials into formulations does not compromise the effectiveness of the NPs. Therefore, the main aim is to investigate the various possibilities for developing low-cost, non-toxic, and environmentally friendly NC materials using solid supports. This review focuses on the consideration of solid materials commonly used to immobilize AgNP, leading to the formulation of NCs.

2. THE EXPERIMENTAL WORKS

2.1. Silver Nanoparticles Immobilize on Clay/ Clay Mineral

Advances in nanotechnology have led to the production of various NPs, which are usually in powder form. However, these NPs often form hard agglomerates that reduce the surface-to-volume ratio, which limits their application performance [25]. The use of solid materials to prevent such occurrences includes, but is not limited to, natural clay. Clay minerals are commonly observed as byproducts of weathering and end products of hydrothermal alteration in rocks [26]. These minerals are present in many soils, fine-grained sedimentary rocks, and metamorphic rocks [27], [28]. Due to their abundance, environmental friendliness, and diverse properties, natural clay materials are considered one of the most reliable and widely used substances for making NC. Numerous clays and clay minerals are used as excipients and active components in both cosmetic and pharmaceutical industries. Clay minerals such as halloysite and montmorillonite are used in the biomaterials industry to produce scaffolds, foams, and hydrogels [29]. These minerals are also known for their effectiveness as carriers for active medicinal molecules, ensuring their controlled and consistent delivery. Therefore, there are many reports of using these minerals as carriers for AgNP for specific purposes. In conjunction with its large surface area, the anionic surface charges of plate-like clay serve as a carrier medium for AgNP [30], [31]. Understanding the charge differences between the clay surface and the immobilized molecules of organic or inorganic origin is crucial for NC formulations [32], [33], [34]. Most of the naturally occurring solid materials can be used to produce NC. For instance, a novel technique for the synthesis of AgNP by employing clay mineral (montmorillonite) and polyvinyl pyrrolidone (PVP) suspensions through an electrochemical strategy has been formulated [35]. This research underscored the potential of clay minerals as a substrate for AgNP. Moreover, the investigation using biosensors based on acetylcholinesterase immobilized on clay, which modified the clay minerals with gold and AgNP, highlighted the fixation of enzymes on clay minerals that could be used for diverse applications [36]. Moreover, the study reports that the immobilization of AgNP on various substrates, such as clays, improves the properties of these minerals [40]. The immobilization of AgNP onto halloysite was observed using nanotubes and was deliberated via in situ reduction of $AgNO_3$ [37]. Using clay minerals as supports for NPs was described as an effective catalyst [38], emphasizing their significance in sensor production. The recent review examined the evolution of clay minerals as nanocarriers for AgNP [39]. The investigation of ZnO/nanoclay hybrids delved into immobilizing AgNP onto clay minerals, demonstrating the potential of noble metal nanomaterials in this domain [40]. Figure 2 outlines how the AgNP can be immobilized on the natural clay to form a nanocomposite material for antibacterial purposes.

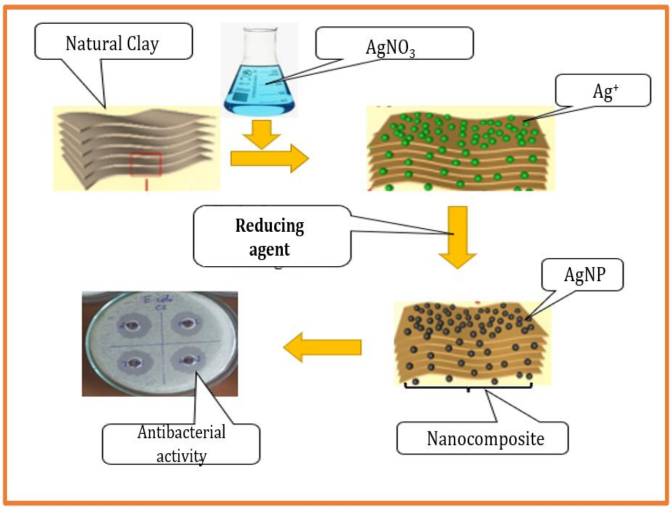

Figure 1. Schematic process of immobilization of AgNP onto natural clay to form a nanocomposite as an antibacterial agent

NCs can be synthesized when NPs of any metal ion have been incorporated into the solid materials for a specific application through certain analyses. Using clay minerals alone or combined with other various clay materials or with clay and other organic or inorganic carriers can be an excellent supporting material. Table 1 shows that the clay alone or in combination with another carrier might be used as a nanoparticle support in various applications. Among them, montmorillonite is the most commonly used clay mineral due to its high surface area, its environmental friendliness, and its availability in large quantities [41].

2.2. Silver Nanoparticles Immobilized on Solid Carbon Materials

The exceptional deposition, adhesion, and stability of AgNP on carbon-based materials, including carbon fibres, carbon nanotubes, and graphene, have attracted great interest among various support materials [58], [59]. The surface modification of these materials can be achieved through acid treatment, leading to the formation of oxygenated compounds such as OH and COOH on the outer surface of carbon-based materials [60]. These functionalized groups introduce significant covalent bonding domains that enable AgNP to adhere to carbon surfaces [61]. However, despite the simplicity of these functionalization processes, long-term exposure to acidic environments is often required, which is both time-consuming and generates hazardous waste [62]. Due to this, an author proposed a simple laser-based method to facilitate the efficient surface functionalization and immobilization of AgNP on carbon membranes made of woven carbon microfibers [65]. This method is described as simple, effective, and reliable compared to the acid-based technique [63]. Figure 2 shows the process of forming carbon-based NC functionalization by modifying the surface of carbon materials and forming carbon fibre NC as an efficient antibiofilm material. Similarly, another author described the successful immobilization of AgNP on a multi-walled carbon nanotube using a Potato Dextrose Agar-assisted technique [67]. An attempt to invent a new material made from a carbon source was produced to improve Faradaic efficiency and lower the overpotential for converting CO2 to CO by using immobilized AgNPs supported on carbon-based materials [68]. Furthermore, it was postulated that a unique hydrothermal process for preparing carbon spheres immobilized with AgNP as a potential antibacterial agent was successfully achieved [69]. The remarkable safety and biocompatibility of carbon-based AgNP suggest that they could also be used as intracellular imaging materials.

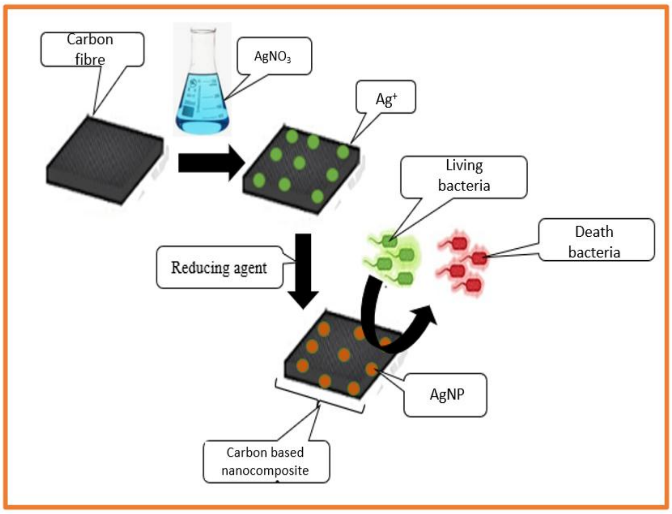

Figure 2. Immobilization of AgNP onto the carbon-based material as an antibacterial nanocomposite

2.3. Silver Nanoparticles Immobilized on Chitosan

Chitin is a naturally occurring biopolymer prevalent in the exoskeletons of crustaceans, the integuments of arthropods, the scales of reptiles, and the cell walls of fungi [64]. It ranks as the second most prevalent biopolymer that yields N-acetyl glucosamine on a global scale [65]. Chitosan, which is derived from the deacetylation of chitin and consists of glucosamine and N-acetylglucosamine interconnected by a (1-4)-glycosidic linkage, exhibits significant potential for application in food packaging owing to its economic viability, antibacterial properties, ability to form films, nontoxic nature, and biodegradability [66], [67]. Chitosan is classified as a biocompatible (BC) and biodegradable (BD) polymer, which offers structural versatility for both chemical and mechanical modifications aimed at engendering novel properties that are particularly applicable in the biomedical domain. Over the past several years, investigations into functional biomaterials, such as chitosan, have facilitated the advancement of innovative drug delivery systems and enhanced tissue regeneration capabilities, which have emerged as one of the most rapidly expanding sectors within the biomedical arena. It is acknowledged as a biomaterial due to its attributes of biocompatibility, biodegradability, and non-toxic characteristics [68]. These attributes suggest that chitosan possesses substantial potential for future applications across diverse scientific disciplines, including drug delivery, gene transfer, cellular imaging, sensor technology, and the treatment and diagnosis of various ailments, including malignancies such as cancer.

Researchers in the biomedical and pharmaceutical industries are interested in utilizing chitosan and its products due to its biocompatibility, biodegradability, and antibacterial nature [69]. The incorporation of cations can be easy due to the negatively charged nature of chitosan, which can easily attract positively charged metals such as Ag^+ for the synthesis of AgNP, and therefore, it could be considered a suitable carrier for the immobilization of AgNP [70]. However, due to spatial limitations, using nanoscale materials would effectively hinder the aggregation of AgNP. Another literature report describes the successful incorporation of AgNP into chitosan, forming NC for food packaging applications [76]. Similarly, the formulated NC material served as a promising novel and innovative composite material used in the food industry [77]. It has been shown that integrating chitosan-incorporated laponite (synthetic smectite clay) with AgNP significantly improves water solubility and mechanical properties while limiting the release of AgNP from chitosan-based films, potentially reducing its harmful effects [71]. In addition, this nanocomposite has shown high antimicrobial potential, which could overcome the limitations associated with the use of nano-silver in food preservation. The use of chitosan-based hydrogel beads immobilized with AgNP by polydopamine (biomimetic and self-adherent polymer) coating improved antimicrobial activity and removed dyes and Cu (II) ions [72]. This composite can enhance the adsorption performance of the beads concerning the aforementioned adsorbates. Moreover, surface-immobilized chitosan AgNP was found to exhibit better antibacterial activity than various other monodisperse colloidal AgNPs. The composite was produced and exhibits an antibacterial effect through "contact killing" and "ion-mediated killing" and subsides the cytotoxic effect of AgNP [80]. Correspondingly, a chitosan-cellulose membrane with integrated AgNP has shown remarkable antibacterial activity against *S. aureus* and *E. coli* [73]. Figure 4 shows how the NC was produced by immobilizing AgNP on chitosan for the oral treatment of pathogenic bacteria.

2.4. Silver Nanoparticles Immobilized on Organics Shells

Approximately 8 million metric tons of shells from crab, shrimp, and lobster are generated on a global scale yearly, in addition to 10 million metric tons of waste originating from oysters and other sea organisms' shells [74]. The cast-off shells are routinely either discarded into marine environments or transported to land disposal sites, where they have a significant impact [75]. The by-products derived from these exoskeletons represent a substantial waste stream that ought to be repurposed as a novel raw material to maximize their utilization. Numerous applications for these waste shells exist across various domains, including agriculture, healthcare, construction, ecological conservation, the cosmetics sector, the food and feed industries [76], and other uses, which are continually being explored and developed, such as NC formulation. Hence, converting industrial and agricultural wastes into useful materials is highly recommended, as they can pollute the environment if deposited in large quantities. For instance, egg shells, a well-known biowaste material rich in calcium carbonate, are widely accessible and have been extensively researched for their multiple applications [77], [78], [79]. Moreover, it has been widely used as a sorbent to remove aromatic compounds and dyes [80], [81]. A research group studied the potential of egg shells for their sorption efficiency in removing inorganic and organic pollutants from wastewater [88]. In addition, a simple and environmentally friendly approach for the synthesis of AgNP using Sapindus mucorossi extract is immobilized on the surface of powdered eggshells [89]. The composite showed strong antimicrobial activity against E. coli, S. aureus, and C. albicans, and its effectiveness in eliminating chromium and industrial dye pollutants. The shell composite with AgNP, which was reduced by Tamarindus indica seed hulls, Ceratonia siliqua locust bean gum, and glucose oxidase, is a promising glucose sensor [69]. Similarly, seashells were used as a carrier of green synthesized AgNP through immobilization, which served as a catalyst and exhibited good catalytic activity for the reduction of dyes [82]. Figure 5 shows the immobilization of AgNP onto the eggshell for dye-removing purposes. In the part using shells from plant-based materials, the literature reports the synthesis of NC with dye-removing potential. AgNPs/peach kernel shell were then produced by Achillea millefolium L. extract by reducing Ag+ ions. It was found highly dispersed on the surface of the shell, which was used for the reduction of 4- Nitrophenol (4-NP), Methyl Orange (MO), and Methylene Blue (MB) in the dye-contaminated water [83]. The formation of AgNP on the supporting carriers demonstrated biocompatibility in clinical applications. Furthermore, incorporating AgNP into biomaterials leads to reduced cytotoxicity and lower chances of cellular uptake of AgNP [82].

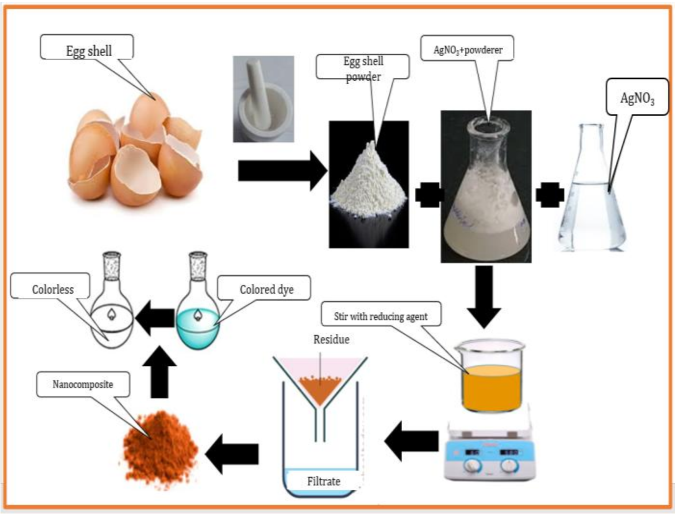

Figure 3. Immobilization of AgNP onto the eggshell used as a dye degradation nanocomposite material

2.5. Immobilization of Silver Nanoparticles on Cellulosic Fibres

Cellulose fibres are an indispensable raw material in the textile industry and play an important role in the manufacture of a wide range of products such as clothing, household materials, and nonwovens. Textiles, which include nonwoven and knitted fabrics, can be made from cellulose alone or in combination with synthetic materials. The market offers a wide range of cellulose fiber-based products, including surgical dressings, shoe covers, pillowcases, nappies, household wipes, sorbents, and feminine hygiene products [84]. The increase in value of cellulose fiber-based products through improved performance is significantly influenced by the surface treatment. Another article demonstrated the efficacy of an in-situ synthesis method to deposit AgNP on the surface of absorbent cotton without the need for reducing agents [93]. Consequently, the antibacterial properties of the silver-loaded cotton fabric were superior to those of the untreated fabric [85]. The potential of nanofibers can be increased by modifying them to improve their surface area, specificity, and reactivity, making them more attractive than unmodified fibres [86]. A novel green in situ approach for immobilizing AgNP on the surface and inside cellulose fibres was proposed, exhibiting antibacterial properties even after several washing cycles [95]. Immobilization of NPs on natural cellulose fibres is possible due to surface charge differences caused by numerous hydroxyl groups in the insoluble glucose polymer of cellulose. Deprotonation (proton removal) of this polymer can lead to negative charges on its surface, which can attract Ag^+. This technique can, therefore, be used for the synthesis of AgNP. AgNP incorporation enhances antibacterial properties in tissues, jute fabrics, and natural fibres like cotton, jute, flax, sisal, and coconut [96]. These fibres have been proven to resist E. coli and B. subtilis, and can also confer additional properties like antimicrobial and super-hydrophilic properties. Coating cotton fibres with acrylic acid also enhances AgNP loading capacity [97]. It investigated the efficacy of natural fibres loaded with AgNP, such as cotton, jute, flax, sisal, and coconut fibres for antibacterial application [98]. They discovered their efficacy against *E. coli* and *S. aureus*. This modification can confer additional properties besides antimicrobial activity. The incorporation of AgNP into the wool fabric-silica composite resulted in antimicrobial and super hydrophilic properties [99]. Additionally, one of the research groups claimed that coating cotton fibres with acrylic acid increases the loading capacity of AgNP, resulting in the highest antibacterial activity and the potential for further properties [100].

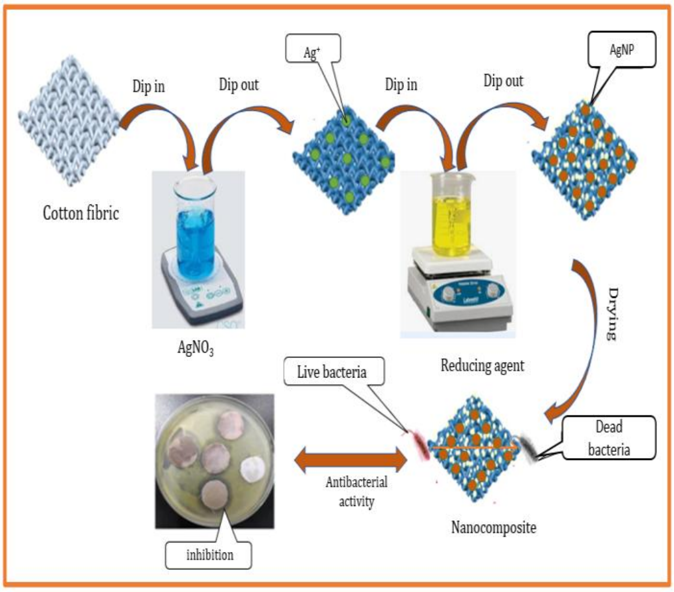

Figure 4. Immobilization of AgNP onto the cotton fabric as an antibacterial material

2.6. Immobilization of Silver Nanoparticles on Synthetic Po;ymers

Synthetic polymers are defined as polymers artificially produced in laboratories, also known as condensation polymers or manufactured polymers [87]. These materials are classified as thermoplastic (moldable at elevated temperature) polymers, thermosetting (obtained through irreversible hardening) polymers, and elastomers (rubbery). Notable examples of synthetic polymers include polyethylene (PE), polyamides (PA), polystyrene (PS), polyvinyl chloride (PVC), polyisoprene (PI), and polytetrafluoroethylene (PTFE), among a plethora of others. Polymers synthesized from petroleum-derived monomers are typically generated in a controlled laboratory environment, with their molecular structure predominantly consisting of carbon-carbon linkages [88]. These materials are prevalent across various sectors, serving critical roles in textiles, packaging, construction, medicine, and a multitude of other significant applications. Synthetic polymers represent a highly versatile and heterogeneous category of materials, many of which are specifically employed in drug delivery systems, solubilization processes, nanoparticle formation, surface modification, drug transport, diagnostic imaging, and implantation procedures [89]. Furthermore, certain synthetic polymers exhibit a range of biological activities, including antitumor, antibiotic, antiviral, and antithrombotic properties, in addition to their capability to inhibit efflux pumps such as P-glycoprotein [90].

There are man-made polymers formed by the reaction of monomeric structural units. The polymers can be synthesized in laboratories using either similar or different monomeric subunits. They are inexpensive and easy to process, but can pollute the environment because they are not biodegradable. These types of polymers are different from natural polymers because they occur naturally. Nylon, polyethylene, epoxy, polyvinyl chloride, polypropylene, and others are just a few examples of synthetic polymers. Some researchers reported the incorporation of NPs into synthetic polymers and pointed out the use of NCs in synthetic polymers for biomedical applications such as tissue engineering, wound treatment, and healing [91], [92]. For example, some reports have mentioned the incorporation of NPs for drug delivery [93], [94], [95]. The use of silver-based synthetic polymer materials for cancer therapy has also been reported [96], [97], [98]. NCs of synthetic polymers can be used as scaffolds for bone regeneration due to their mechanical and BD properties [99]. Similarly, silver-based synthetic polymers can be used as water filters to improve the water purification system [100], [101], [102]. The incorporation and release strategy of AgNP on the polymeric materials can be seen in Figure 7.

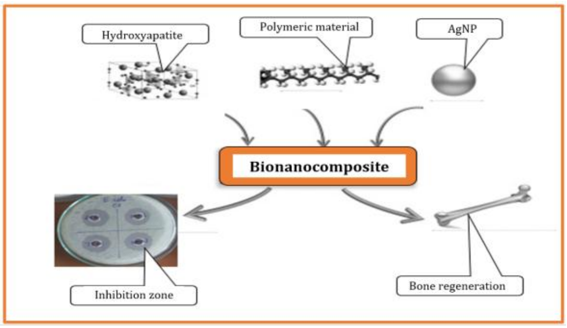

Figure 5. The immobilization of silver nanoparticles using polymeric matrices for biomedical purposes

3. CONCLUSION

In this review, the immobilization of AgNP onto the solid carriers for the formation of NC is feasible. The material in the NC form increases NP stability and increases chemical, mechanical, and thermal stability alongside the numerous strategies for immobilization processes. Various solid supporting materials used in NC were elucidated, such as clay minerals, carbon, fibres, shells, chitosan, and synthetic polymers, as well as their innovative synthetic methods and their diverse applications, which were described herein.

Table 1. Different nanocomposites prepared using clay minerals as carriers and their applications

Nanocomposite Designation	Carrier material	Application	Reference
HDPE/Ag-MMT	Montmorillonite	Antimicrobial agent	[42]
AgNP/kaolinite	Kaolinite	Antibacterial agents	[43]
BC-MMT-Ag	Montmorillonite	Antimicrobial Agent	[44]
AgNP/saponite	Saponite	Antibacterial agent	[45]
MMT/Ag	Montmorillonite	dye removal	[46]
Ag/Tlc and Ag/Tlc/Csn	Talc	Antioxidant/Antibacterial agent	[47]
Cs/Ag NP/clay	Unspecified Clay	Fabric Dying	[48]
O-MMt/Ag	Montmorillonite	Antimicrobial /Dye removal agent	[49]
Agar-CMC/Ag-MMT	Montmorillonite	Antibacterial/ Packaging Agent	[50]
GC/Ag-Bt	Bentonite	Electrocatalytic Agent	[51]
Ag/KlnNCs	Kaolinite	Antibacterial Agent	[52]
LLDPE/EVA/MMT/Ag	Montmorillonite	Mechanical/thermal properties/Antibacterial agent	[53]
AgNP-Zeolite/AgNP-montmorillonite/AgNP-palygorskite	Zeolite, Montmorillonite & Palygorskite	Antifungal Agents	[54]
POEGMA/Halosite-AgNP	Halloysite	Medical face masks	[55]
PALC/AgNP- MDP/AgNP	Palygorskite	Antibacterial agent	[56]
NSAg	Montmorillonite	Antimicrobial agent	[57]

Abbreviations: HDPE/Ag-MMT (High density polyethylene-silver-montmorillonite), AgNP/Kaolinite (silver nanoparticles-kaolinite), BC-MMT-Ag (Bacterial cellulose-silver-montmorillonite), Ag/Tlc (silver/Talc), Ag/Tlc/Csn silver-Talc-chitosan), AgNP/saponite (silver nanoparticles/saponite), Cs/AgNP/Clay (Chitosan/silver/clay), O-MMt/Ag (Organo-montmorillonite/silver), Agar-CMC/Ag-MMT (Agar-carboxymethyl cellulose/silver-montmorillonite), GC/Ag-Bt (Glassy carbon coated-silver-bentonite), Ag/KlnNCs (silver/kaolinite nanocomposites), LLDPE/EVA/MMT/Ag (Linear low-density polyethylene-vinyl acetate montmorillonite-silver), AgNP-zeolite (silver nanoparticle-zeolite), AgNP-montmorillonite (silver nanoparticle-montmorillonite), AgNP-palygorskite (silver nanoparticle-palygorskite), POEGMA/Halosite-AgNP (poly(oligo(ethylene glycol)ethyl ether methacrylate) Halosite-silver nanoparticles), PALC/AgNP (palygorskite-rich clay-silver nanoparticles), MDP/AgNP (multidimensional palygorskite silver nanoparticles), NSAg (Nanoscaling silver).

Therefore, solid natural or synthetic materials could be a promising carrier of NPs for various applications. This can prevent NPs' agglomeration, which is a problem associated with NPs, and control the release of AgNP into the immediate environment to avoid excessive exposure to AgNP, especially in connection with biomedical products, food packaging, and water treatment, as well as other applications involving living organisms and the environment. The fact remains that the immobilized AgNP synthesized from biological reducing agents, especially green-based approaches in NC formulations, are safer, cheaper, and more sustainable than chemically or physically synthesized and immobilized on the carrier.

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REFERENCES

[1] A. Soni *et al.*, “Nano-biotechnology in tumour and cancerous disease: A perspective review,” *J. Cell. Mol. Med.*, vol. 27, no. 6, pp. 737–762, Mar. 2023, doi: 10.1111/jcmm.17677.

[2] A. Ravindran, P. Chandran, and S. S. Khan, “Biofunctionalized silver nanoparticles: Advances and prospects,” *Colloids Surf. B Biointerfaces*, vol. 105, pp. 342–352, May 2013, doi: 10.1016/j.colsurfb.2012.07.036.

[3] L. Marinescu *et al.*, “Comparative Antimicrobial Activity of Silver Nanoparticles Obtained by Wet Chemical Reduction and Solvothermal Methods,” *Int. J. Mol. Sci.*, vol. 23, no. 11, p. 5982, May 2022, doi: 10.3390/ijms23115982.

[4] T. De Muijlder, M. Voué, and P. Leclère, “Laser Ablation Synthesis of Silver Nanoparticles for Polymer Nanocomposites,” *Energies*, vol. 16, no. 12, p. 4625, 2023.

[5] S. Mamdouh, A. Mahmoud, A. Samir, M. Mobarak, and T. Mohamed, “Using femtosecond laser pulses to investigate the nonlinear optical properties of silver nanoparticles colloids in distilled water synthesized by laser ablation,” *Phys. B Condens. Matter*, vol. 631, p. 413727, Apr. 2022, doi: 10.1016/j.physb.2022.413727.

[6] A. M. Ondieki *et al.*, “Fabrication of surface-enhanced Raman spectroscopy substrates using silver nanoparticles produced by laser ablation in liquids,” *Spectrochim. Acta A Mol. Biomol. Spectrosc.*, vol. 296, p. 122694, Aug. 2023, doi: 10.1016/j.saa.2023.122694.

[7] P. Singh and I. Mijakovic, “Strong Antimicrobial Activity of Silver Nanoparticles Obtained by the Green Synthesis in *Viridibacillus* sp. Extracts,” *Front. Microbiol.*, vol. 13, p. 820048, Feb. 2022, doi: 10.3389/fmicb.2022.820048.H.

[8] Y. Yang, S. Matsubara, L. Xiong, T. Hayakawa, and M. Nogami, “Solvothermal Synthesis of Multiple Shapes of Silver Nanoparticles and Their SERS Properties,” *J. Phys. Chem. C*, vol. 111, no. 26, pp. 9095–9104, Jul. 2007, doi: 10.1021/jp068859b.

[9] R. A. Salkar, P. Jeevanandam, S. T. Aruna, Y. Koltypin, and A. Gedanken, “The sonochemical preparation of amorphous silver nanoparticles,” *J. Mater. Chem.*, vol. 9, no. 6, pp. 1333–1335, 1999, doi: 10.1039/a900568dM.

[10] Summer *et al.*, “Bactericidal potential of different size sericin-capped silver nanoparticles synthesized by heat, light, and sonication,” *J. Basic Microbiol.*, p. jobm.202200632, Mar. 2023, doi: 10.1002/jobm.202200632.

[11] S. Gurunathan, J. W. Han, D.-N. Kwon, and J.-H. Kim, “Enhanced antibacterial and anti-biofilm activities of silver nanoparticles against Gram-negative and Gram-positive bacteria,” *Nanoscale Res. Lett.*, vol. 9, pp. 1–17, 2014.

[12] S. Suba, S. Vijayakumar, M. Nilavukkarasi, E. Vidhya, and V. N. Punitha, “Eco synthesized silver nanoparticles as a next generation of nanoproduct in multidisciplinary applications,” *Environ. Chem. Ecotoxicol.*, vol. 4, pp. 13–19, 2022, doi: 10.1016/j.enceco.2021.11.001.

[13] P. Imchen, M. Ziekhrü, B. K. Zhimomi, and T. Phucho, “Biosynthesis of silver nanoparticles using the extract of *Alpinia galanga* rhizome and *Rhus semialata* fruit and their antibacterial activity,” *Inorg. Chem. Commun.*, vol. 142, p. 109599, Aug. 2022, doi: 10.1016/j.inoche.2022.109599.

[14] M. S. Bapat *et al.*, “Evaluating green silver nanoparticles as prospective biopesticides: An environmental standpoint,” *Chemosphere*, vol. 286, p. 131761, Jan. 2022, doi: 10.1016/j.chemosphere.2021.131761.

[15] B. Ureña-Castillo *et al.*, “Organic Waste as Reducing and Capping Agents for Synthesis of Silver Nanoparticles with Various Applications,” *ChemistrySelect*, vol. 7, no. 26, Jul. 2022, doi: 10.1002/slct.202201023.

[16] [16] J. R. Beryl and J. R. Xavier, “Halloysite for clay–polymer nanocomposites: effects of nanofillers on the anti-corrosion, mechanical, microstructure, and flame-retardant properties—a review,” *J. Mater. Sci.*, vol. 58, no. 27, pp. 10943–10974, 2023.

[17] Z. Latif, M. Ali, E.-J. Lee, Z. Zubair, and K. H. Lee, “Thermal and Mechanical Properties of Nano-Carbon-Reinforced Polymeric Nanocomposites: A Review,” *J. Compos. Sci.*, vol. 7, no. 10, p. 441, 2023.

[18] R. Zafar, K. M. Zia, S. Tabasum, F. Jabeen, A. Noreen, and M. Zuber, “Polysaccharide based bionanocomposites, properties and applications: A review,” *Int. J. Biol. Macromol.*, vol. 92, pp. 1012–1024, 2016.

[19] F. de Clippel, M. Dusselier, S. Van de Vyver, L. Peng, P. A. Jacobs, and B. F. Sels, “Tailoring nanohybrids and nanocomposites for catalytic applications,” *Green Chem.*, vol. 15, no. 6, pp. 1398–1430, 2013.

[20] Y. F. Mustafa, “Modern developments in the application and function of metal/metal oxide nanocomposite–Based antibacterial agents,” *BioNanoScience*, vol. 13, no. 2, pp. 840–852, 2023.

[21] Y. Y. Huang and E. M. Terentjev, "Tailoring the electrical properties of carbon nanotube–polymer composites," *Adv. Funct. Mater.*, vol. 20, no. 23, pp. 4062–4068, 2010.

[22] N. Salahuddin, M. Elfiky, and A. Matsuda, "Sensors and biosensors nanocomposites based on polymer/inorganic nanostructures," in *Handbook of Polymer Nanocomposites for Industrial Applications*, Elsevier, 2021, pp. 709–731.

[23] N. T. Dintcheva, R. Arrigo, and F. La Mantia, "Reactive melt blending of functionalized-MW/CNTs with polyolefin," presented at the *AIP Conf. Proc.*, American Institute of Physics, 2012, pp. 369–371.

[24] F. Kamali, R. Saboori, and S. Sabbaghi, "Fe_3O_4-CMC nanocomposite performance evaluation as rheology modifier and fluid loss control characteristic additives in water-based drilling fluid," *J. Pet. Sci. Eng.*, vol. 205, p. 108912, 2021.

[25] S. P. Yeap, "Permanent agglomerates in powdered nanoparticles: Formation and future prospects," *Powder Technol.*, vol. 323, pp. 51–59, 2018.

[26] E. Manchado, M. Suárez, and E. García-Romero, "The Kaolin and Bentonite Deposit of Tamame De Sayago (Zamora, Spain): Mineralogy, Geochemistry, and Genesis," *Clays Clay Miner.*, pp. 1–18, 2023.

[27] S. Das and S. Vasudevan, "Peculiar study of clay minerals with special reference to illite and their climatic significance over the past 12 decades," *Arab. J. Geosci.*, vol. 15, no. 9, p. 924, May 2022, doi: 10.1007/s12517-022-10180-9.

[28] Y. Huang *et al.*, "Characteristics and genesis of ion adsorption type REE deposits in the weathering crusts of metamorphic rocks in Ningdu, Ganzhou, China," *Ore Geol. Rev.*, vol. 135, p. 104173, Aug. 2021, doi: 10.1016/j.oregeorev.2021.104173.

[29] F. Hakimi, H. Jafari, S. Hashemikia, S. Shabani, and A. Ramazani, "Chitosan-polyethylene oxide/clay-alginate nanofiber hydrogel scaffold for bone tissue engineering: Preparation, physical characterization, and biomimetic mineralization," *Int. J. Biol. Macromol.*, vol. 233, p. 123453, Apr. 2023, doi: 10.1016/j.ijbiomac.2023.123453.

[30] C. Nomicisio *et al.*, "Natural and Synthetic Clay Minerals in the Pharmaceutical and Biomedical Fields," *Pharmaceutics*, vol. 15, no. 5, p. 1368, Apr. 2023, doi: 10.3390/pharmaceutics15051368.

[31] R. Petrović *et al.*, "Removal of trivalent chromium from aqueous solutions by natural clays: Valorization of saturated adsorbents as raw materials in ceramic manufacturing," *Appl. Clay Sci.*, vol. 231, p. 106747, Jan. 2023, doi: 10.1016/j.clay.2022.106747.

[32] M. Isah *et al.*, "Preparation and characterization of chlorhexidine modified zinc-kaolinite and its antibacterial activity against bacteria isolated from water vending machine," *J. Environ. Chem. Eng.*, vol. 8, no. 2, p. 103545, Apr. 2020, doi: 10.1016/j.jece.2019.103545.

[33] S. K. Jou and N. A. N. N. Malek, "Characterization and antibacterial activity of chlorhexidine loaded silver-kaolinite," *Appl. Clay Sci.*, vol. 127–128, pp. 1–9, Jul. 2016, doi: 10.1016/j.clay.2016.04.001.

[34] N. A. N. N. Malek and N. I. Ramli, "Preparation and antibacterial properties of cetylpyridinium bromide-modified silver-loaded kaolinite," *Mater. Res. Express*, vol. 6, no. 9, p. 094006, Jul. 2019, doi: 10.1088/2053-1591/ab2e52.

[35] Q. Yuan and T. D. Golden, "A novel method for synthesis of clay/polymer stabilized silver nanoparticles," Surf. Interfaces, vol. 20, p. 100620, Sep. 2020, doi: 10.1016/j.surfin.2020.100620.

[36] A. Phongphut et al., "Clay/au nanoparticle composites as acetylcholinesterase carriers and modified-electrode materials: A comparative study," Appl. Clay Sci., vol. 194, p. 105704, 2020.

[37] Z. Jiang, S. Sun, J. Liu, and X. Sun, "Recent Advances of Halloysite Nanotubes in Biomedical Applications," Small, vol. 20, no. 2, p. 2306169, 2024.

[38] Z. G. Asmare, B. A. Aragaw, M. Atlabachew, and T. A. Wubieneh, "Kaolin-Supported Silver Nanoparticles as an Effective Catalyst for the Removal of Methylene Blue Dye from Aqueous Solutions," ACS Omega, vol. 8, no. 1, pp. 480–491, 2022.

[39] A. Mokhtar et al., "Recent advances in antibacterial metallic species supported on montmorillonite clay mineral: a review," Minerals, vol. 13, no. 10, p. 1268, 2023.

[40] A. Girma, "A Review on Ag/Bentonite and ZnO/Bentonite Nanocomposite: Synthesis and their Applications," J. Equity Sci. Sustain. Dev. JESSD, vol. 5, no. 2, pp. 82–100, 2022.

[41] P. Moradihamedani, "Recent development in polymer/montmorillonite clay mixed matrix membranes for gas separation: a short review," Polym. Bull., vol. 80, no. 5, pp. 4663–4687, 2023.

[42] A. Roy, M. Joshi, B. S. Butola, and S. Ghosh, "Evaluation of biological and cytocompatible properties in nano silver-clay based polyethylene nanocomposites," J. Hazard. Mater., vol. 384, p. 121309, Feb. 2020, doi: 10.1016/j.jhazmat.2019.121309.

[43] Z. Bekissanova et al., "Synthesis, characterization of silver/kaolinite nanocomposite and studying its antibacterial activity," Colloids Surf. B Biointerfaces, vol. 220, p. 112908, Dec. 2022, doi: 10.1016/j.colsurfb.2022.112908.

[44] M. Horue, M. L. Cacicedo, M. A. Fernandez, B. Rodenak-Kladniew, R. M. T. Sánchez, and G. R. Castro, "Antimicrobial activities of bacterial cellulose–Silver montmorillonite nanocomposites for wound healing," Mater. Sci. Eng. C, vol. 116, p. 111152, 2020.

[45] M. Sprynskyy et al., "Preparation of AgNPs/saponite nanocomposites without reduction agents and study of its antibacterial activity," Colloids Surf. B Biointerfaces, vol. 180, pp. 457–465, 2019.

[46] N. Choudhary et al., "Application of green synthesized MMT/Ag nanocomposite for removal of methylene blue from aqueous solution," Water, vol. 13, no. 22, p. 3206, 2021.

[47] S. G. Daghian, M. R. Farahpour, and S. Jafarirad, "Biological fabrication and electrostatic attractions of new layered silver/talc nanocomposite using Lawsonia inermis L. and its chitosan-capped inorganic/organic hybrid: investigation on acceleration of Staphylococcus aureus and Pseudomonas aeruginosa infected wound healing," Mater. Sci. Eng. C, vol. 128, p. 112294, 2021.

[48] M. Rehan, M. E. El-Naggar, H. Mashaly, and R. Wilken, "Nanocomposites based on chitosan/silver/clay for durable multi-functional properties of cotton fabrics," Carbohydr. Polym., vol. 182, pp. 29–41, 2018.

[49] A. Sadeghianmaryan, D. Zarbaf, M. Montazer, and M. MahmoudiRad, "Green synthesis of organo-montmorillonite/silver nanocomposites on dyed cotton with vat dyes to achieve biocompatible antibacterial properties on fashionable clothing," J. Nat. Fibers, vol. 19, no. 15, pp. 10253–10268, 2022.

[50] D. Makwana, J. Castano, R. S. Somani, and H. C. Bajaj, "Characterization of Agar-CMC/Ag-MMT nanocomposite and evaluation of antibacterial and mechanical properties for packaging applications," Arab. J. Chem., vol. 13, no. 1, pp. 3092–3099, 2020.

[51] D. K. Yadav, R. Gupta, V. Ganesan, P. K. Sonkar, and P. K. Rastogi, "Electrochemical sensing platform for hydrogen peroxide determination at low reduction potential using silver nanoparticle-incorporated bentonite clay," J. Appl. Electrochem., vol. 46, no. 1, pp. 103–112, Jan. 2016, doi: 10.1007/s10800-015-0904-2.

[52] S. Moosa, A. N. M. F. Mahadeven, and K. Shameli, "Physiochemical synthesis of Silver/Kaolinite nanocomposites and study their antibacterial properties," J. Res. Nanosci. Nanotechnol., vol. 1, no. 1, pp. 1–11, 2021.

[53] M. Bekhit, S. H. El-Sabbagh, R. M. Mohamed, G. S. El-Sayyad, and R. Sokary, "Mechanical, thermal and antimicrobial properties of LLDPE/EVA/MMT/Ag nanocomposites films synthesized by gamma irradiation," J. Inorg. Organomet. Polym. Mater., pp. 1–15, 2021.

[54] T. L. Ramakutoane, M. P. Roux-van der Merwe, J. Badenhorst, S. Kesavan Pillai, and S. S. Ray, "Antifungal Properties of Nanosilver Clay Composites Against Fungal Pathogens of Agaricus bisporus," ChemistrySelect, vol. 8, no. 36, p. e202301696, 2023.

[55] T. Shevtsova et al., "Temperature-responsive hybrid nanomaterials based on modified halloysite nanotubes uploaded with silver nanoparticles," Colloids Surf. Physicochem. Eng. Asp., vol. 641, p. 128525, May 2022, doi: 10.1016/j.colsurfa.2022.128525.

[56] H. Zhang, Y. Lu, Q. Zhang, F. Yang, A. Hui, and A. Wang, "Structural evolution of palygorskite-rich clay as the nanocarriers of silver nanoparticles for efficient improving antibacterial activity," Colloids Surf. Physicochem. Eng. Asp., vol. 652, p. 129885, Nov. 2022, doi: 10.1016/j.colsurfa.2022.129885.

[57] M. S. Abdel-Aziz, K. S. Abou-El-Sherbini, E. M. Hamzawy, M. H. Amr, and S. El-Dafrawy, "Green synthesis of silver nano-particles by Macrococcus bovicus and its immobilization onto montmorillonite clay for antimicrobial functionality," Appl. Biochem. Biotechnol., vol. 176, pp. 2225–2241, 2015.

[58] M. Harussani, S. Sapuan, G. Nadeem, T. Rafin, and W. Kirubaanand, "Recent applications of carbon-based composites in defence industry: A review," Def. Technol., vol. 18, no. 8, pp. 1281–1300, 2022.

[59] C. Tang, W. Sun, and W. Yan, "Green and facile fabrication of silver nanoparticles loaded activated carbon fibers with long-lasting antibacterial activity," RSC Adv, vol. 4, no. 2, pp. 523–530, 2014, doi: 10.1039/C3RA44799E.

[60] X. Sun et al., "Advance in using plasma technology for modification or fabrication of carbon-based materials and their applications in environmental, material, and energy fields," Adv. Funct. Mater., vol. 31, no. 7, p. 2006287, 2021.

[61] S. Nejati et al., "Laser Functionalization of Carbon Membranes for Effective Immobilization of Antimicrobial Silver Nanoparticles," J. Environ. Chem. Eng., vol. 8, no. 5, p. 104109, Oct. 2020, doi: 10.1016/j.jece.2020.104109.

[62] C. Muratore, A. N. Reed, J. E. Bultman, S. Ganguli, B. A. Cola, and A. A. Voevodin, "Nanoparticle decoration of carbon nanotubes by sputtering," Carbon, vol. 57, pp. 274–281, Jun. 2013, doi: 10.1016/j.carbon.2013.01.074.

[63] H. Lim, A. T. Jafry, and J. Lee, "Fabrication, flow control, and applications of microfluidic paper-based analytical devices," Molecules, vol. 24, no. 16, p. 2869, 2019.

[64] M. Ansari and A. Darvishi, "A review of the current state of natural biomaterials in wound healing applications," Front. Bioeng. Biotechnol., vol. 12, p. 1309541, 2024.

[65] S. Ahmed, M. Ahmad, and S. Ikram, "Chitosan: a natural antimicrobial agent-a review," J. Appl. Chem., vol. 3, no. 2, pp. 493–503, 2014.

[66] S. G. Giteru, A. Ali, and I. Oey, "Understanding the relationship between rheological characteristics of pulsed electric fields treated chitosan-zein-poly (vinyl alcohol)-polyethylene glycol composite dispersions and the structure-function of their resulting thin-films," Food Hydrocoll., vol. 113, p. 106452, 2021.

[67] J. Xu, R. Wei, Z. Jia, and R. Song, "Characteristics and bioactive functions of chitosan/gelatin-based film incorporated with ε-polylysine and astaxanthin extracts derived from by-products of shrimp (Litopenaeus vannamei)," Food Hydrocoll., vol. 100, p. 105436, Mar. 2020, doi: 10.1016/j.foodhyd.2019.105436.

[68] M. Zeshan, N. Amjed, H. Ashraf, A. Farooq, N. Akram, and K. M. Zia, "A review on the application of chitosan-based polymers in liver tissue engineering," Int. J. Biol. Macromol., p. 129350, 2024.

[69] S. Sharma, "Enhanced antibacterial efficacy of silver nanoparticles immobilized in a chitosan nanocarrier," Int. J. Biol. Macromol., vol. 104, pp. 1740–1745, Nov. 2017, doi: 10.1016/j.ijbiomac.2017.07.043.

[70] X. Dai et al., "High antibacterial activity of chitosan films with covalent organic frameworks immobilized silver nanoparticles," Int. J. Biol. Macromol., vol. 202, pp. 407–417, 2022.

[71] Z. Wu, X. Huang, Y.-C. Li, H. Xiao, and X. Wang, "Novel chitosan films with laponite immobilized Ag nanoparticles for active food packaging," Carbohydr. Polym., vol. 199, pp. 210–218, Nov. 2018, doi: 10.1016/j.carbpol.2018.07.030.

[72] G. Wang et al., "Technical development of characterization methods provides insights into clay mineral-water interactions: A comprehensive review," Appl. Clay Sci., vol. 206, p. 106088, Jun. 2021, doi: 10.1016/j.clay.2021.106088.
[73] S. WeiáChook, C. HuaáChia, and H. MináNeoh, "Effective immobilization of silver nanoparticles on a regenerated cellulose–chitosan composite membrane and its antibacterial activity," New J. Chem., vol. 41, no. 12, pp. 5061–5065, 2017.
[74] N. Topić Popović, V. Lorencin, I. Strunjak-Perović, and R. Čož-Rakovac, "Shell waste management and utilization: Mitigating organic pollution and enhancing sustainability," Appl. Sci., vol. 13, no. 1, p. 623, 2023.
[75] K. Poonia et al., "Sustainability, performance, and production perspectives of waste-derived functional carbon nanomaterials towards a sustainable environment: A review," Chemosphere, p. 141419, 2024.
[76] N. R. Putra, D. N. Rizkiyah, M. A. Che Yunus, and L. Qomariyah, "Towards a greener future: Bioactive compounds extraction from shrimp shells using eco-friendly techniques," eFood, vol. 5, no. 3, p. e146, 2024.
[77] K. Dayanidhi, P. Vadivel, S. Jothi, and N. Sheik Eusuff, "White eggshells: a potential biowaste material for synergetic adsorption and naked-eye colorimetric detection of heavy metal ions from aqueous solution," ACS Appl. Mater. Interfaces, vol. 12, no. 1, pp. 1746–1756, 2019.
[78] P. S. Guru and S. Dash, "Sorption on eggshell waste—a review on ultrastructure, biomineralization and other applications," Adv. Colloid Interface Sci., vol. 209, pp. 49–67, 2014.
[79] A. Laca, A. Laca, and M. Díaz, "Eggshell waste as catalyst: A review," J. Environ. Manage., vol. 197, pp. 351–359, 2017.
[80] S. M. Sajadi, K. Kolo, S. M. Abdullah, S. M. Hamad, Hana. S. Khalid, and Ali. T. Yassein, "Green synthesis of highly recyclable CuO/ eggshell nanocomposite to efficient removal of aromatic containing compounds and reduction of 4-nitrophenol at room temperature," Surf. Interfaces, vol. 13, pp. 205–215, Dec. 2018, doi: 10.1016/j.surfin.2018.08.006.
[81] M. N. Zafar, M. Amjad, M. Tabassum, I. Ahmad, and M. Zubair, "SrFe2O4 nanoferrites and SrFe2O4/ground eggshell nanocomposites: Fast and efficient adsorbents for dyes removal," J. Clean. Prod., vol. 199, pp. 983–994, Oct. 2018, doi: 10.1016/j.jclepro.2018.07.204.
[82] A. Rostami-Vartooni, M. Nasrollahzadeh, and M. Alizadeh, "Green synthesis of seashell supported silver nanoparticles using Bunium persicum seeds extract: application of the particles for catalytic reduction of organic dyes," J. Colloid Interface Sci., vol. 470, pp. 268–275, 2016.
[83] B. Khodadadi, M. Bordbar, and M. Nasrollahzadeh, "Achillea millefolium L. extract mediated green synthesis of waste peach kernel shell supported silver nanoparticles: application of the nanoparticles for catalytic reduction of a variety of dyes in water," J. Colloid Interface Sci., vol. 493, pp. 85–93, 2017.
[84] D. Ciechańska, E. Wesołowska, and D. Wawro, "An introduction to cellulosic fibres," in Handbook of textile fibre structure, Elsevier, 2009, pp. 3–61.
[85] T. Jiang, L. Liu, and J. Yao, "In situ deposition of silver nanoparticles on the cotton fabrics," Fibers Polym., vol. 12, pp. 620–625, 2011.
[86] Q. Wei, "Emerging approaches to the surface modification of textiles," in Surface Modification of Textiles, Elsevier, 2009, pp. 318–323. doi: 10.1533/9781845696689.318.
[87] R. Patel, R. Trivedi, M. Raj, and L. Raj, "A brief review of polymeric blends based on natural polymers and synthetic thermoplastics polymers," Chem. Pap., vol. 78, no. 2, pp. 665–697, 2024.
[88] S. Abang, F. Wong, R. Sarbatly, J. Sariau, R. Baini, and N. A. Besar, "Bioplastic classifications and innovations in antibacterial, antifungal, and antioxidant applications," J. Bioresour. Bioprod., 2023.
[89] G. Ayas and G. Karakuş, "Silver Nanoparticles Capped with Poly [(maleic anhydride)-co-(vinyl acetate)]," Cumhur. Sci. J., vol. 44, no. 1, pp. 112–119, 2023.
[90] G. Satchanska, S. Davidova, and P. D. Petrov, "Natural and Synthetic Polymers for Biomedical and Environmental Applications," Polymers, vol. 16, no. 8, p. 1159, 2024.
[91] R. Gobi, P. Ravichandiran, R. S. Babu, and D. J. Yoo, "Biopolymer and synthetic polymer-based nanocomposites in wound dressing applications: a review," Polymers, vol. 13, no. 12, p. 1962, 2021.
[92] F. Heshmatpour and S. Haghbin, "Nanohydroxyapatite/graphene oxide nanocomposites modified with synthetic polymers: promising materials for bone tissue engineering applications," Int. J. Polym. Mater. Polym. Biomater., vol. 70, no. 8, pp. 585–591, 2021.
[93] B. Begines et al., "Polymeric nanoparticles for drug delivery: Recent developments and future prospects," Nanomaterials, vol. 10, no. 7, p. 1403, 2020.
[94] S. Sur, A. Rathore, V. Dave, K. R. Reddy, R. S. Chouhan, and V. Sadhu, "Recent developments in functionalized polymer nanoparticles for efficient drug delivery system," Nano-Struct. Nano-Objects, vol. 20, p. 100397, 2019.
[95] S. Zhao et al., "Application advance of electrosprayed micro/nanoparticles based on natural or synthetic polymers for drug delivery system," Mater. Des., vol. 220, p. 110850, 2022.
[96] A. Aghebati-Maleki et al., "Nanoparticles and cancer therapy: Perspectives for application of nanoparticles in the treatment of cancers," J. Cell. Physiol., vol. 235, no. 3, pp. 1962–1972, 2020.
[97] V. De Matteis, M. Cascione, L. Rizzello, E. Liatsi-Douvitsa, A. Apriceno, and R. Rinaldi, "Green Synthesis of Nanoparticles and Their Application in Cancer Therapy," Green Synth. Nanoparticles Appl. Prospects, pp. 163–197, 2020.
[98] D. Feldman, "Polymers and polymer nanocomposites for cancer therapy," Appl. Sci., vol. 9, no. 18, p. 3899, 2019.
[99] A. Bharadwaz and A. C. Jayasuriya, "Recent trends in the application of widely used natural and synthetic

polymer nanocomposites in bone tissue regeneration," Mater. Sci. Eng. C, vol. 110, p. 110698, 2020.

[100] A. O. Adeola and P. N. Nomngongo, "Advanced polymeric nanocomposites for water treatment applications: A holistic perspective," Polymers, vol. 14, no. 12, p. 2462, 2022.

[101] A. Allafchian, F. Karimzadeh, A. Valikhani, and A. Seraj, "Enhanced antibacterial properties and magnetic removal of Fe3O4/fenugreek seed gum/silver nanocomposites for water treatment," Int. J. Biol. Macromol., p. 126418, 2023.

[102] D. M. Du Plessis, "Fabrication and characterization of anti-microbial and biofouling resistant nanofibers with silver nanoparticles and immobilized enzymes for application in water filtration," 2011.