

Research Article

Towards Sustainable Paddy Disease Control: Exploring the Potential of Silver Nanoparticles

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Abstract | Nanotechnology offers promising solutions for sustainable agriculture, particularly in managing plant diseases. Silver nanoparticles (AgNPs), with their unique properties, have emerged as potent antibacterial agents against various plant pathogens. This review provides an overview of using AgNPs to treat paddy disease, a threat to global food security. The review explores various AgNPs production methods, including chemical reduction, photochemical synthesis, and electrochemical procedures. It delves into the application of AgNPs in combating paddy diseases, highlighting their advantages over conventional chemical treatments. While chemical pesticides and fungicides can effectively control paddy diseases, their overuse leads to pesticide resistance and poses environmental risks. This review demonstrates that AgNPs offer a safer and more sustainable alternative for paddy disease management. Studies have shown the efficacy of AgNPs against major paddy diseases like rice blast and sheath blight. The review discusses challenges and future directions for AgNPs-based treatments, emphasising their potential to develop eco-friendly strategies for global food security.

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Introduction

Nanomaterials are substances with at least one spatial dimension measuring less than 100 nanometres. Nanoparticles are applied in fields such as pharmaceuticals, medicine, materials manufacturing, environmental protection, and agriculture (Masum *et al.*, 2019). They include carbon nanotubes, nanorods,

nanocapsules, and metallic NPs (Castillo-Henríquez *et al.*, 2020). Among these, silver nanoparticles (AgNPs) are a specific type of NP composed of silver atoms. Silver nanoparticles exhibit distinct physical, chemical, and biological properties compared to bulk silver and other nanoparticle types. Their diminutive size and expansive surface area facilitate heightened reactivity, optical attributes, and antibacterial efficacy.

Silver nanoparticles have been widely used across various industries, including healthcare, consumer products (electronics, optics and cosmetics), and materials and surface treatments (textiles, coatings, paints, and pigments) (Temizel-Sekeryan and Hicks, 2020). In addition to these applications, AgNPs have shown promising results in plant disease management and promoting plant growth (Tariq *et al.*, 2022). The silver nanoparticles have exhibited potent inhibitory activity against a broad spectrum of bacterial strains, including both Gram-positive and Gram-negative species (Al-Sharqi *et al.*, 2019). Recent advances in nanoparticle synthesis have focused on safer and more environmentally friendly approaches compared to traditional chemical methods (Ibrahim *et al.*, 2020). Silver nanoparticles are commonly produced by chemically reducing silver salts, such as silver nitrate, utilising reducing agents like sodium borohydride or sodium citrate. These synthesis procedures occur in the presence of stabilising compounds, including polyvinylpyrrolidone (PVP) or citrate, which help maintain the nanoparticles (Vega-Baudrit *et al.*, 2019). AgNPs can also be synthesised using endophytic bacteria or fungi, where the nanoparticles exhibit both plant growth promotion and antibacterial activity against plant pathogens (Kumar *et al.*, 2020; Zhu *et al.*, 2024).

Despite the potential of AgNPs, there are limited studies on their application for paddy disease management. Rice blast, one of the most severe diseases affecting rice-growing regions, poses a significant threat to global food security. Rice, being a staple food for much of the world, is threatened by diseases such as brown leaf spot, bacterial leaf blight and bacterial panicle blight (Asghar *et al.*, 2019; Datta *et al.*, 2021; Raihanah *et al.*, 2023). Traditional disease management techniques, such as breeding resistant varieties and applying pesticides, are widely used (Li *et al.*, 2018). However, the overuse of pesticides has led to serious environmental issues. A safer alternative is the use of AgNPs, which have been shown to prevent damage from bacterial leaf blight in paddy crops (Chowdhury *et al.*, 2022). *Pyricularia oryzae*, the fungus responsible for rice blast disease, threatens around 30% of the world's food grain supply (Parthasarathy *et al.*, 2022).

The challenges faced in paddy production include rising demand, water scarcity, climate change, and disease outbreaks (Ayub *et al.*, 2024). Several major

phytopathogens, including blast disease, sheath rot, brown spot, and bacterial blight, are prominent threats to paddy production globally. Accurate diagnosis and effective treatment are crucial for minimising the detrimental effects of these diseases on crop productivity. However, current diagnostic methods for paddy diseases are neither precise nor efficient, often requiring additional equipment. AgNPs, one of the most significant metallic NPs used in agriculture, offer promising potential in addressing these challenges. While AgNPs have been widely used in other crops, their use in paddy disease management remains underexplored.

This review paper's findings are noteworthy, as they underscore the promising potential of nanoparticles in enhancing crop growth and managing plant diseases. NPs have been employed as treatments in diverse agricultural applications for some time, and researchers continue to explore the most effective NP types for addressing crop diseases. The review provides in-depth insights into how NP-based treatments can improve agricultural productivity and presents a potential environmentally sustainable approach for managing paddy diseases. Consequently, this study makes a vital contribution to advancing future research on paddy disease control strategies.

This review addresses the key issues related to paddy disease, including its causes and the most effective nanoparticle treatments. Additionally, the rationale for selecting AgNPs over organic chemicals is explored. Through these findings, the production of rice could become more stable and less susceptible to disease. Furthermore, the review highlights the properties of AgNPs and examines the advantages and disadvantages of using NPs in agriculture. This research aims to identify common paddy diseases, their causes, and the potential enhancement of treatments using AgNPs. Additionally, it explores the application and challenges of current paddy disease treatments, offering potential improvement solutions.

The overview of paddy (Oryza sativa)

Paddy is a critical food staple in developing nations. Timely and precise assessments of paddy rice cultivation and production can provide valuable insights for government authorities, planners, and policymakers, enabling them to develop effective strategies and policies. In addition to being essential for improving food security, it can create jobs, raise incomes, and decrease

poverty. However, the agricultural sector faces complex challenges, including inconsistent production and relatively low yields. Paddy is a man-made ecosystem that is influenced by human activity, including changing cropping patterns, introducing resistant varieties, and applying pesticides. Paddy viral disease epidemics, characterised by fulminant, migratory, and intermittent outbreaks, originated from inappropriate human involvement that made environmental disruption worse (Ma *et al.*, 2022). The prolonged outbreak of rice stripe disease (RSD), first reported in 2000, has served as a model system for advancing research on effective control strategies for plant viral diseases transmitted by insect vectors. Paddy (*Oryza sativa* L.), a significant cereal crop from the Poaceae family, is a staple food consumed by more than half of the global population, making it one of the world's most crucial agricultural commodities (Simkhada and Thapa, 2021). Continued inaction will cause a marked reduction in paddy production, with serious implications for global food security and rice-dependent economies.

Paddy disease and the causes

Diseases in paddy crops, predominantly caused by pathogenic bacteria, fungi, and viruses, are a major constraint in rice production. These pathogens significantly reduce both grain yield and quality, posing serious challenges to food security in rice-dependent regions. A comprehensive understanding of the different types of pathogens responsible for these diseases is essential for developing effective management strategies.

Fungal pathogens

Paddy blast is one of the most devastating plant diseases affecting a crucial food staple with significant destructive potential in many developing countries (Simkhada and Thapa, 2021). The causal agent is the filamentous ascomycete fungus *Magnaporthe oryzae* (anamorphic form *Pyricularia oryzae*). The most conducive environment for the spread of disease is cloudy, with a relative humidity of 93 to 99%, a low nighttime temperature (15–20 °C), and a longer dew period. The disease impacts all above-ground plant parts, with leaves, nodes, and panicles exhibiting the most severe symptoms. The affected plant components above the infected nodes are fragmented by irregularly shaped dark lesions encircling the nodes. In studies of neck blast, the fungus *Magnaporthe oryzae* attacks the peduncle during the flowering stage, leading to

brownish-black lesions that result in poor or low grain filling. Additionally, leaf and collar blast caused by *Pyricularia oryzae* Cavara 1892 (A) can infect paddy tissues at any growth stage, potentially causing complete crop loss. As reported by Asibi *et al.* (2019), the pathogen infects various plant parts, including the leaves, leaf collars, culms, culm nodes, panicle neck nodes, and panicles, resulting in the development of lesions.

Additionally, the other paddy disease is sheath blight caused by the fungus *Rhizoctonia solani*. This disease is particularly prevalent from the tilling to heading growth stages (Nadarajah *et al.*, 2014). Initial symptoms manifest as lesions on the lower leaf sheaths during late tiller or early internode elongation, which can then coalesce to encompass the entire leaf sheath and stem (Nadarajah *et al.*, 2014).

Furthermore, brown spot disease caused by the fungus *Bipolaris oryzae* is prevalent in both upland and rainfed paddy cultivation methods (Laxman *et al.*, 2016; Shaheen *et al.*, 2024). This pathogen can also persist on contaminated paddy straw and stubble. The disease spreads through airborne spores, thriving under optimal conditions of temperatures ranging from 22 °C to 30 °C. This pathogen can also persist on contaminated paddy straw and stubble. The disease spreads through airborne spores, thriving under optimal conditions of temperatures ranging from 22 °C to 30 °C and relative humidity exceeding 92%. These environmental factors facilitate the development of lesions on the coleoptile, leaf blade, leaf sheath, and glumes, with the leaf blade and glumes exhibiting the most pronounced symptoms. According to Chen *et al.* (2022), it begins as little brown spots and gradually transforms into shapes ranging from cylindrical to round. The entire leaf dries out as these areas coalesce.

Sheath rot, caused by the fungus *Sarocladium oryzae*, is particularly detrimental when it manifests during the late booting stage, potentially resulting in significant crop damage (Fetene *et al.*, 2020). The symptoms showed that the uppermost flag leaf sheaths were infected with the pathogen, which, in the boot stage, encircles the budding new particle. Then, another paddy disease is stem rot caused by *Sclerotium oryzae*, which is a significant soil-borne illness that reduces productivity by roughly 3–45% (Kannan *et al.*, 2021). On paddy leaf sheaths, brownish to black water-soaked lesions without distinct edges were visible

(Bashyal *et al.*, 2021).

Bacterial sheath brown rot, caused by the pathogen *Pseudomonas fuscovaginae*, is a significant disease affecting paddy cultivation. This disease thrives under specific environmental conditions, including low temperatures, high humidity, and elevated altitudes in tropical and subtropical regions. Symptoms of sheath brown rot include grain discolouration, deformities, poorly filled panicles, sheath lesions, and reduced fertility.

Furthermore, *Ustilaginoidea virens*, the fungus that causes false smut, infects paddy during the reproductive and ripening stages (Song *et al.*, 2021). Individual paddy grains get transformed into a mass of yellow fruiting bodies. Being enclosed in the floral parts, the growth of fuzzy spores can be seen. The immature spores exhibit a slightly flattened, smooth, yellow appearance and are enveloped by a membrane. According to Song *et al.* (2021), mature spots are orange in colour and turn yellowish-green or greenish black.

On the other side, leaf scald caused by *Monographella albescens* causes a yield loss in paddy by reducing the photosynthetic area. Leaf scald was first reported in Japan in 1955 and has been identified throughout the world where paddy is the main production (Bueno *et al.*, 2017).

Next, *bakanae* disease which also known as the “foolish seedling” disease, is caused by the fungus *Fusarium fujikuroi* Nirenberg. *Bakanae* disease of paddy is caused by a haploid, heterothallic ascomycete fungus (Volante *et al.*, 2017). Abnormally long seedlings, thin stems, and chlorotic leaves are caused by the high gibberellin secreted by the pathogen (Amr and Abd, 2020). Furthermore, infected plants that are already mature cannot produce normal panicles and grains.

Bacterial pathogens

Panicle blight disease, caused by *Burkholderia glumae*, affects panicles, turning them straw-colored and causing one or all of their florets to become blighted, often resulting in empty or aborted grains (Figure 1) (Raihanah *et al.*, 2023).

Moreover, bacterial leaf streak (BLS) caused by the *Xanthomonas oryzae* P.v. *oryzicola* (Xoc) is a significant bacterial disease affecting paddy crops. Due to a lack

of paddy cultivars with strong disease resistance, it is challenging to control (Wu *et al.*, 2019).



Figure 1: Symptoms of panicle blight disease showing a darker base and a reddish-brown line across the floret, separating the darker straw-colored and lighter straw-colored.

Additionally, bacterial leaf blight (BLB), caused by the bacterium *Xanthomonas oryzae* pv. *oryzae* (Xoo) is a destructive disease affecting paddy crops (Vishakha *et al.*, 2020).

Viral pathogens

Furthermore, Tungro disease, which is transmitted by the green leafhopper vector (*Nephotettix virescens*) in a semi-persistent manner after feeding on infected plants, is another significant paddy disease (Amelia *et al.*, 2022). The leaf yellowing (chlorosis) process was due to cell proliferation and expansion induced a delay in the intercellular gaps' development (Na Phatthalung *et al.*, 2022). On young leaves, the yellowish-orange colour is present starting from the tips to the curly leaves, the reduction of tillers number and the plant growth is stunted (Amelia *et al.*, 2022).

Additionally, the rice yellow mottle virus can severely diminish paddy yields. This virus was first identified in sub-Saharan Africa and Madagascar in 1966 and is transmitted to paddy seedlings by biotic vectors,

such as *Chrysomelidae* beetles. (Syed-Ab-Rahman *et al.*, 2020). Paddy yield loss is severely reduced by the rice yellow mottle virus (RYMV). It was first discovered in sub-Saharan Africa and Madagascar in 1966. RYMV is distributed to paddy seedlings via biotic agents like *Chrysomelidae* beetles. Even a small amount of the virus can cause infection to spread from contaminated soil to healthy transplanted seedlings. The ailment showed mottling, yellowish leaf streaking, shoot stunting, spikelet sterility, and decreased tillering (Sekiya *et al.*, 2022).

Treatment of paddy disease

Various treatments are currently being applied to paddy crops as a means of managing diseases and enhancing overall production. In paddy blast disease caused by *Pyricularia oryzae* Cav, fungicide application, irrigation control, nutrient fertiliser use, and planting-resistant cultivars are all necessary. Extracts from coffee arabica are said to have a disease-inhibiting effect. It has also been successful to treat *Trichoderma viridae* seeds with 5 ml/L of water (Simkhada and Thapa, 2021). In addition, paddy blast disease, which results from infected and contaminated paddy seeds, can be treated using seed treatment. Currently, chemical fungicides for seed treatment have numerous drawbacks, including pathogen resistance, environmental harm, and health risk to farmers and consumers (Hashim *et al.*, 2019). These adverse effects have heightened the demand for non-chemical seed treatment alternatives, such as the utilisation of hot water and antimicrobial biological agents. Hot water seed treatment effectively prevents pathogens in various vegetable crops. Microbial seed treatment can protect against soil-borne diseases and reduce seed-borne infections (Hashim *et al.*, 2019). In comparison to untreated seeds, it was shown that seeds treated with *Trichoderma asperellum*, *Bacillus subtilis*, and hot water at 50°C for 15 minutes decreased the proportion of infected paddy seeds by 4.3% to 52.7%. Furthermore, the application of *B. subtilis* as a seed treatment has been shown to reduce the prevalence and severity of paddy blast disease by 10% to 72.4%.

A possible source of key features, such as novel resistance genes to combat pests like sheath blight and blast disease, is the wild *Oryza* species, which is closely related to cultivated paddy. In the case of bacterial blight and bacterial leaf streak, two mechanisms of resistance have been identified: (i) The qualitative resistance gene locus *Xo1* can effectively

counteract African *Xoc* isolates; (ii) The quantitative trait loci (QTL) qBlr5a (xa5). Next, according to the treatment being applied to the brown spot paddy leaf roller (*Cnaphalocrocis medinalis*) was infested into the field and was eradicated by Foliar applications of Chlorpyrifos and Cypermethrin.

Conversely, the effect of chemical seed treatment on the paddy false smut control was studied by using 4 types of fungicides with different modes of action. The detection of *Ustilaginoidea virens* was conducted by taking paddy tissue samples using a Polymerase Chain Reaction (PCR) method at different rice-growing stages. At the maturation stage, the occurrence of false smut in the paddy was investigated. Seed treatment with fungicides is one of the best options for protecting paddy seedlings. Paddy false smut could infect the coleoptile and young root of paddy seedlings, thus causing the abnormal growth of paddy seedlings (Song *et al.*, 2021). Then, in bacterial blight, antibiotics and chemical biocides are used to manage BLB disease in paddy. Streptomycin is mainly used; however, new research has shown that *Xoo* has a significant level of antibiotic resistance (Vishakha *et al.*, 2020). Additionally, the induced resistance against paddy sheath blight exhibited by strain REB01 is attributed to the modulation of defence enzyme activities, as well as alterations in peroxide and polyphenol oxidase levels (Lin *et al.*, 2021). Additionally, the spread of tungro disease can be addressed through mathematical modelling. Furthermore, the vector-borne model of paddy tungro disease has employed the application of insecticide to infected plants (Amelia *et al.*, 2022).

On the other hand, the fungus *Monographella albescens* causes leaf scald disease, which harms paddy plants. It could drastically diminish paddy harvests by destroying the leaf surface, sterilising blooms, and degrading seeds, resulting in losses of up to 30%. *M. albescens* infection reduces CO₂ penetration, the rate of carbon dioxide assimilation in the liquid phase, as well as the stomatal conductance to water vapour, are diminished even before the manifestation of leaf scald symptoms. The application of the sequence involving BRM-32113 alongside silicon fertilisers demonstrated a reduction in the severity of leaf scald, shielding the photosynthetic machinery and thereby providing a long-term strategy to mitigate the income losses associated with leaf scald in paddy cultivation (Bueno *et al.*, 2017). Meanwhile, the paddy disease

bakanae, commonly called a foolish seedling, is extremely damaging. It is found in practically every area of the planet where paddy is grown (Pathomaree *et al.*, 2019). To prevent the pathogenic *Fusarium* from infecting the seeds, nonpathogenic *Fusaria* are sprayed onto paddy blooms. The pathogen's hyphal expansion in paddy flowers and seedlings is inhibited by the nonpathogenic *Fusaria*'s competition with it. *F. fujikuroi* causes bakanae disease, however, nonpathogenic *Fusaria* can persist in paddy seeds for at least 6 months, shielding the following generation from the illness (Saito *et al.*, 2021).

Apart from that, sheath rot is treated with the use of resistant varieties because it is much cheaper and does not affect the environment. Based on Fetene *et al.* (2020), additionally, resistant variants could be developed through selection/screening or crossing (Fetene *et al.*, 2020). Biological control offers an acceptable and prospective substitute for managing disease. Microbial bioagents employ a range of strategies to outcompete and suppress pathogens, including hyperparasitism, competition for resources and spatial dominance, antibiosis, and the stimulation

of systemic resistance mechanisms within the host plants (Poveda *et al.*, 2020).

In addition, the efficacy of the emulsion formulation in mitigating bacterial sheath brown rot of paddy has been observed through *in vitro* plate assays and greenhouse trials. Meanwhile, in rice yellow mottle virus (RYMV), host plant resistance is the most cost-effective and ecologically sustainable method of controlling the RYMV (Suvi *et al.*, 2020). Table 1 summarises the related paddy diseases with their causes and treatments.

Silver nanoparticles and their characteristics

The growing interest in products made of components at the nano size has increased the demand for the manufacture of nanoparticles, especially AgNPs (Długosz and Banach, 2019). AgNPs have the potential for application as antibacterial agents in medical device coatings and wound dressings (Pal *et al.*, 2017). AgNPs exposure may have unfavourable effects that could have unintended consequences. Comparing AgNPs to Ag ions, it is difficult to determine which

Table 1: The list of paddy diseases, causes, and treatments.

Paddy disease	Fungus or bacteria caused	Treatment	References
Rice blast	<i>Magnaporthe oryzae</i>	Application of fungicides.	(Simkhada, 2021)
Sheath blight	<i>Rhizoctonia solani</i> .	Novel resistance genes.	(Nadarajah <i>et al.</i> , 2014)
Bacterial leaf streak	<i>Xanthomonas oryzae</i> Pv. <i>oryzicola</i> (Xoc).	Gene locus <i>Xo1</i> and trait loci (QTL) qBlr5a (xa5).	(Wu <i>et al.</i> , 2019)
Blast (leaf and collar)	<i>Pyricularia oryzae</i>	Seed treatment of <i>Pseudomonas fluoresce</i> .	(Asibi <i>et al.</i> , 2019; Dey, 2022)
Brown spot	<i>Bipolaris oryzae</i>	Rice leaf roller (<i>Cnaphalocrocis medinalis</i>).	(Laxman <i>et al.</i> , 2016)
False smut	<i>Ustilaginoidea virens</i>	Chemical seed treatment.	(Song <i>et al.</i> , 2021)
Rice grassy stunt and rice ragged stunt	<i>Nilaparvata lugens</i> Stal	Classical miRNA and siRNA- based strategies	(Helina <i>et al.</i> , 2020; Lacombe <i>et al.</i> , 2021)
Bacterial blight	<i>Xanthomonas oryzae</i> pv. <i>oryzae</i> (Xoo)	Antibiotics and chemical biocides	(Vishakha <i>et al.</i> , 2020; Lin <i>et al.</i> , 2021)
Tungro	<i>Nephotettix virescens</i>	Mathematical modelling	(Na Phattalung <i>et al.</i> , 2022)
Leaf scald	<i>Monographella albescens</i>	BRM- 32113 with Si fertilizers	(Bueno <i>et al.</i> , 2017)
Bakanae	<i>Fusarium fujikuroi</i>	Preemptive seed	(Volante <i>et al.</i> , 2017)
Sheath rot	<i>Sarocladium oryzae</i> (Sawada)	Usage of resistant varieties	(Fetene <i>et al.</i> , 2020)
Stem rot	<i>Sclerotium oryzae</i>	The use of native isolates of <i>Trichoderma</i> as a biocontrol agent to treat rice stem rot	(Kannan <i>et al.</i> , 2021; Bashyal <i>et al.</i> , 2021)
Bacterial sheath brown rot	<i>Pseudomonas fuscovaginae</i>	Emulsion formulation	(Syed <i>et al.</i> , 2020)
Rice stripe disease	Rice stripe virus (RSV)	Insecticides application	(Ma <i>et al.</i> , 2022)
Rice yellow mottle virus	Rice yellow mottle virus (RYMV).	Host plant resistance	(Suvi <i>et al.</i> , 2020; Sekiya <i>et al.</i> , 2022)

AgNPs effect is the most notable or what function particle size plays in determining these effects. Engineered nanomaterials (ENMs) were created and developed for a variety of applications in numerous industrial sectors due to their small size within the range of 1 and 100 nm and distinctive chemical and physical properties (Yan and Chen, 2019). Relative to silver in its macroscale state, nanoparticles have exhibited an enhanced surface area to volume ratio and improved functional capacity (Bruna *et al.*, 2021). AgNPs are the most widely used nanomaterial among the many ENMs types. AgNPs are involved in all nanotechnology consumer products, with more than 25%. On the other side, in the agriculture sector, AgNPs were developed as fungicides to prevent fungal infections, plant growth promoters, or agents to accelerate the process of fruit ripening.

Characterisation of silver nanoparticles

Several techniques can be used to characterise the AgNPs. According to Rautela *et al.* (2019), transmission electron microscopy (TEM) analysis estimated the AgNP size to range between 10 and 30 nm (Rautela *et al.*, 2019). Additionally, scanning electron microscopy (SEM), Energy Dispersive Spectroscopy (EDS), and X-ray diffraction (XRD) were utilised to examine the size, morphology, and confirm the presence of silver in the resultant AgNPs pellets (Ibrahim *et al.*, 2020). For the particle size distribution analysis, the produced AgNPs solution was diluted with Milli-Q water and analysed using a dynamic light scattering particle size analyser. (Chowdhury *et al.*, 2022). Meanwhile, the absorbance between 200 and 800 nm with a resolution of 1 nm was determined using UV-Vis spectroscopy (Ibrahim *et al.*, 2019). The surface plasmon resonance (SPR) properties of the produced AgNPs were represented by a large peak in the UV-Vis spectra of the particles. After 0.5% and 1.0% rice leaf extract reacted with AgNO₃ solution, the peak's strength rose however, the concentration of rice leaf extract at 2% caused the intensity to decline. Therefore, 1% of rice leaf extract was consequently thought to be the ideal concentration to produce AgNPs (Ibrahim *et al.*, 2019).

The synthesis of silver nanoparticles

Several studies showed the production of AgNPs. The production of AgNPs through a biological process is referred to as the biosynthesis of AgNPs. According to Ibrahim *et al.* (2020), AgNPs were produced

by an onion endophytic bacterium (Ibrahim *et al.*, 2020). Endophytic bacteria are a form of bacterium known as an endophyte that dwells inside the tissues of a host plant without harming the host plant. The endophytic bacteria are cultivated using the approach on a nutrient-rich medium, and the filtration is then dissolved in an Ag salt solution. The microbial metabolites facilitate the reduction of silver ions, leading to the synthesis of silver nanoparticles.

Synthesising AgNPs using the biosynthesis of endophytic bacteria is a safe and eco-friendly method (Ibrahim *et al.*, 2019). On the other hand, *Magnaporthe oryzae*, the cause of the rice blast, was significantly inhibited by the 40 µg/mL concentration of biosynthesised AgNPs, exhibiting an 88% inhibition rate in terms of mycelial growth. Moreover, *M. oryzae*'s spore germination and appressorium development were markedly reduced by the biosynthesised AgNPs. Therefore, it is inferred that *M. oryzae* growth is effectively inhibited by the AgNPs produced by onion endophytic bacteria (Ibrahim *et al.*, 2020). Additionally, because biosynthesis uses plant extract, which has benign qualities and supplies natural capping agents, biogenic synthesis is a wonderful method for producing AgNPs (Ibrahim *et al.*, 2019). Compared to other chemical processes, this one is thought to be economical and environmentally beneficial. The result nanoparticles may also possess distinctive properties that render them suitable for diverse applications, including antibacterial agents. Due to their distinctive biological, physicochemical, and antibacterial activity capabilities in controlling plant diseases, biogenic AgNPs have received considerable attention (Ahmed *et al.*, 2020). Otherwise, the sunlight-induced synthesis of AgNPs is a method that uses natural sunlight to prepare AgNPs from easily raw materials. The sunlight's energy activates the reduction of Ag⁺ ions to form AgNPs. Following that, the as-prepared AgNPs are analysed under several methods, which are TEM, DLS, XRD, EDS, and UV-vis spectroscopy. This process is regarded as easy, environmentally friendly, and creates no toxic by-products (Rajasekar *et al.*, 2021).

The biosynthesis of silver nanoparticles using *Phyllanthus emblica* fruit extract was achieved by adding varying concentrations to a 100 ml aqueous solution of 1 mM silver nitrate. The mixture was then boiled for 20 minutes at 65°C and subsequently maintained at room temperature in the dark. The synthesis of AgNPs

was confirmed by observing the colour change to dark brown, which is indicative of nanoparticle formation. Further analysis of the AgNPs revealed a UV-visible spectrum with a peak at 430 nm, corresponding to the surface plasmon resonance of the AgNPs produced by the phytochemical agents present in the *Phyllanthus emblica* fruit extract (Masum *et al.*, 2019).

The effects of silver nanoparticles on paddy

In addition to conventional methods such as chemical

treatments, nanoparticles have emerged as promising alternatives for managing paddy diseases. Among these, silver nanoparticles (AgNPs) have gained increasing attention for their application as both biopesticides and nano-fertilizers. This paper focuses specifically on the potential of AgNPs in combating paddy diseases. A total of twelve studies on the application of AgNPs in rice disease management highlighting various rice diseases, their associated phytopathogens, and AgNPs concentrations are summarized in Table 2.

Table 2: Overview of silver nanoparticles (AgNPs) applications in rice disease control.

Rice disease	Phytopathogens	Reducing and stabilizing agent	Synthesis condition	Average particle size/ range (nm)	Concentrations of AgNPs	Reference
Rice blast	Magnaporthe oryzae	Bacillus sp.	1 mM AgNO ₃ at 30 °C under shaking conditions (200 rpm) for 4 days in the dark	2.00 and 15.00	2 µg mL ⁻¹	(Shi <i>et al.</i> , 2023)
Rice blast	Magnaporthe oryzae	Bacillus endophyticus	3 mM AgNO ₃ were shaken at 30°C for 200 rpm. for 3 days in the dark.	4.17 to 26.9	40 µg/mL	(Ibrahim <i>et al.</i> , 2020)
Rice bakanae	Fusarium sp.	Azadirachta indica leaf aqueous extract	2 g AiLAE and 1 mM AgNO ₃ at a 1:19 extract-to-AgNO ₃ ratio, maintained at 85 °C for 4 hours.	4 to 27 nm, average size of 15 nm	17.24 µg/mL	(Akhter <i>et al.</i> , 2024)
Rice sheath blight	Rhizoctonia solani	Ipomoea carnea leaf extract	2 mM AgNO ₃ at a 1:10 leaf extract-to-AgNO ₃ ratio, adjusted to pH 10, and carried out for 30 minutes.	30 to 90	1.5 ppm	(Islam <i>et al.</i> , 2024)
Rice sheath blight	Rhizoctonia solani	Pseudomonas fluorescens OKC (Accession number JN128891)	1 mM AgNO ₃ at a 3:1 extract to AgNO ₃ ratio, maintained at room temperature until a color change was observed.	~74.00	30 ppm	(Lopamudra <i>et al.</i> , 2023)
Rice sheath blight	Rhizoctonia solani	rice leaf extract	0.4% rice leaf extract and 0.6 mM AgNO ₃ , followed by autoclaving at 121 °C and 103 kPa in a domestic pressure cooker for 30 minutes.	~110.80	20 µg/mL	(Kora <i>et al.</i> , 2020)
Rice sheath blight	Rhizoctonia solani	N/A	4000 ppm (commercialized AgNPs)	5.00 to 10.00	50 ppm	(Soltani <i>et al.</i> , 2017)
Bacterial Leaf Blight	Xanthomonas oryzae pv. oryzae (Xoo)	Bacillus cereus	5 mM AgNO ₃ at 28 ± 2 °C under orbital shaking at 150 rpm for 24 hours.	18.00 to 39.00	100 mgL ⁻¹	(Ahmed <i>et al.</i> , 2020)
Bacterial leaf blight	Xanthomonas oryzae pv. oryzae	Calliblepharis fimbriata aqueous extract	1 mM AgNO ₃ at a 9:1 aqueous extract was kept at 35 °C, then incubating the mixture in the dark room for 48 hours.	25.00 to 30.00	50 µg/mL	(Thynraj <i>et al.</i> , 2021)
Bacterial leaf blight	Xanthomonas oryzae pv. oryzae	Arctium lappa fruit	2 mM AgNO ₃ and 3 plant extracts were shaken at 30°C for 200 rpm.	20.18	20 µg/mL	(Tian <i>et al.</i> , 2022)
		Solanum melongena leaves		21.00		
		Taraxacum mongolicum leaves		40.08		
Bacterial leaf blight and bacterial brown stripe	Xanthomonas oryzae pv. oryzae and Acidovorax oryzae	Bacillus siamensis	3 mM aqueous silver nitrate (AgNO ₃) and incubating at 30°C for 24 hours.	25.00 to 50.00	20 µg mL ⁻¹	(Ibrahim <i>et al.</i> , 2019)
Rice brown spot	Bipolaris oryzae	NaBH ₄	1 mmol L ⁻¹ AgNO ₃ were added gradually into 2 mmol L ⁻¹ NaBH ₄ . The AgNPs were kept at 4°C in the dark.	~20	10 µmol L ⁻¹	(Almeida <i>et al.</i> , 2024)

Nanoscale silver exhibits distinctive properties, such as a large specific surface area, high target adhesion, robust permeability, and potent bactericidal activity, making it suitable for various applications. These characteristics make it more effective than other substances like streptomycin and copper at penetrating cell membranes or clinging to bacterial surfaces (Rajasekar *et al.*, 2021). Significant growth of the paddy seedlings was aided by the biosynthesised AgNPs. According to Ibrahim *et al.* (2019), paddy seedlings treated with AgNPs had longer roots, shoots, fresh weight, and dry weight than seedlings treated with water (Ibrahim *et al.*, 2019). Specifically, paddy seedlings treated with silver nanoparticles exhibited enhanced growth characteristics, including root lengths of approximately 7.4 cm, shoot lengths of 11.6 cm, fresh weights of 0.24 g, and dry weights of 0.04 g. In contrast, seedlings treated with water had comparatively shorter root lengths (5.1 cm), shoot lengths (6.5 cm), fresh weights (0.12 g), and dry weights (0.03 g). These findings suggest that the application of AgNPs has a beneficial effect on the growth and development of paddy seedlings.

The research by Ahmed *et al.* (2020) indicates that silver nanoparticles synthesised by *Bacillus cereus* SZT1 have been demonstrated to mitigate the damage caused by the paddy leaf blight. Compared to untreated control plants, AgNP suspensions at various concentrations significantly reduced the lesion length associated with bacterial leaf blight (BLB). The maximum inhibition rate was observed in paddy plants treated with an AgNP suspension at a concentration of 25-100 mg L⁻¹. These findings suggest that biogenic AgNPs have significant potential for the biological management of bacterial leaf blight in paddy cultivation. Meanwhile, synthesised AgNPs from *Phyllanthus emblica* fruit extract exhibited exceptional antimicrobial activity against *Acidovorax oryzae* strain RS-2, which is the pathogen responsible for paddy bacterial brown stripe disease. The AgNPs prevented bacterial growth and interfered with their capacity to form biofilms and swarm. AgNPs caused cell membrane disruption in strain RS-2, which led to an increase in the release of the effector Hemolysin Coregulated Protein (Hcp). It is a particular class of effector protein that many Gram-negative bacteria produce and is regarded as a distinctive element of the Type VI Secretion System (T6SS). Given the circumstances, AgNPs may be a desirable and environmentally acceptable choice to treat *Acidovorax oryzae* strain RS-2-induced paddy

bacterial illness (Masum *et al.*, 2019).

Mechanisms of antimicrobial action and toxicity of silver nanoparticles

The antimicrobial activity of silver nanoparticles (AgNPs) is attributed to their ability to bind to the cell membrane, which disrupts the phospholipid bilayer structure. This disruption suppresses mycelial growth and inhibits the germination of conidia, causing damage to the cell wall and compromising membrane integrity. Therefore, the cell membrane becomes more permeable, allowing the AgNPs to enter the cells. Once internalised, these nanoparticles interfere with intracellular organelles and the interactions of large molecules, leading to the generation of elevated levels of reactive oxygen species (ROS) and free radicals. This accumulation affects the biological processes within the cells by disrupting signal transduction pathways, metabolic processes, and genetic information processing, ultimately leading to cell death (Shi *et al.*, 2023; Akhter *et al.*, 2024).

Silver nanoparticles exhibit toxicity through various mechanisms, primarily involving the release of silver ions (Ag⁺), which interact with cellular components and generate reactive oxygen species. ROS cause oxidative stress, damaging cellular structures like DNA, proteins, and lipids, leading to cell death. The physical properties of AgNPs, such as size, shape, and surface coating, also influence their toxicity. Smaller particles exhibit higher toxicity due to their larger surface area to volume ratio, facilitating greater interaction with biological systems (Khan *et al.*, 2023). The overall working mechanism of silver nanoparticles (AgNPs) in disease control, including their antimicrobial action and interaction with phytopathogens, is illustrated in Figure 2.

While AgNPs demonstrate antimicrobial properties even at high concentrations, their toxicity to other organisms raises concerns about environmental and human health risks. Furthermore, the presence of natural organic matter can alter the toxicity of AgNPs by influencing their aggregation and dissolution behaviour. Sulfidation, a process where silver reacts with sulfur-containing compounds, can reduce the toxicity of AgNPs, but its long-term effects are still under investigation (Li *et al.*, 2019).

Determining the allowable max. concentration of AgNPs is complex and depends on numerous factors,

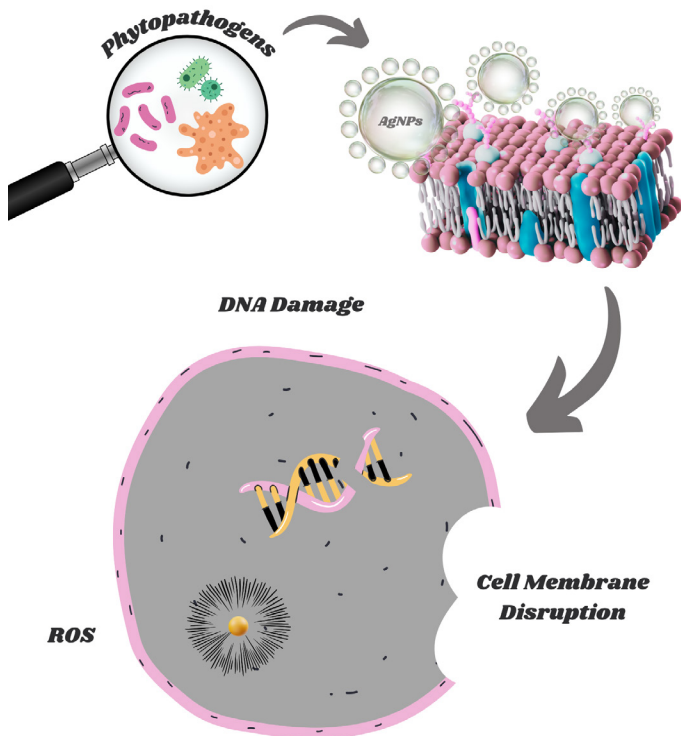


Figure 2: Schematic representation of the overall working mechanism of silver nanoparticles (AgNPs) in disease control, highlighting their antimicrobial action, interaction.

including the specific application, the organism being considered, and the exposure route. Regulatory agencies in different countries have established guidelines for silver content in various products, but specific limits for AgNPs are still evolving. For instance, in the phytotoxicity of AgNPs in rice, 1 mg/L of AgNPs will cause a reduction in root elongation, as well as decreases in shoot and root fresh weights, total chlorophyll, and carotenoid contents, reduce the plant biomass and a reduction in sugar content (Pan *et al.*, 2024). Additionally, there was an increase in malondialdehyde, lipid peroxidation and hydrogen peroxide (H_2O_2) levels in the leaves, shoots, and roots (Pan *et al.*, 2024). At 60 mg/L, the structure and cell

morphology will be altered, decreasing in total soluble carbohydrates, causing the production of reactive oxygen species (ROS) and localised root tissue death. At 1000 mg/L, seed germination and seedling growth were impaired, damaging the cell walls and vacuoles of root cells (Yan and Chen, 2019). Further research is needed to establish comprehensive guidelines for safe AgNPs concentrations in different environments and applications. Table 3 provides a comparative overview of the mechanisms of action and nanoparticle-based treatments used in various crops, including tomato, wheat, and paddy, indicating their potential applicability across plant species

Application of silver nanoparticles in plant disease

Various nanoparticles, nanomaterials and nanobiocides have been developed to prevent and treat plant diseases in crops (Vijayreddy *et al.*, 2023). Recent studies have shown that silver nanoparticles have broad antimicrobial activities against bacteria and fungi due to their diverse inhibitory mechanisms. Furthermore, AgNPs have demonstrated fungicidal effects against plant pathogens like *Fusarium oxysporum* (Huang *et al.*, 2017) and *Tritium aestivum* (Satti *et al.*, 2021). However, only a few studies have been published on the use of AgNPs to treat plant diseases, notably those brought on by *Rhizoctonia solani* species that create sclerotia (Kora *et al.*, 2020). In potato plants, *R. solani* can lead to black scurf and stem canker (Wang and Xu, 2019). Similarly, it can significantly impact canola cultivation, which is predominantly practised in Europe, Canada, Australia, and China. The symptoms observed in affected canola include pre- and post-germination damping-off, seedling root rot, and basal stem rot. The production of canola and rape-seed continues to face a major and ongoing threat from Sclerotinia stem rot, which is brought on by

Table 3: The list of mechanisms of action for other plants.

Plant name	Symptoms	mechanism of action	Nanoparticles treatments	References
Tomatoes (<i>Solanum Lycopersicum</i> L.)	Yellowing and wilting will lead to plant death.	<i>Fusarium oxysporum</i> f. sp. <i>lycopersici</i> (FOL) fungus colonizes the vascular tissues at different physiological phases	<i>In vitro</i> assays using copper nanoparticles (CuNPs). CuNPs contain oxidation states that are effective against <i>F.oxysporum</i>	(Huang <i>et al.</i> , 2019; Lopez-Lima <i>et al.</i> , 2021)
Wheat (<i>Tritium aestivum</i>).	Distinct, elongated, black-brown lesions.	The mycotoxins produced by fungi affect the wheat grains' overall nutritional value.	Exogenous treatments of TiO_2 NPs limit the growth of mycotoxins.	(Satti <i>et al.</i> , 2021)
Paddy (<i>Oryza sativa</i> L.)	In infected nodes, irregular black areas encircle the nodes.	Caused by the fungus <i>Pyricularia grisea</i> (Cooke) Sacc. Various fungal races can affect most rice cultivars.	Application of AgNPs to the <i>Mag-naphorte grisea</i> culture revealed a dose-dependent decrease in hyphal and the number of colonies produced.	(Elamawi and El-Shafey, 2013; Simkhada, 2021)

Sclerotinia sclerotiorum (Zhang *et al.*, 2020). Wheat is similarly harmed by sclerotia. According to Alaoufi *et al.* (2023), the ergot-causing organism, *Claviceps purpurea*, is known to infect various grass species, including wheat. The alkaloids synthesised by this pathogen within its mature sclerotial structures result in reduced wheat quality and potential rejection at market (Alaoufi *et al.*, 2023).

Apart from that, it was intended for the current study to synthesise AgNPs using paddy leaf extract as a dual-functional reductant and stabiliser, while also maximising the quantities of extract, silver nitrate, and reaction time (Kora *et al.*, 2020). Paddy leaf extract was applied in combination with a modified version of the process to develop an easy and environmentally friendly way to create AgNPs. Originally, the fresh paddy leaves were collected and cleaned with distilled water. An aqueous extract was prepared by boiling 5 grams of the leaves in 50 millilitres of distilled water, which was then filtered, and the supernatant collected (Chowdhury *et al.*, 2022). Various ratios (0.5%, 1.0%, 2.0%, and 5.0%) of the paddy leaf extract were combined with a 1 mM silver nitrate solution. The mixture's pH was raised to the alkaline range and then left at room temperature until it turned a yellowish-brown colour, confirming the formation of silver nanoparticles.

Advantages and disadvantages of silver nanoparticles

Due to their exceptional antibacterial and catalytic capabilities, AgNPs have generated a significant amount of interest. Instead, the use of microorganisms like fungi, bacteria, and yeast to biosynthesise these nanoparticles has started to gain greater attention as a more straightforward and environmentally acceptable method of their synthesis (Zhao *et al.*, 2022). According to Kale *et al.* (2021), AgNPs have a high surface area and a high fraction of surface atoms (Kale *et al.*, 2021). Compared to bulk silver, AgNPs have been shown to have a high antimicrobial effect. Additionally, AgNPs are widely known for their anti-inflammatory, anti-viral, anti-bacterial, and anti-fungal effects. Moreover, AgNPs have a variety of effects in both *in vivo* and *in vitro* applications. Due to its qualities, ease of use, simplicity, and environmental friendliness, AgNPs synthesis is gaining a lot of interest (Simon *et al.*, 2022). Furthermore, it does not affect living cells, thus making the researcher show a lot of interest in AgNPs.

Despite their potential, silver nanoparticles entail some notable drawbacks. AgNPs synthesis requires considerable space and energy, which raises the ambient temperature around the source material (Simon *et al.*, 2022). Moreover, achieving thermal stability for AgNPs takes a prolonged duration and necessitates substantial power input, often exceeding several kilowatts, as well as extended preheating periods of several minutes to reach a stable operating temperature. Furthermore, according to Zhao *et al.* (2022), AgNPs preparation involves potentially hazardous reagents like citrate, borohydride, thio-glycerol, and 2-mercaptoethanol, and it is an energy-intensive process, which collectively poses a challenge for their large-scale production (Zhao *et al.*, 2022).

Nanoparticles challenges for paddy disease

The main challenges in using silver nanoparticles to manage paddy diseases are the lack of standardisation across different studies. This makes it difficult to compare findings, as the methods for producing, characterising, and applying AgNPs vary greatly. Additionally, AgNPs tend to aggregate and become unstable, which can reduce their effectiveness and availability in agricultural systems (Lu *et al.*, 2020). To achieve reliable performance, the nanoparticle formulations must be stable and preserve their properties during storage and application.

Furthermore, despite the development of resistance, the efficiency of AgNPs will be reduced over time as a result of pathogens developing resistance with the excessive or continuous use of AgNPs (Huang *et al.*, 2017). It is essential for AgNPs to reach the targeted area, such as particular cells or tissues, to ensure the effectiveness of AgNPs. Nanoparticle size, surface charge, and interactions with biological barriers are a few of the aspects that can make it difficult to achieve targeted distribution. On the other hand, farmers and researchers find it difficult to embrace and implement the technology because there are no clear regulations or guidelines for using AgNPs in agriculture. Regulations and guidelines may apply to the use of nanoparticles in various applications. Testing, registration, and approval procedures might be difficult to manage to comply with these rules.

Conclusions and Recommendations

Nanoparticles are emerging as versatile tools in many fields, with silver nanoparticles showing exceptional

promise in agriculture. AgNPs have demonstrated remarkable efficacy in combating plant diseases, effectively inhibiting a broad spectrum of pathogens while simultaneously promoting plant growth. Combined with lower environmental impact, AgNPs offer a promising avenue for safer, more effective treatments for plant diseases, especially in crops like paddy rice.

Paddy rice, a staple food for a massive portion of the global population, is susceptible to a range of devastating diseases, including blast disease caused by *Pyricularia oryzae*, sheath blight, and bacterial leaf streak. Current disease management strategies often prove inadequate, highlighting the urgent need for more effective and sustainable solutions. This review has highlighted the potential of AgNPs to address this challenge, with research suggesting a possible 30% improvement in disease management through their utilisation.

Despite ongoing challenges in optimising the synthesis, delivery, and understanding the long-term environmental impact of silver nanoparticles, their potential benefits are substantial. Future research should focus on refining AgNPs applications for paddy disease control, exploring their efficacy against a wider range of pathogens, and developing sustainable synthesis methods using biological agents like endophytic bacteria. By addressing these challenges and harnessing the unique properties of AgNPs, we can pave the way for a more sustainable and secure future for paddy rice cultivation and global food security.

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Novelty Statement

This review presents a novel examination of biosynthesised silver nanoparticles as a sustainable and environmentally friendly alternative to conventional

chemical treatments for paddy disease. It highlights the potential of AgNPs to effectively combat paddy diseases like rice blast and sheath blight, addressing the growing concern of pesticide resistance and environmental harm associated with traditional methods.

Author's Contribution

Roslina Ainna Roslan, Athirah Marsya Azizul Rashidi and Norfatimah Mohamed Yunus: Collaboratively conceptualised the research review, conducted the literature review, and drafted the manuscript.

Sharifah Aminah Syed Mohammad and Nurul Aili Zakaria: Assisted in the revision of the manuscript.

Conflict of interest

The authors agree that this research was conducted in the absence of any self-benefits, commercial or financial conflicts and declare the absence of conflicting interests with the funders.

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