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Efficacy of Biologically Synthesized Nanoparticles on Suppression Plant-Parasitic Nematodes: A review

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ABSTRACT

Plant-parasitic nematodes are a taxonomic assemblage of microorganisms classified within the phylum Nematoda that are characterized by their round, worm-like morphology, and their ability to derive sustenance from the live cells of plants. They are responsible for causing harm resulting in economic losses for nearly all cultivated plants on a global scale. The global economic impact of plant-parasitic nematode infection has been estimated at 30 billion USD. A variety of strategies were employed in the management of plant-parasitic nematode infestation. One of the methods that has demonstrated efficacy in managing phytonematodes is the use of nematicides. However, it is worth noting that in recent years, the utilization of these substances has been limited due to their adverse impacts on both the environment and human health. There exist alternate techniques, in addition to or in lieu of nematicides, that show promise in the management of plant-parasitic nematodes. The utilization of nanotechnology-based approaches represents a cost-effective and environmentally sustainable alternative for managing agricultural nematodes and pests. This paper provides a comprehensive overview of several techniques employed for the manufacture of nanoparticles. Additionally, it examines the impact of nanoparticles on phytonematodes and plants, as well as the merits and drawbacks associated with the utilization of nanoparticles for the management of plant diseases.

***Keywords*:** Nanoparticles, Plant-parasitic nematodes, Biosynthesis

INTRODUCTION

Phylum Nematoda is divided into two classes, namely Chromadorea and Enoplea. Both of them include plant-parasitic nematodes. Heteroderidae, which include root-knot nematodes (*Meloidogyne* spp.) and cyst nematodes (*Globodera* spp. and *Heterodera* spp.), is the most pathogenic family. Plant-parasitic nematodes (PPNs) are parasites that feed basically on live plant cells. Almost, every plant species can be infected with at least one species of nematodes. Plant-parasitic nematodes cause very severe damage to plants leading to massive crop yield losses. The economic importance of PPNs is referring to their direct damage to their hosts or act as pathogens' vectors. Nematodes facilitate subsequent infestations of plants with secondary pathogens, such as viruses, fungi and bacteria (Powell, 1971). The synergistic interactions of nematodes with other pathogens produce disease complexes (Abd-Elgawad and Askary, 2015). Moreover, the

facilitation of pathogens entrance by PPNs can breakdown plant resistance causing severe reduction in crop yields (Salam and Khan, 1986; Sharma and Nene, 1990; Askary and Ali, 2012). Sasser and Freckman (1987) assessed agricultural losses due to plant-parasitic nematode infection in the developed world at around 11.3 billion USD and 18.7 billion USD in poor countries. The major losses are caused by the root-knot nematodes that infect mostly all cultivated plants. The estimated losses of food and fiber crops caused by root-knot nematode reached by 125 billion USD annually (Mukherjee et al., 2011).

Most PPNs start their life cycles with an egg, then undergo four juvenile stages (J1, J2, J3 and J4) before developing into an adult (Abd-Elgawad and Askary, 2015). The first moult occurs within an egg after embryogenesis giving second-stage juveniles (J2s). Under suitable conditions of temperature and moisture, J2s are hatching from eggs and move freely in the soil looking for host plant roots. After infection, J2s molt to J3s that quickly develop to J4s. The J4s develop to adults that mate in some cases and females lay eggs again.

Management of PPNs include (a) correct identification of nematode species by using morphological and molecular techniques, (b) application of agricultural management practices, e.g. rotations with non-hosts or fallow periods, (c) use of tolerant and resistant crop cultivars, (d) use of biological agents, e.g. nematophagous fungi and bacteria and (e) application of nematicides (Thompson et al., 2000). However, due to their harmful effects on humans and environment, nematicides are restricted.

Nanoparticles are tiny particles ranging between 1 to 100 nanometres (10^{-9} m) in size. According to Dubchak et al. (2010), nanoparticles with a high surface-to-volume ratio have higher reactivity and biochemical activity. Nanotechnology has recently been applied in a variety of areas, including agricultural, health, pharmaceutical, and food sectors. Nowadays, a multitude of element nanostructures have been produced. They also have a favorable influence on both the environment and humanity.

The use of nanotechnology offers many benefits, such as the mitigation of toxicity, enhancement of shelf-life, and augmentation of the solubility of pesticides that have low water solubility (Worrall et al., 2018). Many methods have been used today for synthesizing nanoparticles such as chemical, physical, and biological methods (Dahoumane et al., 2016; Ali et al., 2020; Song et al., 2020). Among the biological methods, scientists are using plant extracts, bacteria, fungi, viruses, and microalgae to produce bio-nanoparticles (BNPs).

There are several drawbacks associated with this phenomenon. The use of nanoparticles may provide a potential hazard to creatures inside the natural environment. Hou et al. (2018) showed that zinc oxide (ZnO) nanoparticles exhibited toxicity towards macroorganisms and microorganisms. In contrast, the use of ZnO nanoparticles has been shown to successfully reduce plant diseases and enhance plant development, as well as augment carotenoid, chlorophyll, and proline levels (Siddiqui et al., 2019). The toxicity of nanoparticles is primarily influenced by the elemental characteristics including both physical and chemical qualities and environmental factors. Furthermore, different effects can be exhibited by different species as a result of factors such as particle size, dosage, exposure period, method of exposure, surface coating, pH, and temperature.

METHODS OF NANOPARTICLES BIOSYNTHESIS

In contemporary times, researchers have achieved the effective synthesis of nanoparticles derived from plant components, as well as by the use of microorganisms like fungi, bacteria, viruses, and microalgae.

a) Biosynthesis of Nanoparticles from Fungi

Fungal isolates were sub-cultured on PDA media and incubated for 7 days at a suitable temperature. Subsequently, 5 mm in diameter disks are cut and moved to Erlenmeyer flask (500 ml) containing 200 ml PD broth. After incubation for 15 days at a suitable temperature (with or without shaking), fungal hyphae and spores are collected by filtration and washed extensively by sterilized distilled water (SDW). Based on the findings of Balakumaran et al. (2016) and Elamawi et al. (2018)**,** 10 g of wet mycelium were placed in 100 ml SDW and incubated for 48 h at 27 °C with shaking at 120 rpm. Next, totally10 ml of 1 mM silver nitrate can be added to 50 ml of the filtrate and the resultant mixture is incubated in dark at room temperature for 24 h (Magdi et al., 2014) (Figure 1). The nanoparticles were collected by centrifuging the mixture at 10,000 rpm for 10 min twice. Individual metallic solution and fungal filtrate were used as a control for distinguishing the color change of the resultant nanoparticles.

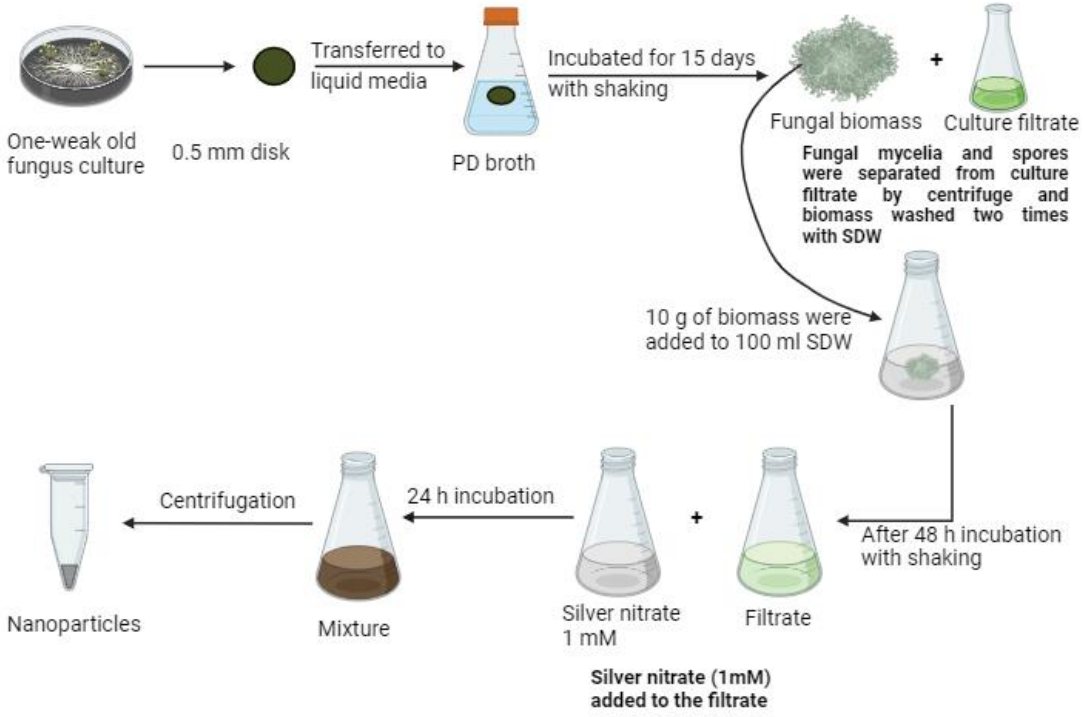

Figure 1: A diagram of the production process of bio-nanoparticles (BNPs) derived from fungi.

b) Biosynthesis of Nanoparticles from Bacteria

Under the right temperature and shaking conditions, bacteria can be cultured in flasks containing acceptable broth media (for example, LB or M9 minimum medium) (Gurunathan et al., 2009). In order to create nanoparticles, bacterial cultures were centrifuged at 10,000 rpm for 10 min. The supernatant was then combined in an

equivalent volume with metal suspensions (for example, 1 mM silver nitrate). The resulting mixture was incubated for 24 hours in the dark at 37°C. To compare the variation in color of bacterial metallic nanoparticles, individual bacterial filtrate and the metal solution were both employed as controls. By centrifuging the mixture at 10,000 for 10 minutes, the bacterial nanoparticles can be extracted (Figure 2).

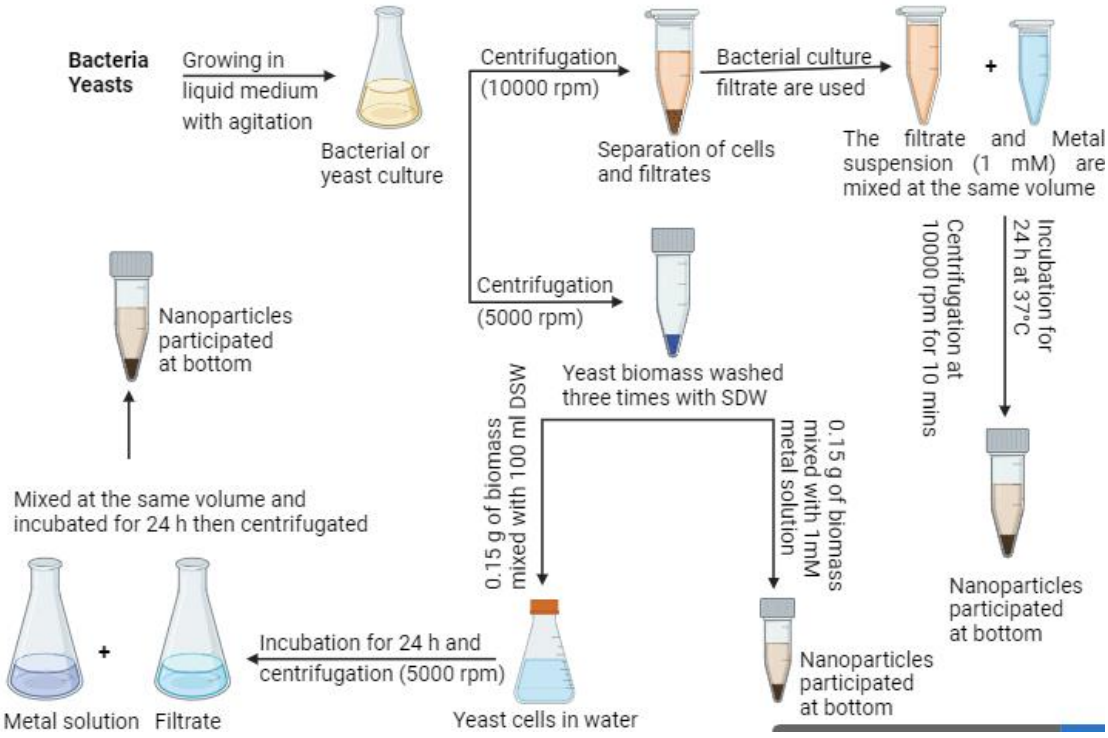

Figure 2: A generalized schematic representation of the manufacturing process of bio-nanoparticles (BNPs) derived from bacteria or yeasts.

c) Biosynthesis of Nanoparticles from Yeasts

According to Mourato et al. (2011), both the biomass of yeasts and their supernatants have the potential to be utilized in the synthesis of nanoparticles. The utilization of Yeast Nitrogen Base Growth (YNBG) liquid medium has been observed to facilitate the cultivation of yeasts at a temperature of 22°C for a period of 96 hours, employing a shaking mechanism at a rate of 160 rpm. The separation of yeast biomass from the culture broth can be achieved using centrifugation at 5000 rpm for a duration of 10 minutes at a temperature of 10°C. Subsequently, the biomass was subjected to a triple washing procedure using sterile distilled water. Subsequently, a quantity of approximately 0.15 g of moist biomass was subjected to a solution containing 1 mM concentration of silver nitrate. An alternative approach involved the suspension of 0.15 g of wet biomass in 100 ml of SDW, followed by incubation of the suspension at a temperature of 22°C with shaking at a speed of 160 rpm. Following a 24-hour period, the suspension was subjected to centrifugation at a speed of 5000 rpm for a duration of 10 minutes, while maintaining a temperature of 10° C. The resulting supernatant was subsequently combined with an equivalent amount of a 1 mM solution of silver nitrate and subjected to incubation for duration of 24 hours at room temperature with agitation (Figure 2).

d) Biosynthesis of Nanoparticles from Microalgae

According to Dahoumane et al. (2016), nanoparticles from microalgae can be synthesized using: 1) extracted biomolecules from disrupted cells, 2) cultural supernatant, 3) whole microalgae cells suspended in SDW, and 4) living microalgae cells maintained under normal culturing conditions (Figure 3). Algae were grown in BG11 medium for 15 days (Patel et al., 2015). The algal biomass and supernatant were then separated by centrifugation at 3000 rpm. The supernatant was mixed with an equal volume of 95% ethanol and kept at -20°C overnight for extracellular nanoparticles synthesis. Polysaccharides were precipitated by centrifugation at 10,000 rpm. The polysaccharides pellet was dried before being re-suspended in an aqueous solution containing 1.3 mg/ml AgNO3 and incubated for 72 hours at 25°C. According to Adenigba et al. (2020), 1 gm algal biomass (powder) can be re-suspended in 100 ml SDW and the resultant suspension was boiled for 20 min at 100°C. The cell-free extract is separated by centrifugation at 5000 rpm. Then, totally 90 ml of 1 mM of silver nitrate was mixed with 10 ml of extract (Figure 3). The mixture underwent incubation, during which the subsequent color shift was observed and tracked until it reached a stable state.

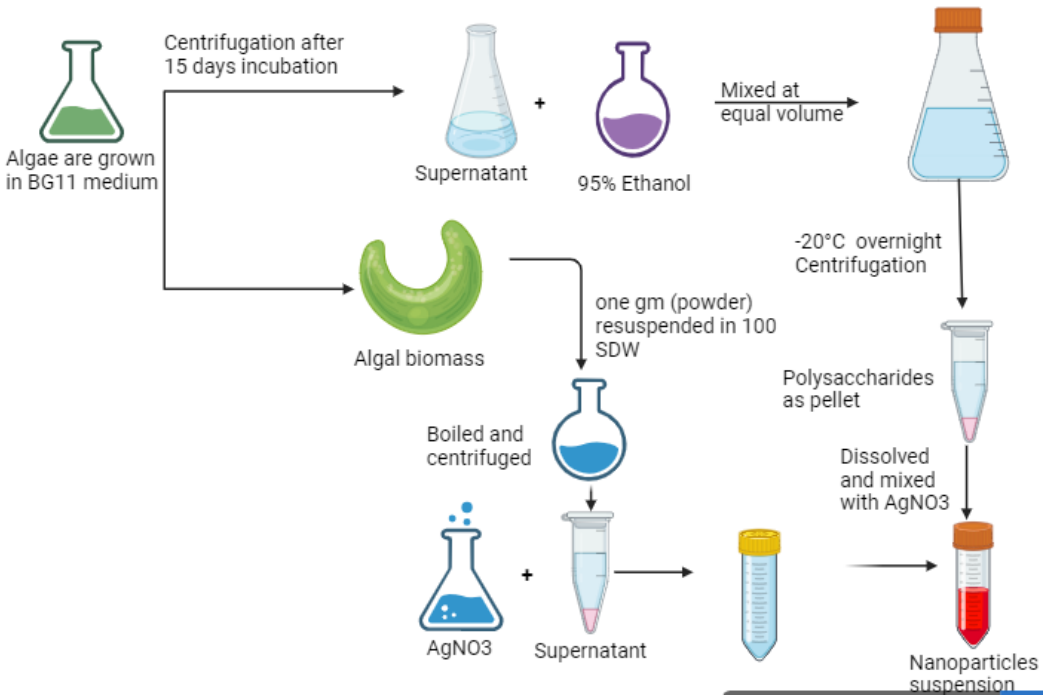

Figure 3: A generalized schematic representation of the production process of bio-nanoparticles (BNPs) generated from microalgae.

e) Biosynthesis of Nanoparticles from Plant Extracts

El-Nagdi and Youssef (2013) described the preparation of an aqueous plant extract by blending 10 grams of fresh leaves with 100 ml of sterile distilled water (at a concentration of 1 g per 10 ml). Next, a volume of 5 ml of plant extract was introduced into a solution containing 40 ml of metal solution with a concentration of 0.1 mM, as described by Singh et al. (2013). Following a 24-hour incubation period at room temperature, the mixture exhibited a discernible alteration in hue when compared to the control group, which consisted of individual plant extracts and a metal solution. The nanoparticles were subsequently purified using centrifugation of a 2 ml mixture in an

Eppendorf tube at a speed of 10,000 rpm for a duration of 10 minutes at a temperature of 15 °C. The weight of the pellet was measured and thereafter subjected to two rounds of washing at a speed of 10,000 rpm for a duration of 2 to 3 minutes each, using SDW at a temperature of 15°C. Subsequently, the pellet was solubilized in 100 µl of distilled water and subjected to vortexing, as depicted in Figure (4).

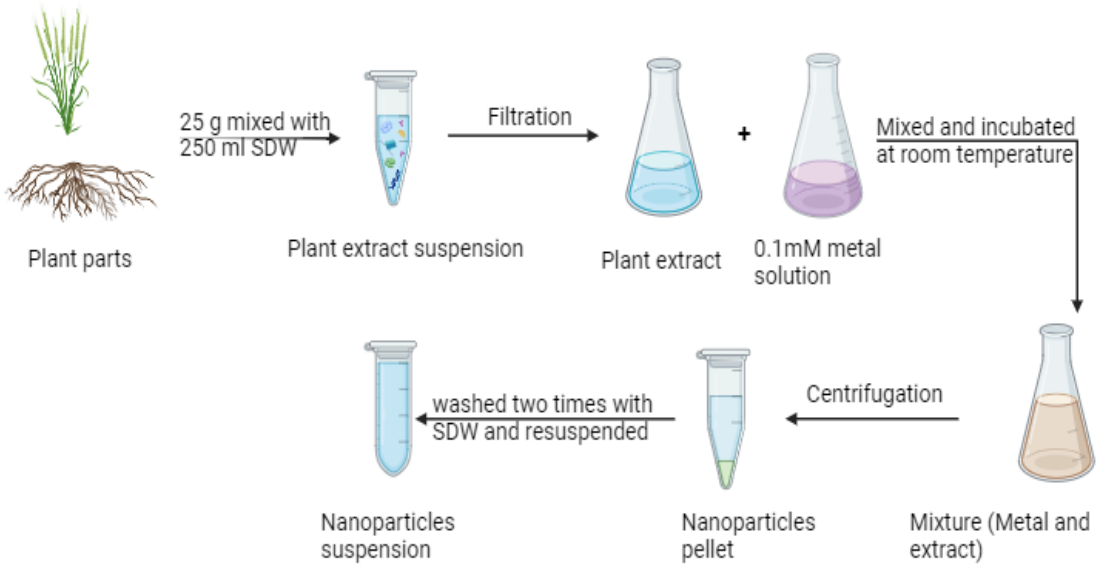

Figure 4: The general methodologies employed for the manufacture of bio-nanoparticles utilizing varied extracts derived from various plant sections.

f) Biosynthesis of Nanoparticles from Viruses

Cao et al. (2015) employed plant viruses as a vehicle for encapsulating abamectin, resulting in the formation of plant virus nanoparticles (PVNs). *Nictiana cleveandii* was subjected to inoculation with the RNA of the red clover necrotic mosaic virus (RCNMV). After a period of ten days, the virions were purified and subsequently kept in a 20 mM sodium phosphate buffer with a pH of 7.2 at a temperature of 4°C. In contrast, the abamectin powder was dissolved in a solution consisting of 90% ethyl alcohol (v/v), resulting in a stock solution with a concentration of 2 mg/ml. The virions concentration was adjusted to 6.43 mg/ml using a solution containing Ethylenediaminetetraacetic acid (20 mM EDTA) for a duration of 1 hour. Abamectin was introduced into the virion at a ratio of 510 to 1, followed by gentle overnight agitation. A solution of calcium chloride at a concentration of 25 mM and sodium acetate at a concentration of 0.2 mM was introduced into the combination in order to lower the pH to 5.2. The mixture was then allowed to incubate for a duration of 30 minutes. The elimination of surplus abamectin molecules was achieved by subjecting the loaded RCNMV to a size exclusion column (specifically, a NAP 10 column manufactured by GE Healthcare). The resulting end product, PVNAbm, was collected using a 0.2 M sodium acetate buffer at a pH of 5.2, as depicted in Figure (5).

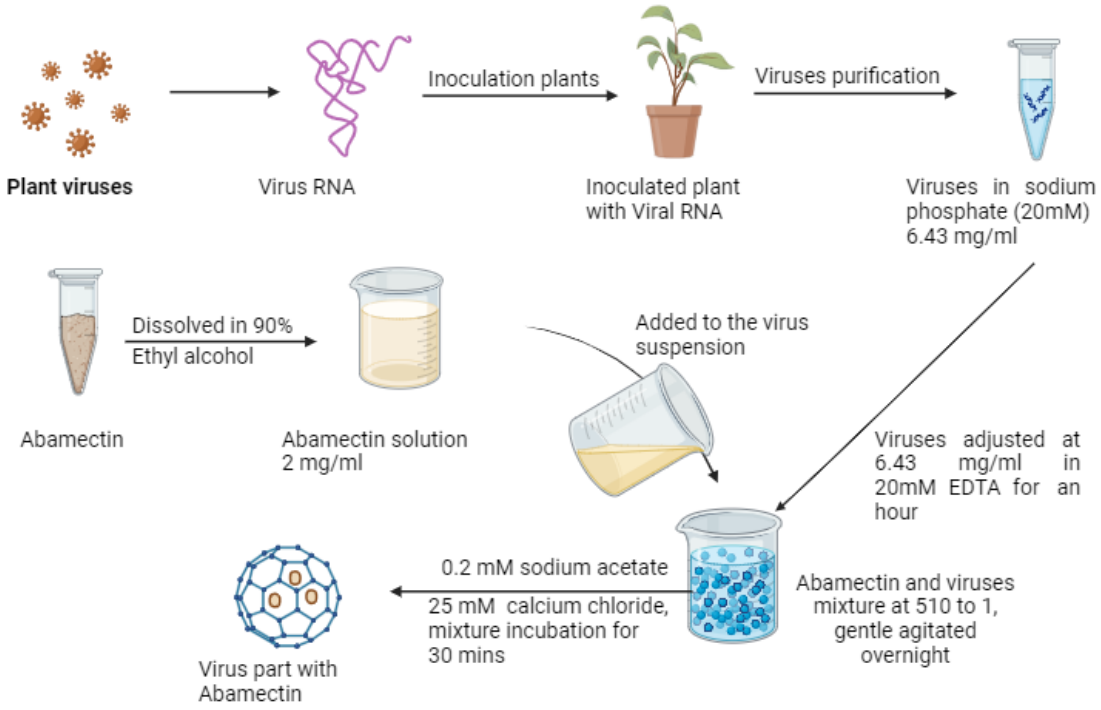

Figure 5: The infusion protocols used to provide abamectin to the Clover necrotic mosaic virus (RCNMV).

INFLUENCE OF NANOPARTICLES ON PLANT-PARASITIC NEMATODES

The field of nanotechnology is experiencing significant growth across various academic areas, encompassing medicine, food sciences, and agriculture. Within the field of agriculture, researchers are actively seeking for novel approaches to mitigate the reliance on pesticides, as these substances present significant hazards to the environment, microbiota, and human well-being. In addition to the chemical and physical processes employed for the production of nanoparticles, an alternative approach involves the utilization of plant components and microorganisms, commonly was referred to as bio-synthesis. The utilization of nanoparticles has proven effective in the management of several plant diseases caused by fungi, bacteria, nematodes, and viral pathogens (Elmer et al., 2018; Cai et al., 2020).

a) Gold Nanoparticles for The Purpose of Managing Plant-Parasitic Nematodes

Nanoparticles have been utilized in both controlled laboratory settings and field environments for the purpose of managing plant-parasitic nematodes. Gold, similar to silver, is classified as a precious metal known as a noble metal (Peterson and Minski, 1985). The element in question is found in several environments such as saltwater, plants, fresh water, and filamentous fungus. However, there is currently no substantiated information about its significance for the survival and functioning of living macroorganisms and microorganisms. According to the findings of Anderson et al. (1999), it has been observed that plants have the inherent ability to absorb gold from their surroundings. Various techniques have been employed for the synthesis of gold nanoparticles (GNPs), encompassing both biological (Thakur et al., 2018) and chemical approaches (Gonzalez-Moragas et al., 2017; Hu et al., 2018). The study conducted by Thakur and Shirkot (2017) demonstrated that the use of GNPs immediately resulted in

the mortality of nematodes. Furthermore, the researchers observed that the effectiveness of GNPs in killing nematodes was enhanced when used in conjunction with nematicides. According to Thakur et al. (2018), *in vitro* experiments showed that gold nanoparticles exhibited significant toxicity against RKN after a direct exposure of 6 hours. Furthermore, *in vivo* studies revealed that these nanoparticles were effective in worm eradication and also stimulated plant development. The study conducted by Hu et al. (2018) observed the harmful impact of GNPs on the tissue and body cavities of *Caenorhabditis elegans*, resulting in hindered locomotion, altered gene expression, and significantly reduced longevity in an in vitro condition. In their study, Bosch et al. (2018) noticed that GNPs induce detrimental effects on the internal architecture of *C. elegans* worms, leading to impairments in growth, fertility, and the functionality of reproductive organs.

b) Silver Nanoparticles in Controlling Plant-Parasitic Nematodes

Previous studies have employed silver nanoparticles (Ag NPs) for the purpose of controlling root-knot nematodes (Ardakani, 2013; Cromwell et al., 2014; Nazir et al., 2019; Baronla et al., 2020). According to Ardakani's (2013) findings, it was observed that silver and titanium oxide nanoparticles exhibited toxicity towards *Meloidogyne incognita* at varying concentrations in both *in vitro* and *in vivo* environments. The observer documented that the mortality of the juveniles (J2s) was detected 24 hours after the treatments were administered. Furthermore, it was shown that the toxicity of nanoparticles towards nematodes was greater in soil environments compared to aqueous environments. According to Ardakani (2013), the utilization of silver nanoparticles resulted in enhanced plant quality, as well as a reduction in the creation of galls and the multiplication of nematodes. The utilization of plant-derived silver nanoparticles, also referred to as green silver nanoparticles, has demonstrated a reduction in the population of J2s of root-knot nematodes (*M. javanica* and *M. incognita*) and cyst nematodes (*Heterodera sacchari*) (Abdellatif et al., 2016; Kalaiselvi et al., 2019; Oluwatoyin et al., 2020). Furthermore, it was shown that the application of green silver nanoparticles had a positive impact on the growth of plants, as reported by Abdellatif et al. (2016). Moreover, El-Batal et al. (2019) conducted a study in which they manufactured silver boron nanoparticles (Ag B NPPs) by the physical means of polyvinylpyrrolidone and gamma rays. Their investigation revealed that the Ag B NPPs exhibited significant nematicidal efficacy against *M. incognita* in both *in vitro* and *in vivo* experiments.

c) The Utilization of Magnesium Nanoparticles in Controlling Root-Knot Nematodes

Magnesium is a crucial mineral for plants, playing a significant role in various physiological and biochemical processes (Ishfaq et al., 2022). Chlorophyll synthesis, enzyme activation for manufacturing, and protein synthesis are all critical procedures that rely on magnesium. The synthesis of magnesium oxide nanoparticles (MgO NPs) was carried out using chemical means as reported by Huang et al. (2005), as well as through the sol-gel approach as described by Tang and Lv (2014). The utilization of MgO NPs has been demonstrated to be effective in the field of antibacterial applications, as evidenced by studies conducted by Huang et al. in 2005 and Tang and Lv in 2014. Additionally, these NPs have also been shown to serve as carriers for anticancer drugs, as demonstrated by Alfaro et al. (2019). A limited number of individuals were discovered to utilize MgO NPs as a means of controlling nematodes,

as reported by Tauseef et al. (2021). MgO NPs serve a dual function by acting as both a nematicidal agent and a plant growth inducer. The application of MgO nanoparticles resulted in alterations to the cuticle surface of second-stage juveniles (J2s) of root-knot nematodes. These alterations were observed as indentations, roughness, and distortions. Furthermore, treatments of the plants that have been infected have shown significant improvement (plants Morphological, yield and biochemicals characteristics). The use of MgO NPs resulted in a decrease in both the fertility and the quantity and dimensions of galls caused by RKN. The study conducted by Tauseef et al. (2021) showed that the application of magnesium nanoparticles resulted in increased levels of plant growth, chlorophyll, carotenoid, seed protein, and nitrogen contents.

d) Copper Nanoparticles as a Nematicide and Plant Growth Promotor

In the form of copper sulfate either alone or combined with organic chemicals, the copper element has been thoroughly researched as a pesticide. It was highly effective in controlling plant diseases, particularly plant-parasitic nematodes (Kim et al., 2022). For instance, RKN was managed under greenhouse conditions using a mixture of malic acid and copper sulfate (Jehyeong et al., 2019). Data showed that the compound's effectiveness reduced RKN infection by 51.72%. Copper was also used to create nanoparticles, either by itself or in combination with other elements. Regarding, Gkanatsiou et al. (2019) revealed that chemically produced Cu, CuFe, and CuFeO2 NPs exhibited nematicidal action against *M. incognita* and *M. javanica*. with an Ec50 value of 0.03 g ai /g soil, CuFe NPs, on the other hand, boosted the fresh shoot and root weight of tomato plants. Furthermore, Copper nanoparticles were created from holoparasitic plant stem extract and successively controlled *M. incognita* (Akhter et al., 2020) under *in vitro* conditions. When compared to Nemaprop® nematicide, both chemical and green biosynthesized Cu nanoparticles significantly killed root-knot nematodes *in vitro* (Soliman et al., 2022). But compared to the untreated control, green biosynthesized Cu NPs recorded the lowest percentage of J2 death, while chemically synthesized Cu NPs recorded the highest percentage of J2 mortality after 24 and 48 hours. At a concentration of 0.2 g/l, Cu NPs that were chemically produced were found to be sufficient to result in 100% mortality (Mohamed et al., 2019). According to Khan et al. (2022), the green biosynthesized nanoparticles have sufficient biocontrol capacity against RKN. The mortality percentage of J2s and inhibition of eggs hatch were the highest at a concentration of 200 ppm after 1 and 6 days of exposure, respectively. Additionally, it facilitated plant development in greenhouse environments and decreased nematode root infection.

e) The Role of Calcium Nanoparticles in Controlling Root-Knot Nematodes

Calcium, in the form of Ca2+, plays a crucial role as a macro-element in promoting plant vitality and facilitating the development of grains and seeds. According to Hirschi (2004), the presence of calcium is essential for plants as it plays a crucial role in fortifying the cell wall. This fortification is necessary to provide protection against various diseases and ultimately enhance plant output. Moreover, it has been established that calcium plays a pivotal role in enhancing the tolerance of plants against abiotic stress conditions (Robertson, 2013). In a study conducted by Toyoda et al. (2021), the efficacy of calcium sulfate and calcium carbonate in silica gel as a means of reducing root-knot nematodes, was investigated. The researchers found that the use of these substances significantly reduced the prevalence of RKN in field conditions. In the study conducted by Tryfon et al. (2019), it was observed that calcium nanoparticles were

employed as a substitute for pesticides, aiming to provide economically viable and environmentally friendly alternatives. The *in vitro* control of RKN species was achieved through the utilization of microwave-assisted synthesis of calcium nanoparticles derived from several compositions, including calcium hydroxide, calcium hydroxide-calcium carbonate, and calcium carbonate. The data presented demonstrated that all calcium-based nanoparticles that were tested exhibited nematicidal activity. Calcium hydroxide had the highest efficacy due to its ability to release hydroxide group (anions), which are essential for the control of nematodes (Tryfon et al., 2019).

f) Zinc Nanoparticles as a Biocide and Its Toxicity

Zinc (Zn) is a crucial micronutrient (Balafrej et al., 2020) and is well recognized as the second most prevalent transition metal in biological systems, following iron (Marschner, 2012). Zinc is known to have significant implications in various aspects of plant physiology, including but not limited to plant development, reproduction, signaling, and enzymatic activities. For instance, zinc serves as a cofactor for enzymes like carbonic anhydrase (Mousavi, 2011: Lehmann, 2014). However, it is important to note that human activity can have detrimental effects on flora, wildlife, and human beings, as highlighted by Balafrej et al. (2020). The presence of excessive zinc in the environment can lead to various morphological, biochemical, and physiological abnormalities in plants. Therefore, it is crucial to minimize the toxicity of zinc to both plants and the environment by employing a minimal quantity (utilizing zinc nanoparticles). According to Siddiqui et al. (2018), the use of zinc oxide nanoparticles (ZnO NPs) through a foliar spray on lentil plants at a concentration of 0.1 mg ml-1 resulted in enhanced nodulation and better plant growth metrics. In a study conducted in 2019, Siddiqui et al. investigated the effectiveness of ZnO NPs in the management of diseases affecting carrot plants. The utilization of ZnO NPs resulted in the effective management of *M. javanica*, leading to a reduction in both root galling index and nematode reproduction. The synthesis of grass-shaped zinc oxide nanoparticles (G-ZnO NPs) was carried out using the sol-gel procedure, as described by Khan et al. (2023). These nanoparticles were then subjected to *in vitro* and *in vivo* investigations to assess their efficacy against RKN. The data presented indicated that G-ZnO nanoparticles had toxic effects on J2s and also demonstrated the ability to suppress the hatching of eggs of RKN. In a comparative study conducted by Elansary et al. (2021), it was observed that ZnO nanoparticles (NPs) exhibited more efficacy against root-knot nematodes compared to Zn-bulk metal and oxamyl, a commonly used nematicide. The mortality percentage of J2s was found to be much higher when exposed to a combination of oxamyl and ZnO nanoparticles. In contrast, the plant characteristics such as shoot weight and length exhibited the highest values in the Zn-bulk treatment. Numerous researches have been conducted to investigate the toxicity of Zn NPs and assess their harmful effects on the model microorganism, *C. elegans*. The study conducted by Toledano et al. (2019) revealed that the application of Zn NPs resulted in a modest enhancement in the growth of *C. elegans* worms. Furthermore, the NPs had no discernible impact on worm mortality or metabolism. According to the findings of Ma et al. (2009), it was observed that Zn-NPs exhibited lethality towards *C. elegans*. This toxicity was believed to be attributed to the dissolution of Zn NPs, leading to the release of harmful Zn^{2-}- ions.

g) The Role of Nanoparticles in Enhancing Plant Defense Systems Against Plant-Parasitic Nematode Infections

In the context of plant defense systems, the utilization of nanoparticles in plants serves the dual purpose of effectively managing plant diseases and enhancing the plant's innate defense mechanisms. As an example, Udalova et al. (2018) employed Selenium nanoparticles as a means to induce resistance in tomatoes against the infection caused by the root-knot nematode *M. incognita*. The expression of the pathogen-induced protein (PR 6) gene exhibited a notable upregulation in both the roots and foliage of the susceptible infection treatment plants when compared to the control group. Furthermore, the application of selenium nanoparticles resulted in a decrease in the infection of plants by *M. incognita* and hindered the morphophysiological progression of nematodes. The study conducted by Siddiqui et al. (2019) revealed that the application of GO (grapheme oxide) and ZnO nanoparticles resulted in an increase in carotenoids, chlorophyll, and proline levels in plants. Furthermore, this treatment was found to have a positive impact on plant growth. The assessment of the expression profiles of Phenylalanine Ammonia-Lyase (PAL), Polyphenol Oxidase (PPO), and Peroxidase (POX) in tomato plants was conducted using Quantitative Real-Time PCR, as described by Ghareeb et al. (2020). This evaluation was conducted subsequent to the inoculation of the plants with *M. javanica* and the application of green synthesized nanoparticles derived from *Cladophora glomerata*. The data presented in this study demonstrated that nanoparticles manufactured by a green method have the ability to stimulate immune responses in plants against infection with nematodes. This immune response was characterized by an increase in the activity of three specific enzymes in plants that have been inoculated and treated with these nanoparticles, as compared to the control plants. In a study conducted by Udalova et al. (2020), it was shown that the application of silicon nanoparticles to tomatoes resulted in a reduction in nematode infection. Furthermore, this treatment was found to have a positive impact on plant growth processes, leading to an increase in photosynthetic pigments as well as the concentration of several essential elements like phosphorus, magnesium, potassium, sulfur, and iron.

h) Nanoparticles as Carriers for Biological Substances for Controlling Plant-Parasitic Nematodes

On the contrary, nanoparticles can be employed to enhance the efficacy of biological substances utilized for nematode control. Abamectin is extensively employed in this region for the purpose of managing plant-parasitic nematodes (PPNs) and has limited mobility within the soil. The utilization of red clover necrotic mosaic virus has been shown in the encapsulation of abamectin, resulting in the formation of plant virus nanoparticles (PVN^{Abm}) (Cao et al., 2015). The efficacy of this substance in safeguarding tomato plants against root-knot nematode infection can be attributed to its capacity for soil mobility, which distinguishes it from the abamectin molecule. Additionally, the occurrence of root galls was minimal. Zhang et al. (2020) reported that the penetration of abamectin nanoparticles into both plant roots and root-knot nematodes was facilitated. In their study, Ureña-Saborío et al. (2017) employed a green chemistry approach to encapsulate bacterial metabolic infiltrates (BMI) derived from four *Bacillus* species. These infiltrates were encapsulated using chitosan and alginate-based nanoparticles. The objective of this encapsulation was to investigate its potential in controlling the burrowing nematode, *Radopholus similis*. The utilization of this particular technique proved to be more effective in managing the population of

burrowing nematodes, resulting in increased stability, wider distribution, and longer persistence of the beneficial BMI in the field. The study conducted by Liang et al. (2018) involved the encapsulation of Avermectin using chitosan and poly-γ-glutamic acid as a means to control pine nematodes. The implementation of this approach resulted in a 20% reduction in avermectin losses. In addition, it was shown that the mortality rate of pine nematodes was significantly higher at a concentration of 1 ppm of avermectin nanoparticles (98.6%) compared to bulk avermectin (69.9%).

i) Toxicity of Nanoparticles on Plant-Parasitic Nematodes

According to Hrács et al. (2018), after examining the toxicity of material nanoparticles, it was determined that *Xiphinema vuittenezi* exhibited greater sensitivity to ZnO nanoparticles compared to Bulk ZnO. The death rate of *X. vuittenezi* exhibited a significant correlation with the toxicity of ZnO. The toxicity of ZnO nanoparticles can be attributed to the particular effects of dissolved Zn and the nanoparticles themselves (Sávoly et al., 2016). The impact of ZnO nanoparticles on lipids, mycopolysaccharides, and glycogen was thought to have a significant effect on the hypodermis and cuticle of nematodes. This effect was mostly attributed to the irregular shape of root-knot juveniles, as noticed through the utilization of a scanning electron microscope (SEM) (Khan and Siddiqui, 2018).

j) Nanoparticles for Controlling Disease Complex

Plant-parasitic nematodes (PPNs) are often found in association with other pathogens, resulting in the formation of a disease complex. In the present context, the use of nanoparticles led to a decrease in the severity of the disease complex. Khan and Siddiqui (2020 a,b) conducted a study on the treatment of the beetroot disease complex. This complex is characterized by the presence of three pathogens, namely *Pectobacterium betavasculorum*, *Meloidogyne incognita*, and *Rhizoctonia solani*. The researchers investigated the efficacy of zinc oxide (ZnO) and silicon dioxide (SiO2) nanoparticles as a method of regulation. Two methods, namely seed priming and foliar spray, were used for the application of nanoparticles to the plants. The application of seed priming using SiO2 and foliar spray with ZnO nanoparticles has been recognized as a very efficacious approach for enhancing plant growth, optimizing photosynthetic performance, and minimizing the adverse consequences associated with galling, nematode proliferation, and disease indices.

k) The Negative Effect of Nanoparticles in Controlling Plant-Parasitic Nematodes

In certain investigations, the impact of nanoparticles on PPN was shown to be negligible. The study conducted by Al Banna et al. (2018) examined the impact of silicon carbide (SiC) nanoparticles on the population of root-knot nematodes (*M. incognita*) in the specified region. The presence of SiC nanoparticles did not result in any observable effects on the hatching of nematode eggs or the mortality percentage of J2s.

ADVANTAGES AND DISADVANTAGES OF NANOPARTICLES

a) Advantages of Nanoparticles

The observation of the influence of nanoparticles on plant-parasitic nematodes can be achieved by directly applying or utilizing them as carriers for nematicides. The reduced

utilization of nematicides and the subsequent protection of individuals and the environment can be attributed to the small size of nanoparticles. In addition, the application of biological approaches, specifically the utilization of microorganisms or plant constituents, in the production of nanoparticles (often known as green nanoparticles) presents a more secure option compared to traditional nematicides, hence reducing potential environmental hazards. The utilization of a tiny quantity of the substance, owing to its diminutive dimensions, results in a greater dispersion. The utilization of nanoparticles has been observed to elicit a beneficial impact on plants through the facilitation of seed germination and the augmentation of overall plant growth. Furthermore, the occurrence of nanoparticles containing trace elements has been reported to elicit a harmful reaction in plant-parasitic nematodes. Moreover, certain nanoparticles possess the capacity to function as an agent that can facilitate systemic resistance in plants against plant-parasitic nematodes. Nanoparticles have the potential to serve as a method for encapsulating unstable bio-chemical substances inside soil, exhibiting notable bio-nematicidal features. The use of nanoparticles led to a notable elevation in the amounts of chlorophyll, carotene, and proline inside the plant. Nanoparticles exhibit unique chemical and physical characteristics that make them well-suited for applications as protective agents or carriers of pesticides.

b) Disadvantages of Nanoparticles

The presence of heavy metal nanoparticles in the natural environment poses significant dangers to both environmental ecosystems and human populations. Some nanoparticles have been found to have harmful effects on plants. However, when used at optimal doses, these nanoparticles have shown the potential to improve plant growth and development. Following this, there have been observations indicating the successful targeting of diseases by silver nanoparticles. Additionally, it has been revealed that these nanoparticles can trigger modifications in the DNA of plants. In several research investigations, it was observed that the presence of nanoparticles did not exert any discernible influence on the hatching process of PPN eggs and the subsequent survival of second-stage juveniles. The effectiveness of nanoparticles with nematicidal properties is subject to the influence of pH levels, potentially constraining their use over a wide range of conditions. The synthesis of nanoparticles has obstacles in acquiring large quantities of metallic components and effectively performing the synthesis methodology. Furthermore, the scalability of bio-synthetic nanoparticle production remains constrained, hindering its widespread application in various industries. Currently, there is a lack of research that supports the use of nanoparticles in field trials.

CONCLUSION

The use of nanoparticles has been effectively regarded as a novel strategy that offers alternate solutions to the use of pesticides. The compound may be readily produced and is expected to be accessible in many global environments. Numerous studies have shown the efficacy of metallic nanoparticles as a biocontrol method for combating plant-parasitic nematodes. Furthermore, they have the potential to be used directly as a means of combating nematodes or as carriers for nematicides. Further research is required to investigate the mechanistic aspects of nematode management with nanoparticles.

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FIGURES

The figures in this article have been designated by the corresponding author on a reasonable request.

DECLARATION

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الملخص العربي

فعالية جزيئات النانو المخلقة بيولوجيا في قمع النيماتودا المتطفلة على النبات : مقالة مرجعية

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النيماتودا المتطفلة على النبات - تصنيفيا- عبارة عن مجموعة من الكائنات الحية الدقيقة التي تقع تحت قبيلة (شعبة) النيماتودا التي تتميز موروفولوجيا بشكلها الاسطواني الشبيه بالدودي وقدرتها على استخلاص الغذاء من الخلايا النباتية الحية. هي مسؤولة عن اضرار تسبب خسائر اقتصادية تقريبا لجميع النباتات المزروعة حول العالم. ويقدر الأثر الاقتصادي العالمي للاصابة بالنيماتودا المتطفلة على النبات بنحو ٣٠ مليار دولار أمريكي. تم استخدام مجموعة متنوعة من الاستراتيجيات في إدارة الإصابة بالنيماتودا المتطفلة على النبات. إحدى الطرق التي أثبتت فعاليتها في إدارة النيماتودا النباتية هي استخدام مبيدات النيماتودا. ومع ذلك، تجدر الإشارة إلى أن استخدام هذه المواد في السنوات الأخيرة كان محدوداً بسبب آثارها الضارة على البيئة وصحة الإنسان. توجد تقنيات بديلة، بالإضافة إلى مبيدات النيماتودا أو بدلاً منها، والتي تظهر نتائج واعدة في إدارة النيماتودا الطفيلية على النبات. يمثل استخدام المواد القائمة على تكنولوجيا النانو بديلاً فعالاً من حيث التكلفة والاستدامة البيئية لإدارة النيماتودا والآفات الزراعية. تقدم هذه الورقة البحثية لمحة شاملة عن العديد من التقنيات المستخدمة لتصنيع الجزيئات النانوية. بالإضافة إلى ذلك، فإنه يدرس تأثير الجزيئات النانوية على النيماتودا النباتية والنباتات، فضلا عن المزايا والعيوب المرتبطة باستخدام الجزيئات النانوية لإدارة أمراض النبات.