

Silver Nanoparticle-Impregnated Agricultural Waste Biomass as a Greener Pathway in Sustainable Wastewater Treatment: A Review

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Abstract

The growing contamination of water bodies necessitates sustainable and cost-effective wastewater treatment methods. The integration of silver nanoparticles with agricultural waste biomass offers promising solutions for improving remediation efficiency. Silver nanoparticles, renowned for their potent antimicrobial and catalytic properties among other attributes, have emerged as effective agents in water purification. Concurrently, agricultural waste biomass such as rice husk, banana peels, coconut shell, fiber and coir, corn cobs, sugar cane bagasse, etc., offers not only a renewable, abundant, and eco-friendly substrate for nanoparticle immobilization but also contributes to environmental sustainability through waste valorization. The incorporation of silver nanoparticles imparts enhanced antimicrobial, adsorption, and catalytic properties that improve the degradation of organic pollutants and inactivation of pathogenic microorganisms. This review critically evaluates recent advancements in the synthesis, characterization, and application of silver nanoparticles impregnated in agricultural waste biomass for wastewater treatment. Emphasis is placed on green synthesis routes leveraging plant extracts and intrinsic functional groups within biomass to facilitate nanoparticle formation and stabilization. The integration of silver nanoparticles enhances the disinfection potential of the biomass as well as its sorption capacity and reactivity, enabling the removal of heavy metals, dyes, and microbial contaminants. This review discusses adsorption, catalytic degradation, impregnation factors, environmental fate, toxicity concerns, and regeneration potential of silver nanoparticle functionalized bio-adsorbents in wastewater remediation.

Keywords

Wastewater, Nanoparticles, Silver, Inorganic, Synthesis

1. Background

Wastewater is contaminated water generated by human activities and industries, including homes, hospitals, and factories. It often contains harmful substances such as heavy metals and microbes, which can adversely affect ecosystems when discharged into water bodies. Effective wastewater treatment is essential to remove these pollutants, enabling the safe reuse of water for purposes like irrigation and laundry, and helping to conserve water resources, especially in drought-prone areas [1].

Treatment of wastewater effectively reduces pollution and mitigates the adverse effects of human activities on the environment. Addressing wastewater generation and developing cost-effective treatment technologies are essential. The treatment supports a circular economy by managing waste as a secondary resource for reuse. Wastewater treatment plants can also recover energy, eliminate nutrients, and make water suitable for reuse [2]. Various methods employed include biological processes, membrane technologies, adsorption, ion exchange, coagulation/flocculation, and advanced oxidation processes, such as using hydroxyl radicals to decompose organic pollutants into harmless substances. The goal of sustainable development is to address societal needs while safeguarding public health and the environment for future generations. Sustainable wastewater treatment requires the adoption of affordable and renewable technologies, known as green technology, which encompasses methods like membrane bioreactors, bioremediation, solar energy, green nanotechnologies, and phytoremediation. These green technologies offer economical solutions that reduce the reliance on harmful chemicals and minimize environmental footprints and climate change [3].

Chen and colleagues introduced multi-soil-layering as an innovative wastewater treatment method effective for municipal, livestock, and polluted river water. This technique outperforms traditional systems by addressing issues like poor hydraulic loading, large space requirements, and clogging. Wastewater treatment includes physical methods (screening, separation, settling), chemical treatments (using polymers), biological treatments (microorganisms for organic matter breakdown), and tertiary treatments (sand filters and disinfectants).

Green nanotechnology, which involves creating nanoparticles and nanocomposites, can reduce pollution, while nature-based techniques like phytoremediation and biofiltration can be used for sustainable remediation. Traditional methods prioritize simplicity and cost-effectiveness, but they often require substantial chemical footprints and energy-intensive operations. Despite their effectiveness, these methods are expensive to build, take up a lot of space, and may result in

disinfection byproducts when chemicals are used [4]. The issue with traditional technologies is that they consume a lot of energy and release greenhouse gases. Aquatic ecosystems may suffer when partially or insufficiently treated effluents are released into the environment due to the unhealthy environmental impact. This is because traditional approaches are inflexible and tailored to certain pollutants; they are less flexible when it comes to changing wastewater concerns. The remediation process is further delayed by the lengthy hydraulic retention periods that biological treatments and activated sludge systems frequently require [5]. The use of conventional cleanup techniques is further restricted by their lack of sustainability [6] and [7]. Innovative technologies such as advanced oxidation processes, nanotechnology (e.g., composites of silver nanoparticles), and nature-based methods are being investigated more intensively for effective and sustainable wastewater cleanup in order to overcome these constraints.

In a circular economic approach to wastewater treatment, wastewater is treated as a resource, allowing for the recovery of valuable materials such as water, nutrients, and energy. This promotes sustainable resource management and minimizes environmental impact. It also incorporates the use of agricultural and industrial byproducts for remediation, encourages waste valorization, and employs renewable energy sources like solar, wind, and geothermal for water purification and pollution reduction, addressing the significant waste management challenges in agriculture that contribute to air pollution and public health issues [8]. This review aims to explore the use of agricultural waste biomass in wastewater remediation as well as the synergistic relationship between agricultural waste biomass, which serves both as a reducing and capping agent in the green synthesis of silver nanoparticles and as a sustainable matrix for the indirect application of silver nanoparticles in wastewater remediation.

2. Role of Agricultural Waste Biomass in Wastewater Remediation

According to Tiwari *et al.* (2022), agricultural waste biomass can be applied directly to treat polluted water up to a certain level to reduce toxins, anti-nutritional factors, and microbial load from the water. This is largely due to its eco-friendliness, renewability, and cost effectiveness. The peels, shells, bagasse, husks, and other agricultural wastes are readily available and often discarded, making them a cheap raw material for the production of silver nanoparticles and an adsorption substrate for the removal of substances like heavy metals and organic contaminants [9]. In addition to its high porosity, agricultural waste biomass also contains minerals including silica, potassium, magnesium, and others that enhance its adsorption efficiency. The presence of some functional groups in agricultural waste biomass renders it to have a high capacity to oxidize reactive oxygen species (ROS), including hydroxyl and sulfate groups. These cutting-edge oxidation techniques have been used to treat wastewater in order to eliminate persistent organic contaminants that are challenging to break down naturally [10].

Agricultural waste biomass (**Figure 1**) used for wastewater remediation can be categorized based on its origin and composition;

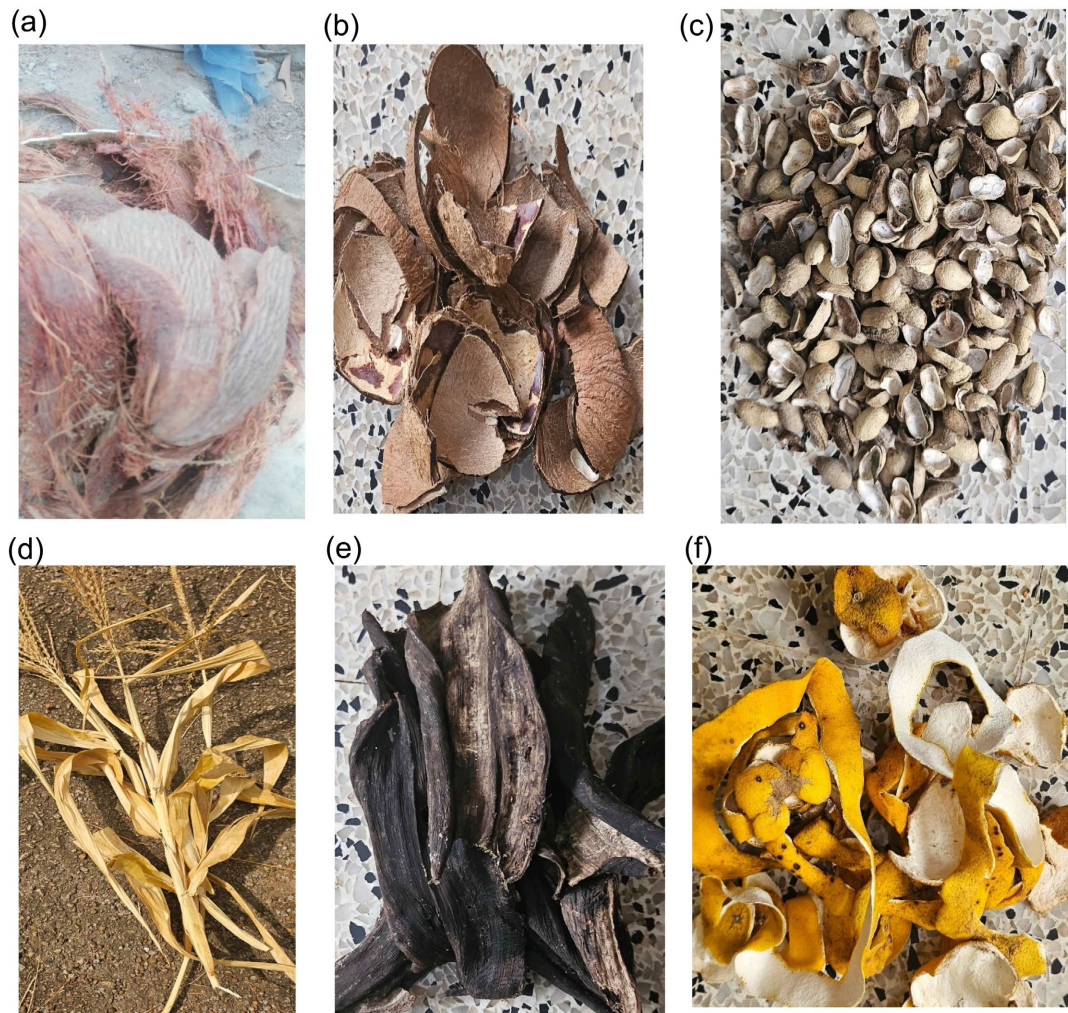


Figure 1. Some examples of agricultural waste biomass. (a) Coconut fiber (b) Coconut shell (c) Groundnut peels (d) Corn stalks (e) Dried banana peels (f) Dried *Citrus sinensis* peels.

2.1. Lignocellulosic Biomass

Agricultural waste such as coconut coir, wheat straw, sawdust, sugarcane bagasse, and wood chips contain significant levels of lignin, cellulose, and hemicellulose. 1-4 glycosidic bonds bind the pyranose units of cellulose, a long-chain polymer of β -D glucose, to form cellobiose repeating units of the polymeric chain. In plants, cellulose is synthesized by the enzyme cellulose synthase. In plant architectures where homo- and heteropolymers are the main structural components, hemicellulose is another polysaccharide that is found to contain suitable phytochemicals which contain $-OH$ and $-COOH$ groups that support adsorption. Their highly porous structure also offers sites for contaminants to be attracted. Among them are β -(1-4) D-xylopyranose, mannopyranoside, galactopyranose, and glucopyranose. Plants have cellulose and hemicellulose in their secondary cell walls. Ether

and carbon-carbon bonds bind the monomeric units of lignin, an aromatic polymer which is made up of three primary components: sinapyl alcohol, coniferyl alcohol, and p-coumaryl alcohol [11]. Coconut (*Cocos nucifera*) is a coniferous fruit that produces waste such as shell, husk, fiber, and coir. According to a study by Zharkenov *et al.* (2024), the wood fibrous structure of coconut coir has a large surface area for the absorption and retention of contaminants. Due to its hydrophilic nature, biodegradability, and eco-friendliness, coconut coir has great potential for removing microplastics from wastewater that have previously proven difficult to remove using conventional wastewater treatment. The study also offered insights into strategies for optimizing coconut coir to further enhance its effective use as a filter. The fiber has high hydrophilicity and a composition of 8.50% hemicellulose, 21.07% cellulose, 29.23% lignin, 14.25% pectin, and 26.00% water. These compounds make it an effective adsorbent for heavy metal removal, such as Cu, Ni, Cd, and Ag [12]. Delignification and activation of coconut fiber can reduce color intensity, COD levels, and pH in industrial liquid waste [13], [14], and [15]. Its surface functional groups remove heavy metals through complexation and cation exchange. Larger substrate surfaces enhance silver nanoparticle adsorption efficiency [16].

Sugarcane bagasse (*Saccharum officinarum* L) is a fibrous material obtained as a byproduct of sugarcane extraction. This material has proven to be useful in wastewater treatment due to its cellulosic structure, ample availability, eco-friendliness, and low cost. In their study, Elshabrawy and coworkers demonstrated the proficiency of sugarcane bagasse pulp in the removal of methyl blue dye [17]. Sugarcane bagasse is also an excellent coagulant precursor in water treatment [18].

Corn cobs (*Zea mays* L.) (Shahin and colleagues have also demonstrated excellent adsorption properties [19]. Tadeballi and coworkers evaluated the economic feasibility of low-cost adsorbents such as corn cobs by comparing their adsorption capacity with that of a commercially procured activated carbon and bone charcoal mixture. They reported that even though the mixed adsorbent demonstrated a better adsorption capacity than corn cobs by a very small margin, the corn cobs showed excellent potential for the removal of cadmium and copper ions from industrial wastewater, proving to be a cost-effective, readily available, and renewable biomass for wastewater remediation [20].

2.2. Nut Shells and Seed Husks

In order to create activated carbon and biochars, which can be utilized as adsorbents for a variety of contaminants such as dyes, heavy metal removal, and desalination processes, researchers have looked at nut shells as raw materials or as precursors. These biomass materials are rich in carbon and present highly porous surfaces. The high carbon content provides excellent adsorption properties. Examples include coconut shells, peanut shells, palm kernel shells, pistachio shells, cashew shells, sunflower seed husk, peanut husk, and walnut shells [21]. Nut shells and seed husks are used effectively for biochar preparation for filtration and as

activated carbon precursors. Rice husk is a by-product biomass of rice processing containing about 20% of bulk grain weight. It is rich in silica with 85% - 90% organic matter. Rice husk has been shown to have a granular structure, chemical stability, and local availability. Masoud demonstrated the potential of rice husk in the raw and activated carbon form in the removal of heavy metals, such as Fe and Mg [22]. Groundnut and mango peels have been employed in the treatment of industrial wastewater [23].

3. Valorization of Agricultural Waste Biomass for Effective Wastewater Remediation

Agricultural waste materials have proven to have excellent absorption capability; however, some of the contained functional groups which aid absorption are shielded or hindered inside the bulk structure of the organic matrix, rendering them inaccessible to interact with pollutants, thereby hindering absorption performance. Hence, there is a need to modify or valorize the plant matrix to enhance the efficiency of absorption. Modification of these materials can be done either chemically or physically. Chemical methods of modification enhance the surface area as well as influence the functional groups for better absorption [24]. These methods include:

1) Acidification: Kumar and colleagues used sulphuric acid modified cashew nut shell for the absorption of Cu^{2+} , Cd^{2+} , Zn^{2+} and Ni^{2+} . They reported that the absorption process was excellent at a short equilibrium time of 30 minutes [25]. Acids such as HCl [26], H_2PO_3 [27], etc. have also been used to modify agricultural waste with amazing absorption results.

2) Esterification: This process increases the hydrophobicity of sorbents by reducing moisture absorption. Al Othman *et al.*, modified the waste of *Tamarix articulata* by esterification using maleic acid to obtain an adsorbent which is carboxyl-rich, thereby enhancing its efficiency towards cadmium ions in aqueous solutions [28]. Tang and colleagues modified raw wheat straw using DMSO to lower its crystallinity, giving it a rough surface containing irregular folds, thereby enhancing its capacity as an oil sorbent [29].

3) Thermal carbonization: The process involves heating biomass at different temperatures to enhance fiber porosity and surface active sites, enhancing pollutant adsorption in water. This is achieved through pyrolysis, chemical treatment, and high-temperature activation in a tubular furnace, resulting in larger surface areas and higher pore volume [30]. The carbonization of agricultural waste biomass can also be achieved at high temperatures and pressures in the presence of water, in this case known as hydrothermal carbonization.

4) Magnetization; Agricultural waste can be modified magnetically by incorporating smart materials exhibiting a rapid response to an external magnetic field. These modified wastes have the potential to remove organic and inorganic as well as biological pollutants from water [31].

5) Pyrolysis. This involves the burning of agricultural waste biomass in the

absence of oxygen in a muffle furnace to produce biochar. Pyrolysis can be slow when the biomass is burnt at lower temperatures of 400°C - 500°C and at longer residence times of several hours to a few days, intermediate with burning temperatures between 400°C - 650°C and maintained at this temperature for several minutes to hours, or fast where burning temperatures are raised to the range of 850°C - 1250°C in seconds to minutes. Flash pyrolysis can be used when shorter residence times are required; this involves very fast heating rates greater than 1200°C within milliseconds to seconds [32].

6) Gasification. This process involves the transformation of agricultural waste biomass into a combustible gas known as “syngas,” accompanied by the production of biochar as a byproduct [32].

Agricultural waste biomass may be used in the raw form, modified slightly by increasing the surface area after shade drying and grinding, or in modified forms or as source materials for the synthesis of biochar and activated carbon [33]. **Table 1** below shows some agricultural waste biomass, their valorization processes, and their applications in wastewater remediation.

Table 1. Valorization of agricultural waste and intended wastewater treatment applications.

Agricultural waste	Valorization Product	Application	References
Coconut fiber	Biofilm formed on coconut fiber using <i>P. aeruginosa</i> and <i>E. coli</i> .	Removal of microplastics from water	Zharkenov <i>et al.</i> (2024) [12]
Coconut coir	Porous coir polyurethane composite adsorbent	A sorbent material for oil spill treatment.	Hoang <i>et al.</i> (2022) [34]
		Removal of organic pollutants and heavy metals like Cu and Ni.	Aravind <i>et al.</i> (2017) [35]
			Okoro <i>et al.</i> (2022) [36]
Rice husk	Raw and activated carbon.	Removal of Fe and Mg	Masoud <i>et al.</i> , (2012) [22]
Sugarcane bagasse pulp	Activated carbon	Removal of divalent Pb, Co, Cu, Zn, Ni, As, and Cr ions from contaminated water and soils.	Elshabrawy <i>et al.</i> (2023) [17]
Sugar bagasse		Removal of methylene blue dye.	Iwuzor <i>et al.</i> (2023). [18]
Sugar cane bagasse	Raw form	Coagulant precursors in water treatment.	Sunday <i>et al.</i> (2021) [37]
	Activated carbon	Treatment of raw water.	Beya <i>et al.</i> (2021) [38]
	Bio char	Treatment of wastewater.	Mansee <i>et al.</i> (2023) [39]
Corn stalk	Raw form		Shahin <i>et al.</i> (2020) [19]
Corn cob	Cellulose hydrogel	Treatment of synthetic greywater.	Lei <i>et al.</i> (2022). [40]
<i>Luffa aegyptiaca</i>	Raw form	Water pollution removal	Adie <i>et al.</i> (2013) [41]

Continued

Coconut shell, neem bark, and sugar cane bagasse.	Raw forms	Water quality analysis	Ayub <i>et al.</i> (2006) [42]
Cashew nut shell	Sulphuric acid modified	Adsorption of pollutants	Kumar <i>et al.</i> (2012)[25]
Tamrix articulate	Esterification Using Maleic Acid		Al Othman <i>et al.</i> (2011) [28]
Raw wheat	DMSO to lower crystallinity	Absorption of Cu ²⁺ , Cd ²⁺ , Zn ²⁺ , and Ni ²⁺	Tang <i>et al.</i> (2018) [29]
Wheat straw and pistachio	Polyvinyl chloride functionalized waste biomass.	Removal of Cd ions.	Mkilima <i>et al.</i> (2024) [43]
Banana peel	Activated carbon	Adsorption of divalent Cu, Cd, Zn, and Ni ions	Mohammed <i>et al.</i> (2015) [44]
	Derived graphene nanosheet.	Adsorption of cadmium	Mkilima <i>et al.</i> (2024) [43]
Soy bean stover, buckwheat stover, <i>Artemisia vulgaris</i> and <i>Chromolaena odorata</i> cob.	Bio char	Removal of pharmaceuticals from wastewater.	Das <i>et al.</i> (2024) [45]
Pomegranate peels	Impregnated with TiO ₂	Removal of heavy metals like As, Cd, Pb, Ni, Zn, and Cu from industrial waste water.	Poudel <i>et al.</i> (2020) [46]
Sugar cane bagasse, maize cobs, and <i>Jatropha</i> oil cake.	Raw forms	Adsorption for the removal of pharmaceuticals from waste water.	Garg <i>et al.</i> (2008) [47]
Citrus <i>sinensis</i> peel	Bio char	Removal of As, Cd, Pb, Ni, Zn, and Cu from water.	
		Mitigation of the concentration of Cd, Zn, and Pb in lettuce grown in soil irrigated with wastewater	Lawal <i>et al.</i> (2024) [48]

7) Impregnation of agricultural waste with silver nanoparticles

In order to improve agricultural waste functionality, silver nanoparticles are now being considered as veritable nanoparticles that can be coated or embedded onto agricultural waste materials in both raw and valorized forms. This impregnation creates a composite material with highly improved adsorption capabilities and efficient filtration in wastewater treatment owing to the enhanced properties of the composite material. This approach to agricultural waste utilization is considered for dual applications in wastewater treatment. It has the capacity for both enhanced adsorption and removal of pollutants such as Pb, Ni, Cd, and dyes from wastewater and for water disinfection, with effective capability as an antimicrobial agent [49]. Neme and team reported the valorization of castor seed hull into activated carbon, followed by the synthesis of silver nanoparticles via a chemical method and impregnation onto the prepared biochar via the *in situ* impregnation method. About 0.0427 wt% of silver nanoparticles were loaded on the activated carbon with 100 mL of silver nanoparticle colloid solution and at 32 hours of impregnation time [50].

4. Silver Nanoparticles as a Promising Antimicrobial and Environmental Remediation Agent

Silver nanoparticles are defined as nanomaterials with all their dimensions ranging from 1 - 100 nm, having higher capacity and a larger surface area compared to their bulk counterparts. At the nanoscale, materials exhibit particular properties such as electrical, optical, catalytic, and antimicrobial properties, which have led to intense research on silver nanoparticles exploring their applications in various fields such as pharmaco-medical, textile, agricultural, electronics, and even environmental remediation. The enhanced antimicrobial activity of silver nanoparticles at the nanoscale has been most valuable in medical and healthcare areas where silver nanoparticles have been incorporated into products such as surgical tools, food handling tools, clothing, cosmetics, catheters, and dressings. Silver nanoparticles have been used as effective antiviral and antimicrobial agents due to their small size and solubility [51]. The antimicrobial properties of silver nanoparticles have been an area of intense study by researchers [52] and [53], etc. Research has shown that silver nanoparticles have high potential to be used to remove toxic substances such as heavy metals, dyes, organic and inorganic contaminants, as well as microorganisms. This is a result of their small particle size, large surface area, and high concentration. Mandal and coworkers reported that the nanobiocomposite containing silver nanoparticles was synthesized from chitosan, demonstrating effective removal of Cu^{2+} and Pb^{2+} ions and crystal-red dye from wastewater [54]. Other studies report the removal of Co and Pb from groundwater, reduction of rhodamine blue dye from aqueous solutions in the presence of NaBH_4 [55], and the removal of crystal violet dye [56].

5. Synthesis and Characterization of Silver-Impregnated Agricultural Waste Biomass

This process involves impregnating silver nanoparticles onto agricultural waste-derived biomass to create a functional material for applications such as water purification, catalysis, and antimicrobial treatments [57]. Silver nanoparticles are kept reactive and prevented from aggregating by the support matrix of agricultural waste. The composite materials' synergistic adsorption and catalytic properties further enhance pollutant removal. Silver nanoparticles in agricultural waste can effectively remove pollutants due to their synergistic adsorption and catalytic properties. This sustainable and economically viable method, combined with the high efficiency of silver nanoparticles, makes waste management a viable solution. These eco-friendly techniques reduce non-renewable resource use, promote reuse and recycling, and conserve resources. Addressing challenges can lower environmental restoration costs and encourage long-term cost savings. Sustainable remediation strategies lower the cost of environmental restoration for future generations while also encouraging long-term cost savings by integrating low-maintenance, low-energy remediation technologies.

5.1. Methods of Impregnation of Silver Nanoparticles onto Substrates (Figure 2)

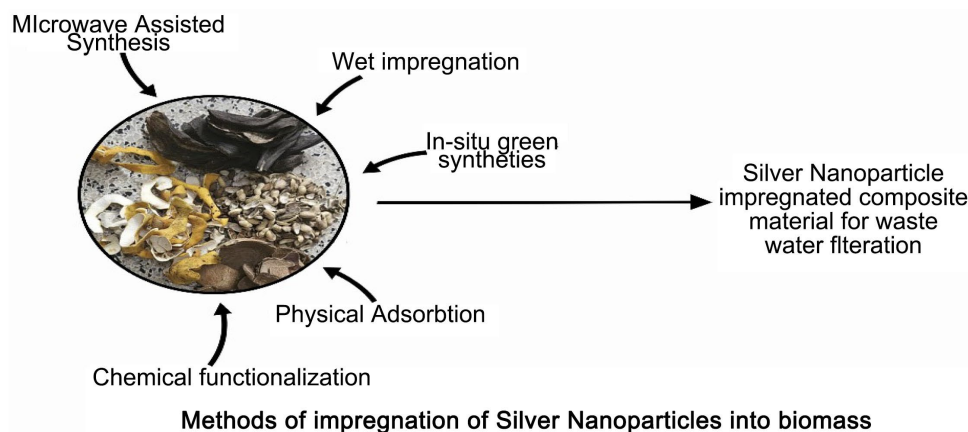


Figure 2. Methods for the impregnation of silver nanoparticles onto agricultural waste biomass.

Chemical Reduction of Silver Salts or *in Situ* Synthesis of Silver Nanoparticles

This is done by directly applying or soaking the substrate in the solution containing silver ions. The silver ions are then adsorbed or sequestered into the substrate where they are reduced by the introduction of a reducing agent. Substrates like cotton structures allow silver ions to become coordinated before their subsequent reduction [58].

1) Sonochemical Coating

This method involves the coating of fabrics or substrates with silver nanoparticles to improve their antibacterial properties. This is done using ultrasound radiation in a one-step reduction process [59]. In a novel method of deposition reported by Perelshtein and colleagues, it was asserted that sonochemical irradiation is an excellent method both for the synthesis of silver nanoparticles and the deposition and insertion of nanoparticles on/into mesoporous ceramics and polymer supports [60].

2) Electro spinning

This is a process in which composite nanofibers such as alginate, keratin polyacetate, polystyrene, etc., are placed on an aluminum collector and sprayed with synthesized silver nanoparticles, thus impregnating their fibers with silver nanoparticles and hence improving or impacting antimicrobial properties [61] and [62].

3) Physical Vapor Deposition

This technique has been employed for the deposition of nanoparticles as well as thin films on or onto substrates. The techniques for physical vapor deposition of silver nanoparticles onto substrates include glancing angle deposition, oblique angle deposition, sputtering, as well as chemical precursor methods [13] and [15].

4) Wet-phase Inversion Process

This process is effective for impregnating silver nanoparticles onto polymer substrates such as polyamine membranes. This technique involves the transformation of a polymer solution into a solid and at the same time impregnating silver nanoparticles into its polymeric matrix to enhance its properties. The polymer solution is prepared and the silver nanoparticles are then synthesized *in situ* or dispersed into the polymeric solution. The polymer solution is then cast onto a substrate or into a mold and immersed into a water or alcohol bath to trigger phase separation, thereby causing the polymer to solidify, trapping the silver nanoparticles in the matrix. These nanofibers or polymers are used in water filtration where the embedded silver nanoparticles prevent biofouling of the polymers [63].

5) Dipping of Substrate in Solution of Silver Nanoparticles

This is a straightforward and efficient method for silver nanoparticle impregnation onto substrates such as polymers, cellulose, silica, etc. The silver nanoparticles are synthesized first using any method, preferably green synthesis; the substrate to be immersed is selected to foster adhesion and distribution of silver nanoparticles. Factors to consider when choosing a substrate include wettability, duration of dipping or immersion, and the surface chemistry of the substrate. After immersion, the substrate is rinsed to eliminate un-adhered silver nanoparticles [16] and [15].

6) Microwave-assisted synthesis

Omo-Okoro and colleagues reported the microwave-assisted synthesis of maize tassel silver nanocomposite at a ratio of 1:1 of silver nitrate and the agricultural biomass powder under optimized microwave conditions of 1 hour, 60°C and 800 W. They activated the nanocomposite produced using air at 400°C, nitrogen at 600°C and phosphoric acid at 500°C [64].

7) Hydrothermal Synthesis

In their study, Tooklang and colleagues carried out an *ex situ* synthesis of a cotton fiber composite impregnated with silver nanoparticles via a simple hydrothermal synthetic route. Prior to impregnation, the cotton fiber surface was enhanced by the use of plasma to ensure adhesion; this method of silver nanoparticle impregnation ensured a uniform deposition of silver nanoparticles on the surface of the cotton substrate [65].

5.2. Mechanism of Adsorption of Silver Nanoparticles onto Substrate during Impregnation

The process of adsorption of silver nanoparticles onto a substrate in the process of impregnation involves exchange, physical, and chemical interactions between the nanoparticles and the surface. The adsorption could be physical, involving weak van der Waals forces. Physisorption involves the adsorption of silver nanoparticles into the pores on the surface using van der Waals forces. Chemical adsorption, or chemisorption, involves electrostatic attraction or complexation between the silver nanoparticles and the molecules on the surface of the substrate [66].

1) Electrostatic interactions

Electrostatic interactions affect adsorption efficiency and stability, largely based on the surface charge of silver nanoparticles and the substrate. Surface charge is determined by capping agents and the surrounding environment, ranging from negative to neutral [67]. The substrate's charge, influenced by surface chemistry and environmental conditions, influences the electrostatic attraction between silver nanoparticles and the substrate, overcoming repulsive forces and promoting adsorption. The electrostatic interaction between silver nanoparticles and the substrate is influenced by their zeta potential, with higher potentials resulting in stronger attraction. This interaction stabilizes adsorption, prevents aggregation, ensures uniform distribution, and prevents leaching. (Khalil-Abad *et al.*, in their study, found that cationic groups on the cotton surface increased silver nanoparticle adsorption, and cationized cotton with silver nanoparticles showed better antibacterial properties [68]. A polyaniline coconut fiber composite also showed enhanced heavy metal adsorption compared to raw coconut fiber, due to the strong electrostatic attraction between positively charged amine functional groups present on the surface of the polymers and negatively charged HCrO^{4-} [69].

2) Ion exchange

The agricultural waste biomass contains exchangeable ions such as Na^+ , Ca^{2+} that can be replaced by silver ions during impregnation. This process ensures the firm adherence of silver nanoparticles to the biomass. Waste materials such as coffee husks and lignin can be modified with silver nanoparticles to enhance their metal sorption ability (Pb (II), Cd (II), Cr (III) and Cu (II)). The capture and exchange of metal ions modify the properties of the agricultural waste biomass to improve the functional characteristics of the agricultural waste [70].

3) Hydrogen bonding

To help with adhesion, the functional groups on the biomass surface can create hydrogen bonds with the ligands or capping agents that surround the silver nanoparticles. Silver ions form bonds with hydrophilic functional groups (like $-\text{OH}$ and $-\text{COOH}$) found in biomolecules. These connections then help to reduce silver ions and produce nanoparticles through hydrogen bonding. Alkanes, amines, phenols, polyphenols, flavonoids, and other compounds all help to create hydrogen bonds during the process of impregnation. Hydrogen bonding facilitates effective silver nanoparticle formation by altering surface energy and selectively attaching to various nanocrystal facets [71].

a) Van der Waals forces

Weak interactions between the nanoparticles and the biomass surface contribute to the overall attachment, especially when other forces are at play. The impregnation leverages these weak molecular interactions to create stable and uniformly distributed silver nanoparticles on the agricultural waste biomass surfaces [72]. However, these interactions are short-range and dependent on the distance between atoms/molecules.

b) Reduction of silver ions (*in situ* synthesis)

Silver ions are reduced to metallic silver atoms by electron transfer and directly

nucleate on the biomass surface when reducing agents (such as phenolic compounds, proteins, alkaloids, or sugars) are present in the biomass. This is typically caused by electrostatic interactions between the negatively charged biomass components and the silver ions, which is followed by the stabilization of the nanoparticles within the biomass matrix. This leads to the creation of uniform nanoparticles and impregnation [73].

c) Physical adsorption (surface porosity)

Physical adsorption, also known as physisorption, is a process where molecules or particles (adsorbate) are held on the surface of a material (adsorbent) by weak intermolecular forces. In order to attract silver nanoparticles and keep them stable without aggregating or precipitating too much, the optimal pH range for silver nanoparticle adsorption or impregnation onto agricultural substrates is between 6 and 9. This is because the functional groups in biomass are sufficiently deprotonated in this range [74].

5.3. Factors Influencing Adsorption

1) pH

Silver nanoparticles and the charge on the biomass surface are likely to be impacted by the pH of the reaction fluid. The biomass material frequently contains functional groups such as amine ($-\text{NH}_2$), carboxyl ($-\text{COOH}$), and hydroxyl ($-\text{OH}$), which are protonated in an acidic environment, lowering the negative or even positive charge. The biomass and silver nanoparticles lose their electrostatic attraction as a result, which lowers the impregnation efficiency. Lower pH also makes silver nanoparticles less stable and more likely to aggregate because of a decreased surface charge, which lessens electrostatic attraction. The deprotonation of the functional groups ($-\text{COO}^-$) at high pH increases the negative charge on the biomass surface, which improves adsorption and increases electrostatic attraction with silver nanoparticles [75].

2) Temperature

Temperature affects the stability of the nanoparticles, their kinetics, and the characteristics of the biomass when they are impregnated into agricultural waste biomass. Although higher temperatures are meant to facilitate impregnation by increasing the rate of reaction, the rate of impregnation will actually decrease because the silver nanoparticles become unstable and have a strong tendency to cluster. Impregnation is therefore preferred at lower temperatures when equal dispersion and stability of the nanoparticles are guaranteed [76].

3) Concentration of Silver Nanoparticles

Agricultural waste biomass's adsorption capability declines as the concentration of silver nanoparticles rises. This might be because there are a lot of sorption sites on the biomass, but active sites on the biomass surface prevent more metal ions from adhering to the solution [77].

4) Biomass concentration

The adsorption capability of silver nanoparticles is strongly influenced by the

dosage or concentration of biomass from agricultural waste. Higher biomass dosages increase the number of active sites available for the attachment of silver nanoparticles, increasing the effectiveness of adsorption. Adsorption properties can be further impacted by changes in the type of biomass and the impregnation technique, underscoring the need to optimize these variables for successful environmental applications [57].

5.4. Adsorption Studies on Silver Nanoparticle-Impregnated Agricultural Waste Biomass

The extent of adsorption of silver nanoparticles onto a substrate can be determined using a batch adsorption experiment by measuring the adsorption equilibrium and kinetics of solutions. A known mass of adsorbent is added to a fixed volume of liquid at an initial concentration. The solution is then agitated for enhanced contact between the adsorbent and adsorbate within the equilibrium time. To obtain an adsorption isotherm, the experiment is repeated while varying parameters such as time, concentration, adsorbent dose, pH, point of zero charge, etc., while keeping others constant. The effects of time, concentration, adsorbent dose, and pH on the rate of adsorption are studied. Adsorption isotherm models such as Langmuir, Freundlich, Temkin, etc., are used to identify the mode of adsorption of silver nanoparticles onto agricultural waste biomass surfaces. The adsorption reaction kinetics can also be tested using kinetic models such as the first-order model, second-order, and pseudo-second-order reaction.

6. Applications of Silver Nanoparticles Modified Agricultural Biomass

Silver nanoparticles can be incorporated into cellulose-based biomass to produce a hybrid system that enhances the sensing, targeting, and degradation of pollutants in wastewater. These modified materials exhibit enhanced adsorption capacity and catalytic activity in removing heavy metals, dyes, and pathogens from wastewater due to their enhanced antimicrobial capacity. There exists a great synergy between silver nanoparticles and agricultural waste materials in the treatment of wastewater for the removal of heavy metals, catalytic activity, and removal of pathogens [77] and [78] (**Figure 3**).

According to previous studies, silver nanoparticles have been incorporated with adsorbents such as corn cobs [79], silica [79], and activated carbon from sugar cane bagasse [80]. KOH activated rice husk [81] has been used. Activated carbon from coconut shell has been employed for the removal of hexavalent chromium in contaminated waste water [82]. Banana leaves powder has been utilized for the removal of Zn (II), Pb (II), and Fe (II) [49]. Polymers based on sugar cane bagasse have been applied for the removal of bisphenol A from water [83]. Cashew nut shell activated carbon [84] and alkali treated palm kernel shell activated carbon have been used for the removal of phenol in simulated waste water [85].

In all the reported studies, the enhanced adsorbents showed excellent capability

for the removal of dyes, heavy metals, and organic pollutants from water. Apart from agricultural waste, successful attempts have been made to impregnate silver nanoparticles into the matrix of nanocomposite filters such as cellulose filters for the degradation of organic dyes [86]. Blotter paper for antibacterial action against *E. coli* and *E. faecalis* [87], microcrystalline cellulose for antimicrobial application [84], ovoid ceramic water filters for the removal of *E. coli* [88] and [89], and vermiculite within water filtration systems for disinfection of bacteria as well as silver reabsorption [90]. Other attempts include the impregnation of silver nanoparticles into fiberglass for water disinfection [91], antimicrobial carbon fiber [92], polypropylene fibers for the correction of the odor of air [93], sand substrates for the removal of pathogenic bacteria from contaminated water [94], cellulosic fabric [95], and textile fabrics [96].

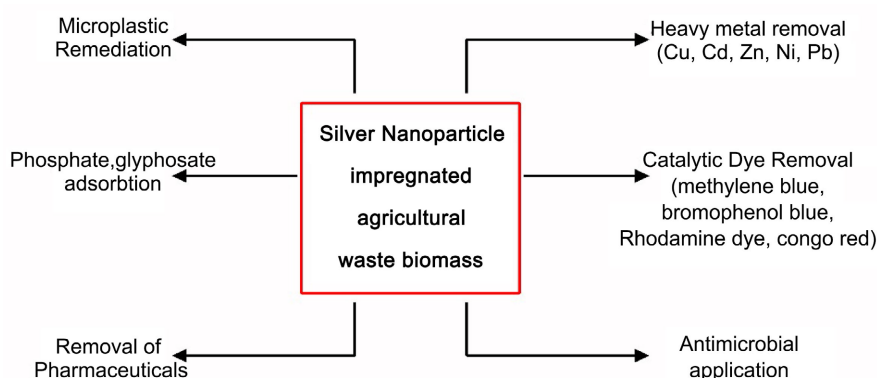


Figure 3. Application of silver nanoparticles impregnated in agricultural waste biomass.

Table 2 below shows silver nanoparticle-impregnated agricultural waste biomass.

Table 2. Silver nanoparticle impregnated agricultural waste biomass.

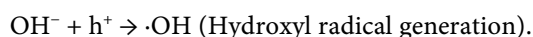
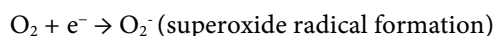
Agricultural waste	Method of Impregnation	Application	References
Kenaf-based activated carbon	Facile photo irradiation.	Adsorption of Cd (II) up to 95.1%.	Mandal <i>et al.</i> (2022) [54]
Activated carbon from Pyrolysed sugar cane bagasse	Wet impregnation	Removal of methylene blue and phenol	Goncalves <i>et al.</i> (2016) [80]
Rice husk (AgNPS-KOH-RH)		Evaluation for use as wastewater adsorbents	Hossain <i>et al.</i> (2022) [81]
Rice straw	<i>In-situ</i> impregnation	Anaerobic digestion of landfill leachates	Alshemsi <i>et al.</i> [97]
Sugar cane bagasse	<i>In-situ</i> impregnation assisted by blue LED light	Remediation of endocrine disruptor –bisphenol A	Mpatani <i>et al.</i> (2022) [74]
Biochar	Wet impregnation with agitation for 12 hours		Moreno <i>et al.</i> (2024) [98]
Modified palm kernel shell activated carbon	Incipient wet impregnation	Catalytic and antibacterial application	Aremu <i>et al.</i> [85]

Continued

Solanumtuberosum peel	<i>In-situ</i> synthesis/impregnation at room temperature with stirring for 72 hours	Removal of phenol	Akpomie <i>et al.</i> [99]
Commelinaerecta	Photocatalysed <i>in-situ</i> impregnation	Adsorption of bromophenol blue	Mallick <i>et al.</i> (2024) [100]
Commercial activated carbon loaded silver nanoparticles	<i>In-situ</i> impregnation	Removal of Rhodamine B dye. Removal of Cr (VI) up to 27.70 mg/g.	Nguyen <i>et al.</i> (2019). [82]
Coffee husk and Lignin powder	Wet impregnation	Removal of Pb(II), Cd(II), Cr(III) and Cu(II) as well as antifungal activity with candida fungi species	Guevara-Bernal <i>et al.</i> (2022) [70]
White and black rice husk ash.	<i>In-situ</i> reduction reaction.	Antibacterial application	He <i>et al.</i> (2013) [101]
Banana leaves powder.	Coating	Removal of Zn (II), Pb (II) and Fe(III).	Darweesh <i>et al.</i> (2022). [49]
Coconut shell activated carbon.	Hydrothermal treatment	Removal of methylene blue.	Van <i>et al.</i> (2018). [102]
Corn cob and red mombin seed.	Incipient wet impregnation technique.	Antibacterial application.	Cruz <i>et al.</i> (2021). [103]
Semercarpusanacardiumderived activated carbon.	Wet impregnation method.	Antibacterial activity.	Mohammed <i>et al.</i> (2023). [44]
EragrostisplanaNeesderived activated carbon.		Catalytic degradation of 4-Nitrophenol.	Fransisco <i>et al.</i> (2024). [104]
Rice husk derived silica	Physical adsorption.	Water treatment	Golmohammadi <i>et al.</i> (2023). [105]
Corn cob derived activated carbon		Adsorption of glyphosate.	Sen <i>et al.</i> (2021). [106]
Poultry manure derived bio char.		Removal of Congo red dye.	Obayomi <i>et al.</i> (2023) [107]
Teff straw derived silica gel	<i>In-situ</i> synthesis and impregnation.	Disinfection of E coli and S. aureus	Tessema <i>et al.</i> (2024) [108]
Coffee husk and Lignin.		Removal of Cd (II), Cr (II), Pb (II) and Cu (II) from aqueous solutions.	Guerverra-Bernal <i>et al.</i> (2022) [70]
Rice husk and rice husk ash	Wet impregnation using a hydroalcoholic medium	Antibacterial materials for water disinfection.	He <i>et al.</i> (2013) [109]
Aryl-sufonated sugarcane bagasse pulp-derived bio char	Dip-coating method	Catalytic activity	Yousef <i>et al.</i> (2022) [110]
Hemp hull activated carbon.	Sonochemical coating	Antibacterial application.	Chaisen <i>et al.</i> (2023) [111]
Sunflower husk biochar.	Wet impregnation/physical adsorption	Removal of tetracycline	Tomczyk <i>et al.</i> (2022) [112]
Arylated bio char derived from sugarcane bagasse	Physical adsorption	Antifungal agent against Trichodermaasperellum.	Snoussi <i>et al.</i> (2022) [113]
Hazelnut husk	Pyrolysis of silver nitrate impregnated olive stones at 400°C for 15 minutes.	Antibacterial activity For food packaging.	Nadir <i>et al.</i> (2024) [114]
Barley straws	Physical adsorption	Anti-kinetoplastids activity	Abdel-Ghany <i>et al.</i> (2018) [115]

6.1. Mechanism of Catalytic Degradation Imparted by Impregnated Silver Nanoparticles

Silver nano composites are used in wastewater treatment for organic dyes, enhancing adsorption and catalytic activity. They catalyze electron transfer reactions, generating reactive oxygen species (ROS) such as hydroxyl radicals ($\cdot\text{OH}$), superoxide (O_2^-) and hydrogen peroxide (H_2O_2) that oxidize or degrade organic contaminants.



Silver nanoparticles exhibit plasmonic behavior, which involves the oscillation of conduction electrons under light (UV or visible) irradiation, which can enhance catalytic activity by increasing the generation as well as the transfer of charge carriers, thus leading to the generation of electron-hole pairs [116].

These ROS are highly reactive and can selectively oxidize organic pollutants. This process is more efficient with biomass or support. The ROS or silver nanoparticle active sites interact with pollutant molecules such as dyes, breaking bonds like C=C, C-H, N-H, or aromatic rings, converting them into smaller, less harmful compounds like CO_2 , H_2O , etc. [117]



The impregnation of silver nanoparticles onto a biomass support prevents aggregation of the nanoparticles, enhances surface area and dispersion, provides adsorption sites for pollutants, and stabilizes the nanoparticles, allowing reuse and increasing durability.

6.2. Mechanism of Microbial Deactivation Imparted by Impregnated Silver Nanoparticles

The mechanism of microbial deactivation by impregnated silver nanoparticles involves multiple, synergistic pathways that disrupt the cell membranes, enzymes, proteins, and DNA of microorganisms such as bacteria, fungi, and some viruses. The impregnation of silver nanoparticles onto a support enables them to retain antimicrobial activity while improving stability and reusability.

Silver nanoparticles continuously release silver ions, especially in moist biological environments. The released silver ions interact with bacterial cell walls, membranes, proteins, and DNA. The silver ions bind to thiol ($-\text{SH}$) groups in enzymes, leading to enzyme inactivation; this disrupts ion transport across the membrane, allows them to penetrate into the cell, and bind to DNA to inhibit replication [118].

Silver nanoparticles also have the ability to attach themselves to bacterial cell membranes due to electrostatic interaction or hydrophobic affinity. This attachment leads to disruption of membrane integrity by causing leakage of cellular contents, causing deformation and pitting of the cell wall, and triggering cell lysis [13].

Silver ions enter the cell and bind to phosphate groups of DNA, condensing the

helix and inhibiting DNA replication, RNA transcription, and protein synthesis.

The impregnation of silver nanoparticles onto biomass support enhances the contact surface area with microbes, regulates the silver ion release rate, prevents the agglomeration of silver nanoparticles, and improves mechanical and chemical stability.

7. The Synergistic Relationship between Silver Nanoparticles and Agricultural Waste Biomass in Wastewater Remediation

The synergistic relationship between silver nanoparticles and agricultural biomass represents a novel, sustainable, and effective approach for wastewater remediation. This is an emerging and promising area of research. This synergy harnesses the unique properties of both materials to improve the efficiency of contaminant removal from wastewater. This synergistic relationship also offers a powerful sustainable solution for wastewater remediation by combining the high reactivity of silver nanoparticles with the eco-friendliness and adsorption capacity of biomass; this approach addresses key environmental challenges while promoting circular economy principles.

Green synthesis of silver nanoparticles is achieved mostly by the use of plant extracts. Research has shown that extracts of plant waste have been successfully used to synthesize silver nanoparticles. Agricultural waste such as coconut shell [119], used parsley stem and potato peels [120], safflower waste [121], pistachio peels [122], grape and orange waste [123], carbo furan, corn cob, rice husk, guinea corn chaff [124], and pomegranate and watermelon wastes [125] are among the examples. The synthesized silver nanoparticles were applied for various uses such as antimicrobial, antiviral, and larvicidal activities, etc. Silver nanoparticles have also been proven to be excellent in environmental remediation practices such as the removal of dyes, heavy metals, and organic pollutants.

The synthesis of silver nanoparticles from agricultural waste extracts leverages bioactive compounds that can reduce silver ions to silver atoms, thus minimizing waste generation. Agricultural waste biomass, such as sugar cane bagasse and coconut coir, serves as a sustainable and cost-effective material for environmental remediation due to its natural abundance and functional properties. This biomass is capable of adsorbing heavy metals and removing organic pollutants, making it an attractive option for water purification. Its biodegradable nature and minimal environmental impact highlight its advantages over chemical and synthetic alternatives for wastewater treatment [126].

Despite the advantages of using agricultural waste biomass for wastewater remediation, challenges such as low adsorption efficiency, structural degradation, logistical issues, toxicity, and variable removal rates persist. To address these setbacks, it is essential to develop advanced materials through the modification or valorization of these waste materials, such as producing activated carbon, biochar, or employing nanoparticle impregnation to improve the efficiency and stability of

biomass in remediation.

Despite the benefits accruing from the use of agricultural waste biomass for wastewater remediation, setbacks such as low adsorption efficiency, structural degradation, and logistical challenges such as collection, storage, and transportation in certain areas, as well as toxicity and inconsistent removal rates, may be experienced. Hence, the need to develop advanced materials by using modification or valorization of these waste materials, such as activated carbon, biochar production, or nanoparticle impregnation, so as to enhance the efficiency and stability of biomass for remediation [127]. Agricultural biomass such as rice husks, corn cobs, or banana peels contains pores and functional groups that provide active sites for the attachment of or *in situ* synthesis of silver nanoparticles. Silver nanoparticles are impregnated or embedded into biomass matrices to create hybrid materials that exhibit enhanced stability and reusability compared to silver nanoparticles alone or biomass. The use of agricultural waste biomass extracts as green reducing agents for nanoparticle synthesis and impregnation or immobilization of synthesized silver nanoparticles onto biomass supports for wastewater treatment are increasingly being combined into a single synergistic strategy in sustainable wastewater treatment [121]. In fact, this integrated approach is gaining popularity due to its green chemistry principles, cost-effectiveness, and multifunctionality; for instance, banana peel extract biochar forms a multifunctional composite for dye degradation via catalytic action, heavy metal adsorption via biochar, as well as bacterial inactivation via silver nanoparticles. Such systems are bio-based, cost-effective, and environmentally friendly, aligning with circular economy principles [25] and [116]. Some studies, however, stop at just the green synthesis of silver nanoparticles using plant extracts. Others focus only on adsorption using raw biomass or biochar, but the trend in recent years has been toward integrating synthesis, support, and application.

This synergy provides a very effective, sustainable, and economical solution to the waste management problem. The functionalization of silver nanoparticles onto agricultural waste biomass provides an indirect method of applying silver nanoparticles for environmental remediation without the additional risk of secondary contamination, but the leaching of silver nanoparticles into the environment during wastewater treatment is crucial because it can result in secondary contamination. The process's scalability and ensuring that the filters' deployment complies with environmental regulations to encourage broad use remain the process's greatest obstacles to date.

7.1. Regeneration and Reusability of Silver Nanoparticle-Impregnated Agricultural Biomass Adsorbents

Silver nanoparticle-impregnated agricultural waste biomass in wastewater has practical viability based on pollutant removal, robust regeneration, and reusability over multiple cycles. While some studies have addressed regeneration and reusability in silver nanoparticle-modified biomass or carbon supports, more data are needed under realistic wastewater conditions.

In their studies, Liu *et al.* investigated wood-based activated carbon fibers modified with silver nanoparticles and coated with TiO₂ films. These nanocomposites reportedly showed excellent self-regeneration durability in cyclic trials for methylene blue photodegradation attributed to homogeneous immobilization of silver nanoparticles and the reduction of silver nanoparticle agglomeration and exfoliation by TiO₂ films and maintenance of porosity so as to enable both adsorption of dye and photocatalytic regeneration [24]. In a related study, Mandal *et al.* synthesized a Kenaf-based activated carbon loaded with silver nanoparticles within a chitosan matrix for the removal of heavy metals such as Cd²⁺, Cr⁶⁺, Ni²⁺, and Co²⁺. They reported that the desorption capacity of the adsorbent remained unaltered after five successive cycles. The adsorbent material was regenerated by desorption using 2 M HNO₃ followed by washing and drying followed by reuse [54]. In addition, Al-Raimi *et al.* reported synthesizing an absorbent silver-cellulose nanocomposite from agricultural residue for the catalytic removal of Safranin O and Methylene Blue dyes. The adsorption effectiveness drastically decreased after five cycles. To remove the adsorbed dyes, the nanocomposite was regenerated using an acidic wash (0.1 M H₂SO₄) [128]. In many studies, performance tends to decline after just 3 - 5 cycles due to either biomass breakdown or solvent loss [55]

Reusability is one of the benefits of silver nanoparticle-based composites in dye removal and degradation, according to Palani review article from 2023. They point out that numerous studies report recovery of silver nanocomposites and reuse for multiple cycles, albeit with widely differing retention of activity [129]. In their review, Silva-Holguin *et al.* also highlighted the difficulties in preserving the structural support during repeated uses, preventing leaching, and maintaining the immobilization of silver nanoparticles [130]. The exploration of the regeneration and reuse of silver nanoparticle-loaded agricultural waste for wastewater treatment is highly expedient, as studies such as (ALChE 2024) reported the use of agricultural waste (rice husk)-derived biochar loaded with silver nanoparticles for catalytic and antibacterial capabilities; however, reuse cycles and measurement of silver nanoparticle leaching over those cycles were not investigated [131].

7.2. Downside of Using Silver-Impregnated Biomass for Wastewater Remediation

Potential for Silver Nanoparticles Release and Environmental Impact

Nanoparticles, due to their unique size and properties, pose significant environmental concerns as they can be released through pathways like industrial emissions, waste disposal, and agricultural applications. They can contaminate air, water, and soil, leading to potential toxicity in organisms and disruption of ecosystems. In particular, materials like silver and zinc oxide can harm aquatic life and plants by causing cell membrane damage, cell death, and oxidative stress. This results in adverse effects on cellular function and DNA alteration in exposed organisms [132]. Silver nanoparticles also have a tendency to accumulate in organisms and move through the food chain, potentially reaching higher concentrations

in top predators. Human exposure to silver nanoparticles through skin contact may also pose risks. When inhaled, nanoparticles can be deposited in the lungs, potentially causing respiratory issues.

Studies have demonstrated that low levels of silver nanoparticles can disrupt microbial biofilms and impair biological nutrient removal processes [133]. Although silver nanoparticles are valued for their strong antimicrobial properties, this same trait poses a risk to non-target beneficial bacteria involved in conventional biological wastewater treatment.

The use of agricultural biomass loaded with silver nanoparticles for wastewater treatment over time becomes susceptible to degradation over multiple use cycles. Thermal, chemical, or acid regeneration methods can cause structural collapse, loss of functional groups, or detachment of embedded silver nanoparticles [134]. Moreover, silver nanoparticle aggregation during regeneration reduces the active surface area, diminishing adsorption and antimicrobial efficiency. Despite widespread interest, very few studies report quantitative silver nanoparticle leaching data over repeated adsorption–regeneration cycles, particularly under real wastewater conditions.

Another significant challenge of the use of silver nanoparticle-loaded nanocomposites emanates from the difficulty in ensuring uniform distribution and anchoring of silver nanoparticles within porous biomass supports. This also affects their scalability [135].

8. Future Prospects and Challenges

8.1. Optimization of Silver Nanoparticle Impregnation and Wastewater Treatment Processes

This document discusses the synthesis process for silver nanoparticles, emphasizing cost, environmental safety, and efficiency. It suggests optimizing stabilizers to control particle size and prevent aggregation, and highlights the importance of substrate characteristics like porosity and surface charge for effective biomass material impregnation. Key variables such as temperature, contact time, and nanoparticle concentration should be adjusted to improve retention time and minimize leaching. To further reduce silver nanoparticle leaching, functionalization with polymers or biomolecules is recommended. Silver nanoparticles can be incorporated into materials like zeolites and activated carbon to prevent uncontrolled release. Additionally, methods for recovering and reusing these impregnated materials should be explored to mitigate environmental impact.

8.2. Development of Novel Biomass Composites Impregnated with Silver Nanoparticles

To improve stability, reusability, and environmental safety, silver nanoparticles are incorporated into natural or synthetic bio-based products. These composites can minimize the leaching of silver nanoparticles while increasing antibacterial activity, pollutant adsorption, and catalytic qualities. The synthesis, processing, and

integration of silver nanoparticles into wastewater treatment plants must be carefully optimized for the scale-up and deployment of silver nanoparticle-biomass systems. This is done to maintain high efficiency while guaranteeing cost-effectiveness, environmental safety, and regulatory compliance.

9. Conclusion

The study explores various agricultural waste materials, including sugarcane bagasse and corn stalks, for wastewater treatment. It identifies key contaminants, such as organic pollutants and heavy metals, highlighting the enhanced remediation capabilities of biomass treated with silver nanoparticles. While this method shows potential in disinfection and adsorption, the toxicity of silver and the risk of leaching present significant challenges. The need for improved synthesis methods and careful environmental consideration is emphasized, suggesting further research on deposition techniques and long-term impacts before this approach can be deemed viable.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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