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Nanoagrosomes: Future prospects in the management of drug resistance for sustainable agriculture☆

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ABSTRACT

Agriculture plays a crucial role in sustaining the global population with food safety and security. The inadequacy of current agrochemicals in effectively controlling microbial infestations necessitates immediate attention. The over usage of agrochemicals has posed significant threat to agriculture by hampering the crop productivity, increased disease outbreaks and spread resistant microorganisms. This review addresses the pressing issue of drug-resistant microbial pathogens and their detrimental impact on the agricultural system. The use of nanoagrosomes has gained significant attention as a potential solution for combating drug-resistant pathogens due to their unique physicochemical properties, which can be tailored to target specific activities. A diverse of nanoagrosomes is widely practiced to attenuate specific roles which has been outline in the review. It also shed light on their effectiveness in combating drug-resistant pathogens and their role in promoting agricultural sustainability by expanding scientific understanding of nanoagrosomes as a future prospect for management of drug resistance.

1. Introduction

In recent years, advanced scientific domains have emerged, unleashing technological advancements in all aspects of life (Dragan et al., 2018; Singh et al., 2021). The agriculture sector has been revolutionized by numerous scientific research endeavors aimed at improving existing technologies (Rose et al., 2021). In order to contribute to scientific knowledge, nanotechnologies have been developed to design and create scientific tools that are gaining increasing interest in daily life (Grumezescu abd Holban, 2020). In agriculture, the application of nanomaterials at the ultramolecular level has demonstrated numerous potential uses (Tuantranont et al., 2021). The physicochemical properties of these nanomaterials suggest untapped mechanisms that can be tailored and manipulated to attenuate specific activities (Deng et al., 2022; Nadar et al., 2021). This can be achieved efficiently since their exuberant magnetic properties are coupled with plasmonic and optical characteristics, leading to the quantum confinement of atoms (Baig et al., 2021; Deb, 2021). Furthermore, their size-dependent properties provide a larger surface area in comparison to bulk materials of the same composition (Pabari, 2022). These unique properties are well documented, with an increasing number of articles exploring their potential applications. As a result, nanomaterials represent one of the most reliable and excellent platforms for developing advanced scientific tools that are more compatible (Saleh, 2020; Khan et al., 2019). In agriculture, there is a high demand for nano-based technologies to produce food commodities and meet the needs of the growing world population (Zhao et al., 2020). The farming communities face a range of challenges from sowing to harvest and post-harvest processes which must be addressed precisely (Usman et al., 2020; Bratovcic et al., 2021).

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1.1. Impact of agrochemicals

Agrochemicals are chemical entities which are in use to crop productivity and protecting plants from pests, diseases, and weeds. In contrast to this, the over usage of these hazardous chemicals can lead to biomagnification in an ecosystem (Singh et al., 2021). This can have a major impact on groundwater contamination which can lead to entering of pesticides into human bodies and detected in breast milk (Thapa et al., 2022). Groundwater contamination with pesticides and harmful chemicals is reported, and recent studies highlight the detection of pesticides in breast milk (Kuang et al., 2020; Bexfield et al., 2022). These chemically bound agromaterials also infect live animals, directly or indirectly entering the food chain and reaching the masses (Baker et al., 2019a). The deleterious effects of pesticides have been extensively discussed and verified at the global level, leading to the prohibition of many pesticides that enter ecosystems by various governing bodies (Vryzas, 2018). These pesticides are known to contaminate groundwater, persist in the environment, and readily penetrate the tissues of humans and animals, leading to adverse health outcomes (Kapsi et al., 2019). Even at low concentrations, these pesticides pose a significant risk and are of great concern as they can have transgenerational health implications (Kalyabina et al., 2021). The impacts of pesticides can range from mild symptoms such as headaches and fever to chronic conditions like carcinogenicity, which disrupt the reproductive and endocrine systems (Sabarwal et al., 2018; Nisha Raj et al., 2021). Therefore, it is imperative to overcome the limitations of chemical-based pesticides. Advanced and reliable technologies have been developed, which can be easily used even at the farm level, to avoid these issues. Nanotechnology is emerging as a key player in addressing these global challenges by offering advanced and dependable technologies (Okey-Onyesolu et al., 2021; Ali et al., 2021).

1.2. Nanoagrosomes

Nanoagrosomes combines nanotechnology and agrochemicals to improve the targeted delivery and efficacy of agricultural inputs (Baker et al., 2017). These nanoscale structures offer precise control over the release of nutrients and pesticides, leading to increased crop yields, reduced environmental impact, and enhanced resource efficiency (Baker et al., 2019b). Nanoagrosomes can be defined as nano-sized particles specifically designed for use in agriculture, particularly for combating phytopathogens (Baker et al., 2017). In recent years, there has been a dramatic increase in drug resistance among microbial pathogens, including those affecting humans and plants (Lai et al., 2021). Genetic exchange among pathogens in the environment has led to serious implications, such as the devastating impact of flies on crops in different countries throughout history (Straub et al., 2021). Antimicrobial resistance is rapidly increasing worldwide and is predicted to be a major cause of mortality and morbidity by 2050, according to the WHO (Michael et al., 2014). The development of resistance is not limited to clinically important pathogens, and ineffective management strategies and chemicals have led to a paradigm shift in drug resistance for both veterinary and plant pathogens (Miller et al., 2022). If not addressed scientifically, antimicrobial resistance may lead to similar devastating situations in the coming decades (Ayukekbong et al., 2017; Kumar et al., 2021). Therefore, novel strategies need to be developed and implemented to control the expansion of antimicrobial resistance. This review discusses the use of nanoagrosomes for managing phytopathogens and explores the latest technologies and future prospects (Worrall et al., 2018).

The utilization of nanomaterials and the creation of multi-functional components that can effectively target pathogens with multiple modes of action is a potential strategy for disease management (Prasad et al., 2017; Kah, 2015). Numerous scientific studies have confirmed the antimicrobial properties of various nanomaterials (Table 1), with many demonstrating efficacies against both clinical and phytopathogenic pathogens (Rajwade et al., 2020; Yadav, Meena, 2021). The size-dependent properties of nanomaterials are advantageous for targeting microbial pathogens (Wang et al., 2020), and nano-sized "nanoagrosomes" have the potential to be a superior alternative to bulk materials, with added plant growth promoting properties. The synthesis of nanoagrosomes is critical for fine-tuning their multi-functional properties (Saravanan et al., 2022). This can only be achieved through the application of nanotechnological principles, and this review discusses the development of various types of nanoagrosomes and their potential applications for managing phytopathogens.

2. Synthesis and stabilization of nanoagrosomes

The synthesis and stabilisation of nanoagrosomes involve intricate processes for creating nanoscale structures and ensuring their long-term stability in agricultural applications (Castillo-Henríquez et al., 2020). The synthesis of nanoagrosomes can be broadly classified into two categories: top-down and bottom-up approaches (Fig. 1). Top-down approaches involve gradual processing of macroscopic structures to produce controlled nanostructures (Iqbal et al., 2012; Gutiérrez-Cruz et al., 2022). These methods include the use of mechanical thermal cycles, attrition, and laser ablation, which generate polydispersed nanoparticles with sizes ranging from 10 to 100 nm. In contrast, bottom-up approaches involve the synthesis of nanostructures through pyrolysis, inert gas condensation, solvothermal reactions, gel fabrication, and structured media (Baker et al., 2013a). Bottom-up approaches are more widely used due to their compatibility and advantages over top-down approaches (Shakiba et al., 2020). One popular bottom-up approach is the use of reducing agents, such as hydrogen, sodium borohydrate ($NaBH4$), Tollen's reagent, polyol process, and N-dimethylformamide (DMF), which reduce metal ions and form agglomerates that eventually lead to nanoparticle formation (Iravani, 2011; Baker et al., 2013b).

To stabilize nanoparticles during the formation phase, protective agents are necessary to avoid agglomeration and maintain their surface properties. Surfactants containing amines, thiols, alcohols, and acids can be used as protective agents, which absorb onto or bind onto the surface of nanoparticles (Abid et al., 2022). In recent years, there has been a growing interest in using biological resources such as plants and microbial compounds as reducing agents to synthesize nanomaterials (Kavitha et al., 2013). The choice of nanoagrosome synthesis protocol depends on the intended application properties and the composition of the nanomaterials, which can include bimetallic and bioconjugated nanomaterials, widely used in managing phytopathogens.

2.1. Nanoagrosomes as phytobactericides

Nanoagrosomes have emerged as promising phytobactericides, utilizing their unique properties to combat plant diseases caused by bacteria. Nanoagrosomes delivery enable efficient penetration into plant tissues, enhancing the efficacy of bactericidal agents and providing an environmentally friendly approach to disease management in agriculture (Baker et al., 2019a, 2019b; Chauhan et al., 2020). The action of nanoagrosomes is based on their nanoscale size and associated properties, the studies demonstrate wide range of effects against the targeted pathogens (Syed et al., 2018). The bactericidal properties of nanoparticles induce morphological damage by targeting the cell wall of pathogens, damaging the cell and loss of cellular content (Fig. 2). Additionally, these particles have been found to inhibit the activity of vital enzymes responsible for microbial growth and multiplication, disrupting ATP production (Baker et al., 2020a, 2020b). Although, large number of scientific literatures on nanoparticles and their activities are reported. The following section accounts only recent findings of nanoparticles as phytobactericides acting against the important pathogens is discussed. The effectiveness of copper oxide nanoparticles was studied against bacterial wilt disease which showed significant suppression of pathogen *Ralstonia solanacearum*. The nanoparticles disrupted the

Table 1
Nanoagrosomes and their activity against drug resistant and phytopathogens.

Type of Nanoagrosomes /nanoparticles	Activity	Pathogens	Reference
Silver nanoparticles	Antibacterial activity	MDR-*Pseudomonas aeroginosa*, MRSA	Mohamed et al., 2020
Silver nanoparticles	Antibacterial activity	Extended-spectrum beta lactamase producing pathogen and MRSA	Qais et al., 2019
Silver nanoparticles functionalised with antimicrobial peptides	Antibacterial activity	Drug resistant *E. coli*	Zharkova et al., 2021
Copper doped chitosan nanoparticles	*Antibacterial activity*	*E.coli and S.aureus*	Huang et al., 2017
Silver nanoparticles with hydrogen peroxide	Antibacterial activity	*S. typhimurium*, *E.coli* 0157:H7, *L.Monocytogens*, *K.Pneumoniae*, *P. aeruginosa*	El-Gohary et al., 2020
Zinc oxide nanoparticles	Antibacterial activity	*E.coli*, B.*subtilis, S.aureus, K.Pneumoniae*,	Khatana et al., 2021
Nano hybrid silver-copper	Antibacterial activity	*P.aeruginosa, A.baumanni, E.coli, K.Pneumoniae*	Baker et al., 2020a, 2020b
Silver and zinc oxide nano bactericides	Antibacterial activity	MRSA strain	Baker et al., 2019a, 2019b
Bimetallic (Ag-Au)	Antibacterial activity	*E.coli*, B.*subtilis, S.aureus, S.typhi*	Syed et al., 2019
Hydrophillic nanoparticles	Antibacterial activity	MRSA, Vancomycin resistant *S.aureus*, Gentamicin resistant *P.aeruginosa*	Jiang et al., 2022
Electrodynamic Pd-Pt nano Sheets	Antibacterial activity	E.coli, *S.aureus*	Qiao et al., 2022
Copper nanoparticles	Antibacterial activity	E.coli, *K.Pneumoniae, Proteus* species	Wu et al., 2020
Silver nanoparticles	Antibacterial activity	*Xanthomonas oryzae pv. oryzae*	Ibrahim et al., 2019
Silver nanoparticles	Antibacterial activity	*Xanthomonas oryzae pv. oryzae*	Ahmed et al., 2020
Antifungal activity			
Silver nanoparticles	Antifungal activity	*Aspergillus* species and *Fusarium soleni*	Khan et al., 2020
Silver nanoparticles	Antifungal activity	*Fusarium oxysporum* f. sp. Radices-lycopersici (FORL) strains	Akpinar et al., 2021
Silver and selenium nanoparticles	Antifungal activity	*Macrophomina phaseolina, Sclerotinia sclerotiorum* and *Diaporthe longicolla*	Vrandecic et al., 2020
Copper oxide nanoparticles	Antifungal activity	*Candida albicans*	Garcia-Marin et al., 2022
Zinc oxide nanoparticles	Antifungal activity	Azole resistant *Aspergillus flavus*	Alhazmi and Sharaf, 2023
Copper and copper oxide nanoparticles	Antifungal activity	*Penicillium*	Eslami Chalandar et al., 2017
Nanoparticles encapsulated with porphyrin	Antifungal activity	*Candida* species	Kodedová et al., 2023
Chitosan nanoparticles	Antifungal activity	*Penicillium digitatum Lasiodiplodia pseudotheobromae and Alternaria alternate*	Cuong et al., 2022
Silver nanoparticles	Antifungal activity	*Fusarium graminearum*	Ibrahim et al.,2020
Silver nanoparticles	Antifungal activity	*Fusarium oxysporum*	Gopinath and Velusamy, 2013
Silver nanoparticles	Antifungal activity	*Bipolaris sorokiniana*	Mishra et al., 2014
Silver nanoparticles	Antifungal activity	*Sclerotium rolfsii*	Mishra et al., 2017
Silver nanoparticles	Antifungal activity	*Poria hypolateritia*	Ponmurugan et al., 2016
Silver nanoparticles	Antifungal activity	*Fusarium graminearum*	Ibrahim et al., 2020
Silver nanoparticles	Antifungal activity	*Fusarium oxysporum*	Gopinath and Velusamy, 2013
Copper nanoparticles	Antifungal activity	*Bipolaris sorokiniana*	Mishra et al., 2014
Antiviral activity			
Silver and Gold nanoparticles	Antiviral activity	*Herpes Simplex Virus* (HSV-1)	El-Sheekh et al., 2020
Copper-graphene nanocomposite	Antiviral activity	Influenza virus	Das Jana et al., 2020
Zinc nano oxide nanoparticles	Antiviral activity	*Herpes Simplex virus* 1	Melk et al., 2021
Chitosin nanoparticles	Antiviral activity	*Bean Yellow Mosaic virus*	El Gamal et al., 2022
Gold nanoparticles	Antiviral activity	*Influenza virus*	Babaei et al., 2021
Zinc oxide nanoparticles	Antiviral activity	*Corona 229E virus*	Alqahtani et al., 2022
Zinc oxide nanoparticles	Antiviral activity	*Hepatitis C* and *Hepatitis E*	Gupta et al., 2022
Silver nanoparticles	Antiviral activity	Bean yellow mosaic virus	Elbeshehy et al., 2015

physiological functioning and damaged to the cytoplasmic membrane. This was tested under the green house conditions, the nanoparticles were also able to improve the growth of the crop (Chen et al., 2019).

The synergistic effect of rhamnolipid and chitosan nanoparticles showed activity against *Xanthomonas campestris* NCIM 5028 and *Fusarium* species. The synergistic factor impacted the antimicrobial properties with increase fold dilution (Karamchandani et al., 2022). The use of chitosan nanoparticles is increasing in the agricultural sectors, the efficacy of chitosan nanoparticles is enormous against wide range of pathogens including both bacteria and fungi. The tomato crop was protected against *Erwinia carotovora* and *Xanthomonas campestris* with the application of chitosan nanoparticles. The nanoparticles damaged the cell membrane and interacted with vital components essential for functioning (OH et al., 2019). The process of bioconjugation of nanoparticles with antimicrobial agent can be beneficial to control the microbial infestation. The use of silver nanoparticles with 2,4 DAPG was evaluated against *Xanthomonas vesicatoria*, *Xanthomonas oryzae*, and *Xanthomonas campestris*. The pathogens were found to be more susceptible to the action of bioconjugated nanoparticles in comparison with individual assessment of silver nanoparticles and 2,4 DAPG respectively (Baker et al., 2017).

2.2. Nanoagrosomes as phytofungicides

Nanoagrosomes exhibit immense potential as phytofungicides, offering a novel approach to combating fungal diseases in plants. Through their controlled release mechanisms and enhanced penetration capabilities, nanoagrosomes effectively deliver fungicidal agents, minimising crop damage and promoting sustainable fungal disease management in agriculture. Numerous studies have investigated the potential of nanoagrosomes as antifungal agents, utilizing various nanomaterials against a range of fungal pathogens that infect various crops. The effectiveness of silver nanoparticles was tested against major agriculture contaminants like *A. niger*, *A. flavus*, and *Sclerotium rolfsii*. The activity was highest against *A. niger* compared to other pathogens. This indicates the interaction of nanoparticles depends on the type of organisms tested (Elumalai and Vinothkumar, 2013). The biogenic silver nanoparticles obtained from aqueous extract of *Elettaria*

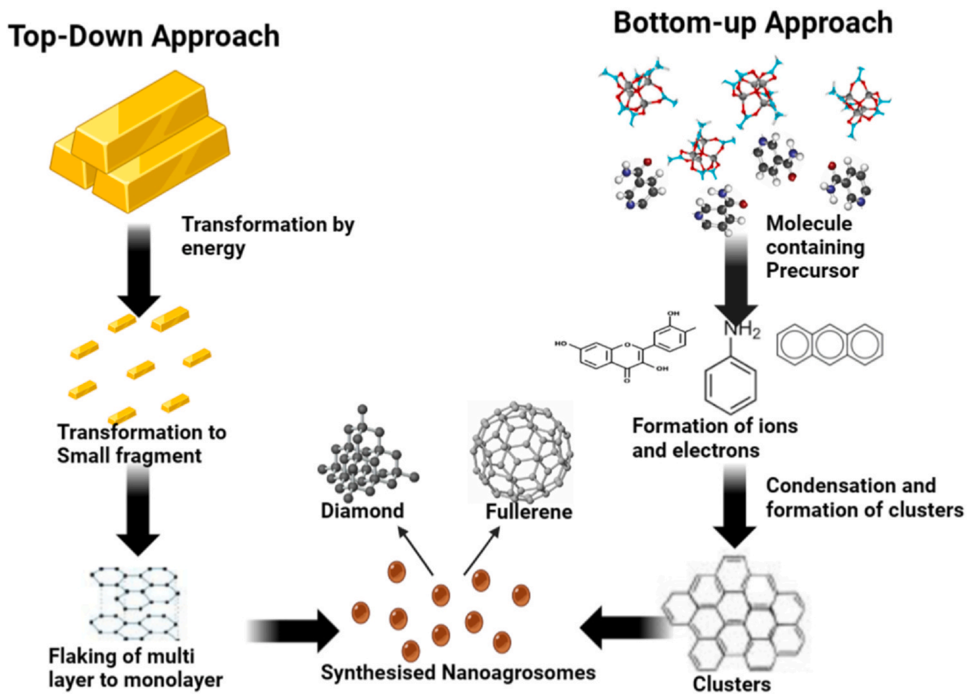

Fig. 1. Top down and bottom up approaches: Synthesis of nanoagrosomes.

cardamomum with average size of 29.96 nm showed activity against fungal pathogens. The activity was reported to be size dependent and was highest against *A. niger*, *A. alternata*, *B. cinerea, F. oxysporum* and least activity was expressed against *P. expansum* (Jamdagni et al., 2021). The use of silver nanoparticles as antifungal agents, with nanoparticle sizes ranging from 3 to 10 nm. The study showed significant activity against *Alternaria* sp. followed by *Fusarium* sp., and increased concentration resulted in higher activity of nanoparticles against the test pathogens (Win et al.,2020).

The magnesium nanoparticles have also demonstrated efficacy in controlling plant pathogens (Mansoor et al., 2021). The use of magnesium oxide nanoparticles was found to reduce the incidence of tobacco black shank and black rot disease by 36.58 % and 42.35 %, respectively, while also displaying significant activity against *Phytophthora nicotianae* and *Thielaviopsis basicola*. Scanning electron microscopy revealed changes in the morphology of the pathogen cells, suggesting that magnesium oxide nanoparticles have biocontrol potential in agriculture (Chen et al., 2020). The hybrid copper-zinc oxide nanoparticles exhibited potent antifungal activity against *Neofusicoccum arbuti, Alternaria alternate, Fusarium solani*, and *Collectrotrichum gloeosporioides,* surpassing the activity of pure oxides and composite materials (Paraguay-Delgado et al., 2022).

The silver, copper oxide, and zinc oxide nanoparticles showed antifungal activity against *Alternaria alternata, Pyricularia oryzae*, and *Sclerotinia sclerotiorum* (Consolo et al., 2020). The iron nanoparticles fungal pathogens such as *Alternaria mali*, *Botryosphaeria dothidea*, and *Diplodia seriata*, which infect the cash crop apple (Ahmad et al., 2016). The profound activity of nanoparticles as antifungal agent is reported to generate reactive oxygen species and free radicals, which disrupt the protein and nucleic acid synthesis. In addition, silver nanoparticles cause cell wall damage and proton leakage leading to cell death.

2.3. Nanoagrosomes as phytovirocides

Nanoagrosomes hold great promise as phytovirocides, providing a groundbreaking solution for controlling viral infections in plants. Leveraging their unique properties, nanoagrosomes enable targeted delivery of antiviral agents, mitigating viral diseases and contributing

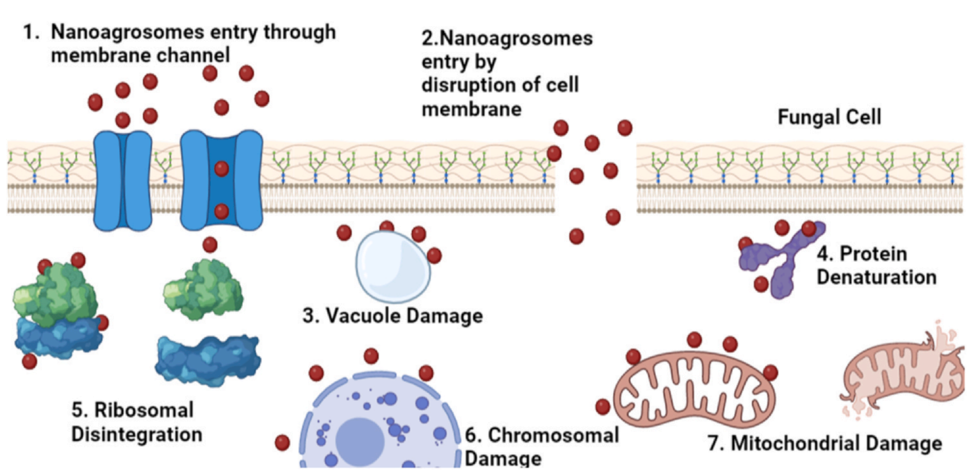

Fig. 2. Schematic representation of possible mode of action of nanoagrosomes against pathogenic bacteria.

to the health and productivity of agricultural crops. The chitosan and dextran nanoparticles were found to be effective against the viral infection in *Nicotiana glutinosa* plants; the foliar applications of these nanoparticles reduced the infection of alfalfa mosaic virus, and the plants were protected under greenhouse conditions (Abdelkhalek et al., 2021). The silver nanoparticles synthesized from *Ocimum basilicum* were found to have antiviral properties against cucumber mosaic virus, which resulted in the reduction of infection and growth promotion of *Cucurbita pepo* L. (Abdelkhalek et al., 2022). The silver nanoparticles were found to have antiviral properties, and when applied to tomatoes and potatoes under growing conditions, they showed suppression of the infection and increased photosynthetic pigments, total soluble protein, and peroxidase activities (El Dougdoug et al., 2021). The application of silver nanoparticles at a concentration of 50 ppm was found to have reduced the viral infection of banana bunching virus and increased chlorophyll content, phenols, proline, and oxidative enzymes (Mahfouze et al., 2020). The extracellular silver nanoparticles were synthesized from *Bacillus* species and found to have antiviral activity against Bean yellow Mosaic Virus in Fava bean crops (Elbeshehy et al., 2015). The zinc oxide nanoparticles synthesized from *Mentha spicata* were found to be effective on the reduction of accumulation of tobacco mosaic virus (Abdelkhalek and Al-Askar, 2020). Overall, these studies suggest that nanoparticles can effectively reduce viral infections in plants and improve their growth. The application of nanoparticles could provide a safe, low-cost, and novel treatment for agricultural practices.

3. Nanoagrosomes mode of action

The size-dependent properties of nanoagrosomes have multiple modes of action against different phytopathogens. The exact mode of action of nanoagrosomes remains to be fully understood, but recent studies suggest that they interact with pathogens through various mechanisms. For instance, when nanoagrosomes encounter fungi, they pass through the membrane and interact with ions before binding to vital proteins necessary for their growth and multiplication (Sardella et al., 2017; Auger et al., 2018; Renzi et al., 2021). This interaction can disrupt cell permeability, affect electron transport, protein oxidation, and membrane potential, ultimately leading to cell death (Fig. 3). Furthermore, nanoagrosomes can cause reactive oxidative stress, trigger oxidation, damage DNA, and suppress the replication process, resulting in fungal cell death (Kumari et al., 2019; Slavin and Bach, 2022). Similarly, nanoagrosomes interact with vital components of bacterial pathogens, such as enzymes required for replication, resulting in disruption of structural integrity and weakening of mechanical strength (Mishra and Singh, 2015; Delattin et al., 2014). Additionally, nanoagrosomes can damage the cell wall of bacterial pathogens, leading to the loss of cellular content (Kasprowicz et al., 2010; Ing et al., 2012). The mode of action of nanoagrosomes can be modulated by their physicochemical properties and the type of synthesis employed. Moreover, recent studies demonstrate that the use of biological entities can enhance the target specificity and applicative properties of nanoagrosomes. Further studies are needed to elucidate the dose-dependent properties of nanoagrosomes and their effects on the ecosystem to ensure their safe use in agriculture (Nguyen et al., 2018; Gabrielyan et al., 2020; Rajamani, 2022).

4. Pros and cons of nanoagrosomes

4.1. Pros

Nanoagrosomes can influence the plant growth and yield, increasing efficiency, enabling precision agriculture, and remediating contaminated soils (Shang et al.,2019). One of the most promising benefits of nanoparticles in agriculture is their ability to enhance nutrient uptake, water retention, and stress tolerance in plants (El-Saadony et al., 2022). This can lead to improved growth and yield, especially in

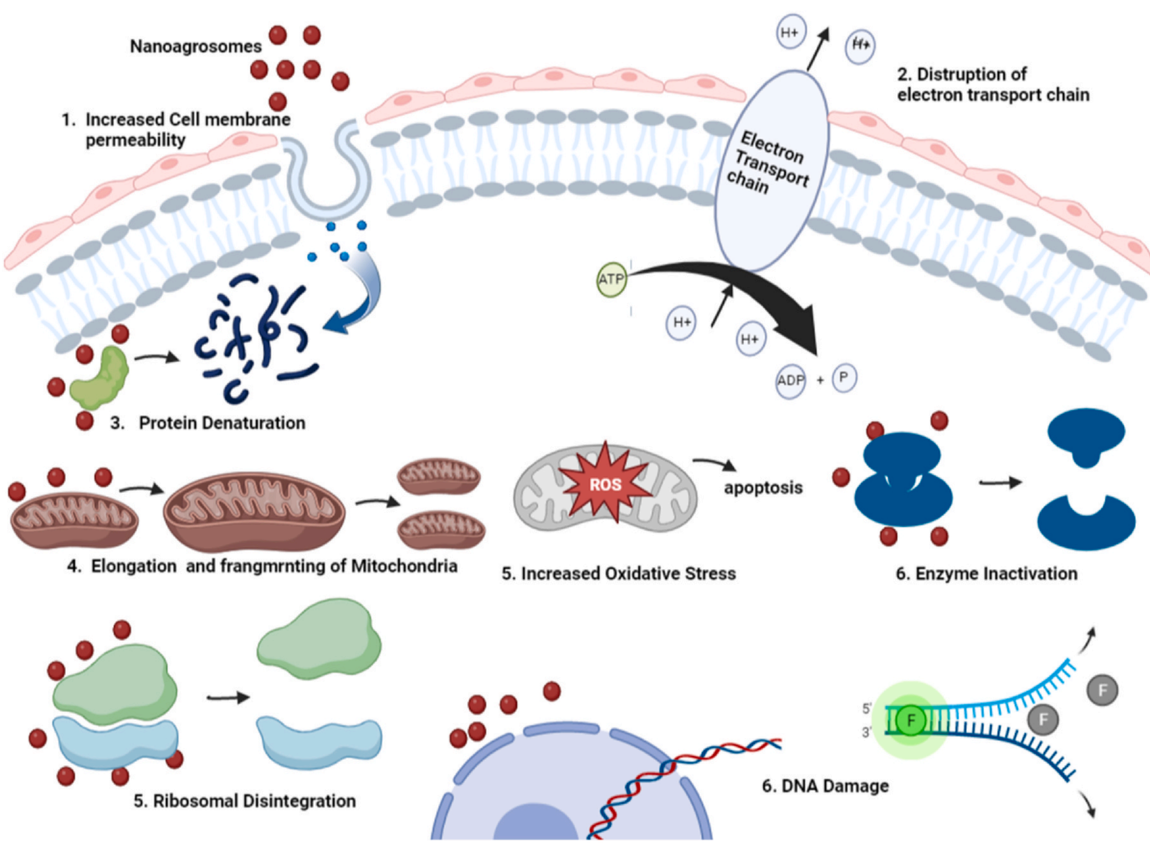

Fig. 3. Schematic representation of possible mode of action of nanoagrosomes against pathogenic fungi.

regions with poor soil quality or water scarcity. Additionally, nanoparticles can increase the efficiency of fertilizers and pesticides, reducing the number of inputs needed and minimizing waste and environmental impact (Neme et al., 2021).

4.2. Cons

There are concerns about the potential toxicity and environmental impact of nanoparticles, as they can accumulate in soil, water, and organisms and affect human and animal health (Rajput et al., 2020). There is a lack of standardized testing and regulation of nanoparticles in agriculture, making it difficult to assess their safety and efficacy. Nanoparticle-based agricultural products can be expensive, which may limit their adoption by farmers, especially in developing countries where financial resources are often constrained (Iavicoli et al., 2017).

5. Possible effects of nanoagrosomes on soil

Nanoagrosomes can have both beneficial and detrimental effects on soil, depending on their type, concentration, and mode of application. Some of the effects of nanoagrosomes on soil include nutrient availability, soil structure, microbial activity, contamination, and ecotoxicity (Ameen et al., 2021). Nanoagrosomes can enhance the availability of nutrients in soil by increasing their solubility and mobility (Simonin et al., 2021). For example, iron oxide nanoparticles can increase the availability of iron in soil, while titanium dioxide nanoparticles can enhance the uptake of phosphorus by plants (Elemike et al., 2019). Nanoagrosomes can improve soil structure by increasing the aggregation of soil particles and reducing erosion. For example, clay nanoparticles can improve soil structure and water retention, while silica nanoparticles can enhance the stability of soil aggregates (Huang et al., 2022). Nanoagrosomes can affect the activity and diversity of soil microorganisms by altering their nutrient availability, pH, and surface properties. For example, silver nanoparticles can inhibit the growth of soil bacteria and fungi, while carbon-based nanoparticles can stimulate microbial activity (Zhai et al., 2016; Cruz et al., 2021). At the same time, some of the deleterious effects include altering the physicochemical properties of soil and adsorbing pollutants. Studies show that metal oxide nanoparticles can adsorb heavy metals and organic compounds in soil, affecting their bioavailability and toxicity (Alengebawy et al., 2021).

6. Toxicity of nanoagrosomes in agricultural field

The toxicity of nanoagrosomes in agricultural fields is a growing concern due to their potential to accumulate in soil, water, and organisms, and affect human and animal health (Rajput et al., 2020). Some of the ways in which nanoagrosomes can be toxic in agricultural fields include direct toxicity to organisms, where nanoagrosomes can be toxic to soil microorganisms, plants, and animals if they are ingested or absorbed through the skin (Okereafor et al., 2020). Further indirect toxicity through the food chain is also noted (Maharramov et al., 2019). Hence, in order to overcome these limitations, the use of biogenic synthesis for nanoparticles is implemented. Further use of carrier molecules is required for the controlled release of nanoparticles (Panda et al., 2020). Apart from these, minimal quantities of nanoagrosomes are used to attenuate the desired activity. There are several studies underway to minimize the toxicity of nanoparticles (Singh et al., 2018).

7. Parameters influencing the activity of nanoparticles

The activity of nanoparticles in agriculture is influenced by various parameters, which can impact their efficacy, toxicity, and environmental fate (Paramo et al., 2020). One of the critical parameters that can influence nanoparticle activity is their physicochemical properties, such as size and shape (Khan et al., 2019). Smaller nanoparticles have a higher surface area and reactivity, while different shapes, such as nanorods or nanowires, can have unique properties (Albanese et al., 2012). The surface chemistry and functionalization of nanoparticles can also affect their stability, solubility, and interactions with other molecules or surfaces (Ahmad et al., 2022). The concentration and dose of nanoparticles can impact their activity and potential toxicity, with higher concentrations potentially leading to increased activity and toxicity (Gupta and Xie., 2018). The mode of application, such as spraying, injection, or incorporation into soil, can affect nanoparticle distribution and activity in the environment. Environmental conditions, such as temperature, pH, and moisture, can also influence nanoparticle reactivity and stability. Furthermore, nanoparticle interactions with other molecules or particles in the environment can affect their activity and fate. Overall, understanding these various parameters is crucial to evaluate the risks and benefits of nanoparticles in agriculture and ensure their safe and effective use in specific applications and environmental conditions (Nile et al., 2020).

8. Commercially available product in usage

Some of the nanoparticle-based products practiced in agriculture sectors are NanoAgro Silver (NAS), a silver nanoparticle-based plant protection product that can be used as a foliar spray to control plant diseases (Mehmood, 2018) NanoZyme, a nanoparticle-based soil amendment that contains enzymes to improve nutrient availability and soil health (Wang et al., 2023), NanoGuardian, a nanopesticide product that uses chitosan nanoparticles to enhance the effectiveness of existing pesticides and reduce their environmental impact, NanoFert, a nanofertilizer product that uses nanoparticles to improve nutrient uptake and reduce fertiliser requirements, NanoCrop, a nanocarrier-based plant growth regulator that uses nanoparticles to deliver the active ingredients more effectively to the plants, Nufarm Conquest, a nanopesticide product that uses nanoemulsions to improve the effectiveness of herbicides and reduce drift and volatilization (Camara et al., 2019), NanoRevolution, a nanoclay-based soil amendment that can improve soil structure, water retention, and nutrient availability, NanoAgri, a nanosensor-based precision agriculture product that can monitor soil conditions and plant growth in real-time, enabling farmers to optimise their inputs and reduce waste, NanoRem, a nanoremediation product that uses iron nanoparticles to remove contaminants from soil and groundwater, and NanoFarm, a nanocatalyst-based composting aid that can accelerate the breakdown of organic matter and reduce the time required for composting (Elemike et al., 2019).

9. Future perspective

The field of nanotechnology has found numerous applications across various scientific domains, including agriculture. Recent scientific advances in nano-agrotechnology indicate a growing interest in this field, with several product-oriented research studies currently being evaluated for commercial use. In this context, this review focuses on the use of nanomaterials as nanoagrosomes in managing plant diseases and controlling microbial infestation. With the rapid increase in drug resistance among microbial pathogens, including those affecting agriculture, it is important to address this issue precisely, as it can impact global food safety and security, as well as the environment. However, using nanoagrosomes effectively requires considering various factors, such as the type of crop and the type of nanomaterial used. Dose-dependent nanoagrosomes with minimal usage have shown the most desirable activity. Additionally, it is crucial to account for the potential toxicity of nanomaterials and mitigate this risk using biological resources for their synthesis or bioconjugation with bioactive compounds to minimize toxicity. Overall, this review provides scientific insights into the growing knowledge of nanomaterials in agricultural applications. Future studies will further elucidate the economic benefits of using nanoagrosomes, which have immense potential for combatting drug-resistant pathogens and improving food safety and security.

10. Conclusion

In summary, the review provides intriguing scientific insights into the expanding drug resistance observed among microbial pathogens. This phenomenon is particularly concerning in agriculture, where genetic exchange between pathogens can result in more virulent strains that can infect crops and livestock, ultimately posing a significant threat to society with highly drug-resistant pathogens. Nanoagrosomes offer promising potential as multifunctional agents in agriculture, serving as effective fungicides, bactericides, virocides, and promoters of plant growth. Their unique properties, such as high surface area and controlled release capabilities, allow for targeted delivery of active compounds to combat fungal, bacterial, and viral pathogens. Additionally, nanoagrosomes can enhance nutrient uptake, stimulate plant growth, and improve overall crop productivity. Their multifaceted nature makes them a valuable tool in sustainable agriculture, addressing multiple challenges while minimizing environmental impact. The review highlights the crucial role of scientific communities in addressing this urgent issue by developing sustainable agriculture practices that effectively combat antimicrobial resistance.

Data availability

No data was used for the research described in the article.

Declaration of Competing Interest

All authors confirm that they have no conflict of interest what so ever.

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