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RESEARCH ARTICLE

Use of silver nanoparticles biosynthesized from leaf extracts of three allelopathic weeds for the management of water hyacinth (*Pontederia crassipes* Mart.)

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ABSTRACT

Silver nanoparticles (AgNPs) were biosynthesized from the leaf extracts of *Lantana camara* L. (*Lc*), *Parthenium hysterophorus* L. (*Ph*) and *Coleus amboinicus* Lour. (*Ca*), which possess allelopathic effects on the aquatic weed 'water hyacinth' (*Pontederia crassipes* Mart.). Their herbicidal efficacy was physically characterized and assessed. The absorption maxima of the synthesized nanoparticles (NPs) were typical to those of AgNPs according to spectroscopy, and they possessed a face-centred cubic structure according to X-ray diffraction. Among the three biosynthesized NPs, *Ph*-AgNPs exhibited better stability, with a zeta potential of -32.7 mV, and dynamic light scattering at a size range of 213 nm. There was a significant difference in necrosis on water hyacinth leaves after spraying with a 1 ppm *Ph*-AgNP suspension as compared to that on leaves sprayed with *Lc*-AgNP and *Ca*-AgNP suspensions with the same concentration. The water hyacinth plants sprayed with 10 ppm *Ph*-AgNPs had the lowest number of leaves, leaf length, leaf width, bud diameter, root length and plant height at 15 days after treatment (DAT). *Ph*-AgNPs at a concentration of 10 ppm significantly decreased the total chlorophyll content, carbohydrate content, protein content, photosynthetic rate and stomatal conductance in the leaf tissue of water hyacinth at 5 DAT. The phenol content and superoxide dismutase (SOD) activity in water hyacinth plants significantly increased in response to the application of the biosynthesized NPs. This study revealed the feasibility of utilizing a noxious weed, by exploiting its natural chemical properties, to manage by suppressing growth of another difficult-to-control noxious weed. The use of AgNPs biosynthesized from *P. hysterophorus* leaf extract effectively inhibited the growth of water hyacinth. However, accurate evaluation of AgNPs toxicity requires comprehensive, long-term studies under realistic environmental conditions to understand ecological factors interactions.

Keywords: Allelopathic potential, *Coleus amboinicus*, *Lantana camara*, *Parthenium hysterophorus*, Silver nanoparticles, Water hyacinth, Weed management

INTRODUCTION

Water hyacinth (*Pontederia crassipes* Mart.), also known as 'Bengal terror,' is a Brazilian aquatic plant introduced to India in 1896 as an ornamental plant. Currently, it is recognized as the most problematic aquatic weed globally as it invasively proliferates in water sources such as rivers, irrigation channels, and lakes. The International Union for Conservation of Nature (IUCN) considers it one of the most dangerous invasive species globally, causing substantial environmental and social risks, and involving drudgery for its removal from water bodies (Téllez *et al.* 2008). High levels of aquatic pollution from fertilizers containing nitrates, nitrites, and phosphates (eutrophication) have been linked to the rapid growth of water hyacinth. This noxious weed is predominantly found in rice fields, lakes, streams, and channels, making a sizable portion of waterbodies inaccessible, unusable, and non-navigable (Jayan and Sathyanathan 2012). Under ideal conditions, water hyacinth plants grow rapidly, and their population doubles in 10 days. Average fresh weight of water hyacinth plants is reportedly increased by 201 and 788% by the end of the first and fourth week, respectively (Prasetyo *et al.* 2021). Various control methods (*e.g.*, mechanical, chemical, and biological) are in use (Sushilkumar 2011, Swetha *et al.* 2012, Dutta *et al.* 2015), but they are ineffective against water hyacinth.

Mechanical methods are time- and labor-consuming and cost-prohibitive. Herbicide use pollutes waterbodies, causing harm to aquatic organisms. Biological control methods through the release of chevroned weevil (*Neochetina bruchi*),

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mottled weevil (*N. eichhorniae*) and water hyacinth borer (*Sameodes albiguttalis*) were found environmentally safe, cost-effective, and beneficial for aquatic animals and plants. These weevils feed on the stem tissue of water hyacinth, resulting in a loss of buoyancy for the plant, which eventually sank (Gupta and Yadav 2020). However, the life cycle of these weevils as biological predators on water hyacinth was the main limitation as it completes within 90 days.

Nanotechnology, a significant and appealing area of research, has distinctive features and broad applications in agriculture, food, and biomedicine. Various plant secondary metabolites, such as polysaccharides, proteins, polyphenols, flavonoids, terpenoids, tannins, alkaloids, amines, ketones, and aldehydes, play roles as reducing, stabilizing, and capping agents in converting metal ions to nanoparticles (NPs). Silver nanoparticles (AgNPs) have stood out among other NPs in the last two decades due to their distinctive biological, chemical, and physical properties (Meena *et al.* 2020). The physiological, chemical, and metabolic processes of plants are influenced by AgNPs, leading to alterations in growth, water absorption, nutrient uptake, transpiration, photosynthesis, and respiration. Additionally, AgNPs induce the generation of reactive oxygen species (ROS) and trigger antioxidant responses (Rani *et al.* 2016; Xu *et al.* 2025). Prolonged exposure to elevated levels of silver nanoparticles caused toxicity, mortality, bioaccumulation, and tissue damage in *Cyprinus caripo*, the common carp (Kakakhel *et al.* 2021). However, managing troublesome weeds with the use of AgNPs biosynthesized from plant extracts with herbicidal properties or allelopathic potentials is a novel attempt to explore the prospects of nanotechnological application in agriculture.

Congress grass (*Parthenium hysterophorus*) is an important weed that exhibits significant allelopathic (herbicidal) properties on the growth of water hyacinth (Pandey 2015). Likewise, common lantana (*Lantana camara*), a terrestrial plant, has been reported to have allelopathic effects on water hyacinth, and exhibit natural herbicidal potentials (Qureshi *et al.* 2019). The *Coleus* spp. dried leaf powder (25 g/l of water) was found most effective in reducing the fresh weight and chlorophyll content of *E. crassipes* and showed 100% reduction on 6 days after treatment (Gnanavel and Kathiresan 2013). Thus, eco-friendly NPs biosynthesized from the extracts of allelopathic weeds may offer the possibilities for a new range of bioherbicides. With this view, a study was conducted to assess the comparative efficacy of AgNPs biosynthesized from the leaf extracts of *Lantana camara* L. (Lc), *Parthenium hysterophorus* L. (Ph) *and Coleus amboinicus* Lour. (Ca) on the growth and development of water hyacinth.

MATERIALS AND METHODS

Collection of plant materials

Water hyacinth plants were collected from Vellayani Lake, and uniformly sized offsets of the plants were raised in earthen pots (of 30 cm diameter and 11 L capacity) filled with soil from the rice field up to 8–10-inch thickness, at the College of Agriculture, Vellayani (Kerala Agricultural University), Thiruvananthapuram, Kerala during 2022. Fresh leaves of *L. camara*, *P. hysterophorus*, and *C. amboinicus* were utilized for synthesizing AgNPs. *P. hysterophorus* leaves were collected from Coimbatore, Tamil Nadu and Varthur, Karnataka, whereas *L. camara* and *C. amboinicus* leaves were procured from the College of Agriculture, Vellayani. After washing twice in running water and double-distilled water, the midrib was removed, and the leaves were dried in the shade for 1-2 hours to remove excess moisture. The chopped and weighed leaves were then used for extraction. Aqueous leaf extracts (3%) of *L. camara*, *P. hysterophorus*, and *C. amboinicus* and the NPs biosynthesized from the extracts at 1 ppm and 10 ppm were applied to the pots by drenching at 7 days after planting, in three replications.

Biosynthesis of AgNPs

Dried leaves of *L. camara*, *P. hysterophorus* and *C. amboinicus*, each weighing 10 g, were thoroughly washed twice in distilled water. Finely chopped leaves were boiled in 100 ml of sterile distilled water in a round bottom flask for 90 minutes. Once cooled, the crude extract was filtered through Whatman No. 1 filter paper, and the resulting filtrate was utilized for the biosynthesis of AgNPs. A 1 mM solution of silver nitrate ($AgNO_3$) in double distilled water was prepared. It was then combined with leaf extract at a 1:4 ratio and left in darkness overnight at room temperature. Following incubation, a dark brown colour in the solution indicated the reduction of silver ions to AgNPs. The suspension was centrifuged at 10,000 rpm for 20 minutes. The resulting pellet was resuspended in sterile deionized water and then centrifuged again at 10,000 rpm for 20 minutes before being dried in a hot air oven at 40°C for 20 minutes, after which its dry weight was recorded. AgNPs were named as *Lc*-AgNPs, *Ph*-AgNPs, and

Ca-AgNPs, based on weed species used *viz. L. camara* (*Lc*), *P. hysterophorus* (*Ph*) and *C. amboinicus* (*Ca*), respectively.

Physical characterization of AgNPs

UV visible spectroscopy

Silver ion reduction to AgNPs in the colloidal solution was tracked by measuring absorption peaks using a UV-Vis spectrophotometer (SPECORD 210 PLUS - 223F1427) by scanning the wavelengths from 200 to 800 nm in a quartz cuvette with sterile deionized water as a reference.

Dynamic light scattering and zeta potential analysis

A Particle Size Analyser operating at a 90° scattering angle and a temperature of 25°C was used to examine the size and distribution of the produced NPs. The surface charge of the developed NPs was measured using Zeta Pals (Brookhaven, NY, USA).

Scanning electron microscopy

The water-based suspension containing AgNPs was drop-cast onto a scanning electron microscope stub using carbon tape and subsequently dried. Scanning electron microscopy (SEM) analysis was performed with a JEOL/EO JSM-6390 instrument to determine the morphology of the synthesized NPs.

X-ray diffraction analysis

The crystalline structure of the synthesized AgNPs was examined using an X-ray diffractometer (PANalytical-XPERT PRO diffractometer system) operating at 40 kV and 30 mA. Cu-K*a* radiation with a wavelength of 1.54 Å was used to capture diffraction patterns within the 2θ range from 20° to 120°. The crystallite size was calculated using Debye-Scherrer's equation: $D = 0.94\ \lambda/\beta \text{Cos}\ \theta$.

Treatment with biosynthesized NPs

The prepared AgNPs were added to the water in the pots to achieve final concentrations of 1 mg/L and 10 mg/L. The addition of distilled water served as a control. The treatments consisted of *L. camara* (*Lc*) aqueous extract at 3%, *Lc*-AgNPs at 1 ppm, *Lc*-AgNPs at 10 ppm, *P. hysterophorus* (*Ph*) aqueous extract at 3%, *Ph*-AgNPs at 1 ppm, *Ph*-AgNPs at 10 ppm, *C. amboinicus* (*Ca*) aqueous extract at 3%, *Ca*-AgNPs at 1 ppm, *Ca*-AgNPs at 10 ppm and distilled water (control). Growth parameters such as leaf number, leaf length, leaf width, bud diameter, root length and plant height of water hyacinth were measured at the time of application and 15 days after treatment (DAT). The root and shoot fresh weights and the root and shoot dry weights of water hyacinth plants were also recorded at 15 DAT. Leaf samples were collected on 5 DAT for biochemical analysis to determine the total chlorophyll content, total phenol content, carbohydrate content, and protein content. Superoxide dismutase activity was measured by analysing the leaf sample at 5 DAT.

Physiological and biochemical parameters

The photosynthetic rate and stomatal conductance were measured directly by using an LCA-4 - leaf chamber analyser or portable CO_2 analyser, manufactured by Analytical Development Co., Ltd., UK, at 5 DAT. The superoxide dismutase (SOD) activity (units/mg of protein) was estimated by the procedure described by Abedi and Pakniyat (2010). The chlorophyll content in the leaf samples was determined, following the method of Hiscox and Israelstam (1979). It was calculated by substituting the absorbance value (Arnon 1949) and expressed as mg/g.

Chlorophyll a = $(12.7 \times A_{663} - 2.69 \times A_{645}) \times V/1000 \times 1/\text{Fresh weight}$

Chlorophyll b = $(12.7 \times A_{645} - 2.69 \times A_{663}) \times V/1000 \times 1/\text{Fresh weight}$

Total chlorophyll (a+b) = $(8.02 \times A_{663} \pm 20.2 \times A_{645}) \times V/1000 \times 1/\text{Fresh weight}$

The total phenol content was assessed using Folin–Ciocalteu's method. Following incubation, the absorbance at 750 nm was measured using a spectrophotometer (Model-ELICO SL 218, Double beam, UV VIS, Spectrophotometer, India). The total phenolic content data are presented as milligrams (mg) of gallic acid equivalent weight (GAE) per 100 g of dry mass (Kamtekar *et al.* 2014). The total carbohydrate content was determined through the anthrone method (Hedge and Hofreiter 1962), and the protein content was assessed using Bradford's method (Bradford 1976). The results are expressed in mg/g of fresh weight.

Data analysis

The data obtained was subjected to analysis of variance (Panse and Sukhatme 1967). When the difference was significant, the critical difference was calculated at 1% and 5% using GRAPES software developed by Kerala Agricultural University (Gopinath *et al.* 2020).

RESULTS AND DISCUSSION

Characterization of biosynthesized AgNPs

The reduction of $AgNO_3$ by the leaf extracts in aqueous solution was verified through UV visible spectroscopy. The absorbance of the *Ph*-AgNPs was observed in the range of 430-450 nm (**Figure 1**). The

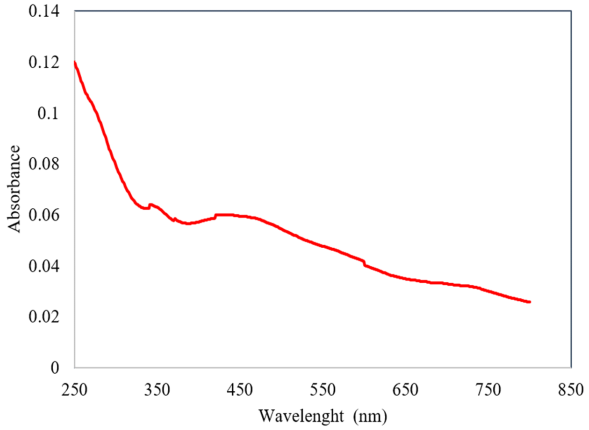

Figure 1. The UV-Visible spectrum of bio-synthesized *Parthenium hysterophorus* mediated silver nanoparticles

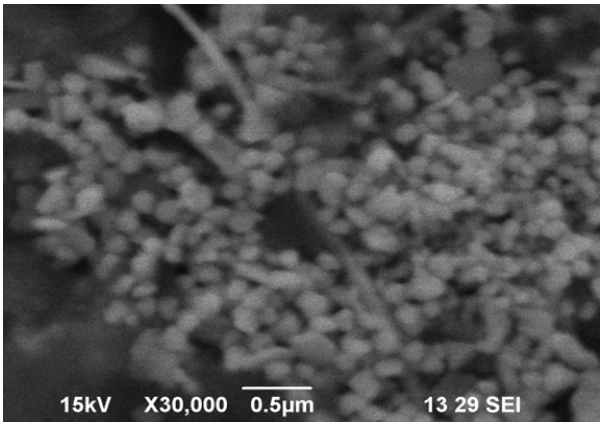

Figure 2. Scanning electron microscopy image of *Parthenium hysterophorus* mediated silver nanoparticles (*Ph*-AgNPs)

maximum size range of the AgNPs in the UV Vis spectrometer analysis was between 300 and 500 nm. This closely resembled the findings of Krithika *et al.* (2014). The reduction of Ag^{+} to Ag^{0} when exposed to plant extracts was qualitatively assessed by colour change. The surface plasmon resonance phenomenon was responsible for the shift in colour. The absorption band of surface plasmon resonance was due to the release of electrons from the metal NPs. Because of the collective oscillation of electrons on the metal surface triggered by light, AgNPs exhibit intense interactions with light (Panigrahi 2013). Earlier, Ag^{0} NPs were synthesized by the reduction of Ag^{+} ions using leaf extracts of *L. camara* (Shafaghat 2015; Ajitha *et al.* 2015). The biosynthesis of AgNPs, using *P. hysterophorus (*Kumar (2012) and *C. amboinicus* (Vanaja and Annadurai 2013) was reported earlier.

The average zeta potential (ZP) of -32.7 mV obtained from the analysis indicated that the *Ph*-AgNPs were stable, possibly due to the phytoconstituents in the leaf extract that could act as capping layers for the AgNPs, which might be responsible for the greater negative ZP. Negatively charged particles could repel one another, preventing agglomeration and resulting in NP stability. The proteins in the plant extracts also cap the AgNPs, preventing aggregation (Reddy *et al.* 2020). Thus, when the particle travels under the influence of Brownian motion, the hydrodynamic diameter provides information about the size of the core, the presence of any coating materials, and the solvent layer connected to the particle. As a result, the measured diameter of the particle is larger than its real size. Dynamic light scattering (DLS) revealed that the *Ph*-AgNPs had a particle size of 213 nm and a polydispersity index (PDI) of 0.52.

SEM provides additional insight into the shape and structure of AgNPs. The *Ph*-AgNPs were spherical in shape (**Figure 2**). Although the *Lc*-AgNPs and *Ca*-AgNPs were spherical, they were less uniform than the former. Similar SEM studies indicated that AgNPs synthesized from *L. camara, P. hysterophorus*, and *C. amboinicus* leaf extracts were spherical in shape (Vanaja and Annadurai 2013, Shafaghat 2015, Ahsan *et al.* 2020).

The X-ray diffraction (XRD) patterns of *Lc*-AgNPs, *Ph*-AgNPs, and *Ca*-AgNPs were examined and showed distinct peaks at different angles, with corresponding Miller indices (**Figure 3 a-c**). Sharp XRD peaks typically indicate crystallite materials (Bykkam *et al.* 2015). The AgNPs biosynthesized in this study were crystalline and had a face-centered cubic (FCC) crystal lattice structure, as confirmed by the XRD peaks (**Figure 3 a,b,c**). The reactivity of AgNPs depends on their size, with smaller particles having higher activity and toxicity due to their greater penetration ability (Panacek *et al.* 2006). AgNPs of various sizes (20-80 nm) induced toxicity in *Arabidopsis thaliana* seedlings (Ma *et al.* 2010). The tendency to release silver ions increases as the size decreases (Nowack *et al.* 2010). The phytotoxicity response is significantly affected by the size, shape, and concentration of NPs (Siddiqi and Husen 2016).

Effect on water hyacinth growth

The aqueous extracts of *L. camara, P. hysterophorus*, and *C. amboinicus* at 3% and the biosynthesized NPs at 1 ppm and 10 ppm affected the growth of water hyacinth (**Table 1**). It was found that the *Ph*-AgNPs affected water hyacinth growth in a concentration-dependent manner, with a notable effect on the number of leaves and bud diameter at 6 DAT and on the length and width of leaves at 9 DAT

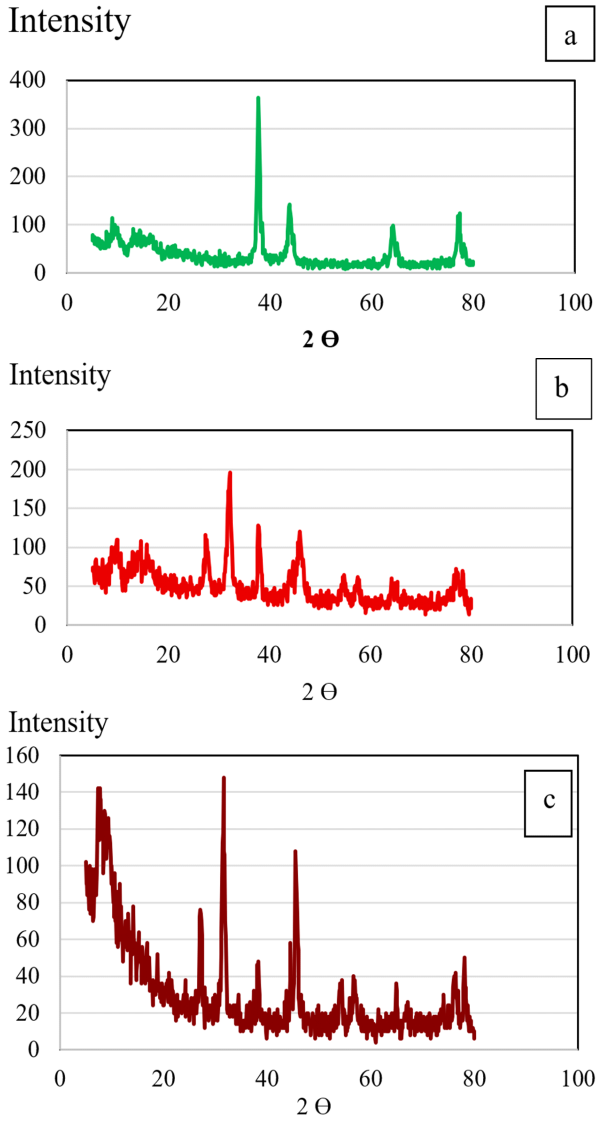

Figure 3. X-ray diffraction spectroscopy of bio-synthesized silver nanoparticles

a. *Lantana camara* mediated silver nanoparticles b. *Parthenium hysterophorus* mediated silver nanoparticles and c. *Coleus amboinicus* mediated

(**Figure 4**). Among the treatments, *Ph*-AgNPs at 10 ppm inhibited the growth of water hyacinth from 6 DAT to a 100% reduction in the biomass of water hyacinth within 15 DAT (**Table 1**). Abiotic stress can negatively affect plant development, growth, and performance by causing changes at the morphological, physiological, biochemical, and molecular levels. Oukarroum *et al.* (2013) reported a notable increase in the formation of intracellular ROS with the exposure of duckweed (*Lemna gibba*) to 1 and 10 mg/L AgNPs. The induced oxidative stress was connected to the accumulation of Ag within the plant cells of *L. gibba* and corresponded to the increase in the concentration of AgNPs in the medium.

At three-days post-treatment with *Ph*-AgNPs at 10 ppm, water hyacinth plants displayed chlorotic and necrotic symptoms, with leaf wilting and rolling from the margins (**Figure 4**). The entire leaf then became necrotic, resulting in the drooping and drying of the entire plant. The water hyacinth growth decreased due to a reduction in leaf dimensions and bud diameter, which could be attributed to the uptake of *Ph*-AgNPs. Previous studies reported similar growth inhibition effects on *Lemna minor* and *Lemna paucicostata* upon exposure to chemically synthesized AgNPs (Gubbins *et al.* 2011, Kim *et al.* 2011a, Kim *et al.* 2011b). Plants treated with AgNPs had shorter root hairs (Mittler 2002, Nel *et al.* 2006). The *Arabidopsis thaliana*, when exposed to AgNPs, could exhibit reduced root development and altered cell walls or cell shapes (Geisler-Lee *et al.* 2014). When exposed to chemically reduced AgNPs for 14 days, *Lemna minor* and *Pontederia crassipes*, experienced significant growth inhibition. Accumulation of AgNPs in plant tissues and roots led to necrosis and disrupted metabolic processes, resulting in reduced growth. The toxicity of AgNPs increases with increasing exposure time (Gubbins *et al.* 2011, Rani *et al.* 2016). Heavy metals were found to affect the root growth, development, and relative growth rate of *P. crassipes* and *Pistia stratiotes* plants (Odjegba and Fasidi 2007).

Plant height is a key indicator of plant growth. The use of *Ph*-AgNPs had a significant impact on the growth of water hyacinth at both concentrations tested. Application of 10 ppm *Ph*-AgNPs resulted in a significant decrease in plant height, root length, root and shoot fresh weight, and root and shoot dry weight, ultimately leading to complete growth inhibition (**Table 1** and **2**).

Effect on physiological parameters of water hyacinth

Metal stress alters enzymes that lead to chlorophyll degradation, resulting in yellowing, necrotic spots, and wilting of leaves. This affects plant photosynthesis, stomatal conductance, and carbohydrate and protein levels. The present study revealed that the application of 10 ppm *Ph*-AgNPs significantly decreased the total chlorophyll content, photosynthetic rate, stomatal conductance, carbohydrate content, and protein content in water hyacinth leaf tissue at 5 DAT (**Table 3, Figure 5**). Silver nanoaprtilces can disrupt the thylakoid membrane structure, which is crucial for photosynthesis, and can also affect the fluidity and permeability of cell membranes, influencing nutrient uptake and potentially leading to reduced chlorophyll

synthesis (Qian *et al*. 2013). However, there was a noticeable increase in the total phenol content in the presence of *Ph*-AgNPs at both concentrations, with the maximum increase observed at 10 ppm (**Figure 5**). In response to metal stress, plants produce higher levels of phenols (Dudjak *et al*. 2004). Phenols play a role in plants growing under heavy metal stress by acting as antioxidants. Water hyacinth plants treated with synthetic and biosynthesized AgNPs increased the total phenol content (Rani *et al*. 2016). Synthetic AgNP treatment of castor resulted in increased contents of phenols and phenolic acids (Jyothsna and Rani 2013).

AgNPs inhibited the activity of photosynthetic pigments in the aquatic plant, *Spirodela polyrhiza* (Jiang *et al*. 2012). Exposure to AgNP at 0.002 mg/L for 4 days increased oxidative stress in Seagrass, while exposure to AgNP at 0.02 mg/L for 8 days severely damaged cell organelles and photosystem II (PS II) (Mylona *et al*. 2020). A decrease in carbohydrate content in water hyacinth was noted after 5 days of application of synthetic AgNPs, possibly because of a decrease in chlorophyll content that indirectly affects photosynthesis (Rani *et al*. 2016). A reduction in protein concentration can occur due to the degradation of preexisting proteins and a decrease in protein synthesis, which can serve as a biomarker for metal stress in plants (Mane *et al*. 2011).

The uptake of AgNPs disrupts the balance of water and small molecules, reduces photosynthetic activity, decreases photosynthetic efficiency, increases ROS production, and damages chloroplasts, potentially leading to plant growth retardation or death in *A. thaliana* (Qian *et al*. 2013). A similar study showed that water hyacinth plants treated with higher concentrations of AgNPs exhibited increased SOD activity due to metal stress (Rani *et al*. 2016). AgNPs cause oxidative stress in plants through the generation of ROS (Mittler 2002; Nel *et al*. 2006). Elevated SOD activity indicates oxidative stress-induced ROS imbalance, contributing to photosynthetic damage and reduced chlorophyll content and activity (Xu *et al*. 2025). In

Table 2. Root and shoot weight of water hyacinth plants as influenced by treatment with different aqueous extracts and bio-synthesized AgNPs at 15 DAT

Treatment	Root fresh weight (g/pot)	Root dry weight (g/pot)	Shoot fresh weight (g/pot)	Shoot dry weight (g/pot)
Lc aq. extract 3%	16.90^{d}	1.65^{d}	21.33^{e}	1.64^{e}
Lc-AgNPs 1 ppm	36.91^{a}	3.27^{a}	36.29^{bc}	2.59^{b}
Lc-AgNPs 10 ppm	31.50^{b}	2.90^{b}	37.97^{b}	2.70^{b}
Ph aq. extract 3%	23.51^{c}	2.10^{c}	33.72^{c}	2.42^{c}
Ph-AgNPs 1 ppm	10.33^{f}	0.87^{e}	14.72^{f}	0.87^{f}
Ph-AgNPs 10 ppm	0^{g}	0^{f}	0^{g}	0^{g}
Ca aq. extract 3%	25.64^{c}	2.22^{c}	29.28^{d}	2.54^{bc}
Ca-AgNPs 1 ppm	21.92^{c}	2.02^{c}	33.04^{c}	2.57^{bc}
Ca-AgNPs 10 ppm	14.15^{de}	2.03^{c}	21.43^{e}	1.58^{e}
Distilled water	37.66^{a}	3.40^{a}	43.37^{a}	3.53^{a}
LSD (p=0.05)	2.893	0.274	3.445	0.165

Lc- Lantana camara, Ph- Parthenium hysterophorus, and *Ca-Coleus amboinicus;* aq. extract-aqueous extract AgNPs- Silver nanoparticles; DAT – days after treatment

Table 1. Growth parameters of water hyacinth as influenced by treatment with different aqueous extracts and bio-synthesized AgNPs

Growth parameters	Number of leaves/plants		Length of leaves (cm)		Width of leaves (cm)		Bud diameter (cm)		Root length (cm)		Plant height (cm)	
	0 DAT	15 DAT	0 DAT	15 DAT	0 DAT	15 DAT	0 DAT	15 DAT	0 DAT	15 DAT	0 DAT	15 DAT
Lc aq. extract. 3%	5.2	6.33 (2.6)^{c}	5.0	5.80 (2.51)^{cd}	6.6	6.82(2.70)^{cd}	6.5	6.35(2.62)^{bcd}	20.9	19.6(4.48)^{e}	16.4	18.1(4.32)^{b}
Lc-AgNPs 1 ppm	5.8	9.33 (3.14)^{b}	6.2	6.39 (2.62)^{ab}	7 .6	7.87(2.89)^{abc}	6.6	7.67(2.85)^{ab}	23.6	24.7(5.02)^{c}	17.9	19.5(4.47)^{ab}
Lc-AgNPs 10 ppm	5.0	8.83 (3.05)^{b}	5.9	6.14 (2.58)^{abc}	7.0	7.23(2.78)^{bcd}	6.8	7.7(2.86)^{a}	23.8	24.6(5.01)^{c}	16.6	18.8(4.40)^{ab}
Ph aq. extract 3%	5.3	6.67 (2.68)^{c}	5.9	4.67 (2.27)^{e}	7.5	7.55(2.83)^{bc}	7.9	5.58(2.46)^{cde}	22.9	18.5(4.37)^{f}	16.5	18.3(4.33)^{b}
Ph-AgNPs 1 ppm	4.5	4.50 (2.23)^{d}	5.5	4.40 (2.21)^{e}	6.7	6.33(2.61)^{d}	6.4	4.68(2.27)^{e}	24.9	18.9(4.41)^{ef}	16.1	14.7(3.89)^{c}
Ph-AgNPs 10 ppm	4.5	0 (0.7)^{e}	5.6	0 (0.7)^{f}	7.0	0 (0.7)^{e}	6.4	0 (0.7)^{f}	25.0	0(0.7)^{g}	17.6	0(0.7)^{d}
Ca aq. extract 3%	4.5	9.33 (3.14)^{b}	5.4	6.25 (2.60)^{ab}	7.0	7.37(2.80)^{bc}	6.6	6.75(2.69)^{abc}	22.7	23.0(4.85)^{d}	16.1	18.3(4.34)^{b}
Ca-AgNPs 1 ppm	5.0	8.83 (3.05)^{b}	5.9	6.07 (2.56)^{bc}	7.3	8.10(2.93)^{ab}	6.9	7.97(2.91)^{a}	25.0	28.1(5.35)^{b}	16.6	19.0(4.41)^{ab}
Ca AgNPs 10 ppm	5.3	8.33 (2.97)^{b}	6.3	5.53 (2.46)^{d}	8.0	8.17(2.94)^{ab}	7.0	5.43(2.43)^{de}	25.8	22.1(4.76)^{d}	17.3	19.2(4.44)^{ab}
Distilled water	5.5	11.33(3.44)^{a}	5.9	6.47 (2.64)^{a}	7.1	8.88(3.06)^{a}	6.7	7.97(2.91)^{a}	26.0	29.7(5.49)^{a}	18.0	19.9(4.52)^{a}
LSD (p=0.05)	NS	0.205	NS	0.077	NS	0.189	NS	0.233	NS	0.111	NS	0.178

Lc- Lantana camara, Ph- Parthenium hysterophorus, and *Ca-Coleus amboinicus*
aq. extract-aqueous extract AgNPs- Silver nanoparticles; DAT – days after treatment

Table 3. Physiological parameters of water hyacinth as influenced by treatment with different aqueous extracts and bio-synthesized AgNPs at 5 DAT

Treatment	Photosynthetic rate (µmole CO_2 /m^2/s)	Stomatal conductance (mmole H_2O /m^2/s)	Chlorophyll (mg /mL FW)	SOD (units/mg protein)
Lc aq. extract 3%	19.74^{f}	843.00^{f}	1.15^{cd}	428.17^{c}
Lc-AgNPs 1 ppm	25.86^{c}	1284.67^{d}	1.16^{cd}	372.74^{e}
Lc-AgNPs 10 ppm	25.37^{c}	1257.33^{d}	1.31^{a}	400.15^{d}
Ph aq. extract 3%	23.29^{d}	925.67^{e}	1.15^{cd}	411.42^{d}
Ph-AgNPs 1 ppm	22.26^{e}	886.33^{ef}	1.13^{d}	440.58^{b}
Ph-AgNPs 10 ppm	17.69^{g}	598.67^{g}	0.49^{e}	474.68^{a}
CA aq. extract 3%	26.88^{ab}	1466.67^{b}	1.29^{ab}	335.18^{f}
Ca-AgNPs 1 ppm	26.23^{bc}	1447.33^{bc}	1.22^{bc}	364.86^{e}
Ca-AgNPs 10 ppm	25.64^{c}	1380.00^{c}	1.10^{d}	403.38^{d}
Distilled water	27.70^{a}	1579.67^{a}	1.36^{a}	319.40^{g}
LSD (p=0.05)	1.002	67.890	0.073	11.396

Lc- Lantana camara, *Ph- Parthenium hysterophorus*, and *Ca-Coleus amboinicus*
aq. extract-aqueous extract; AgNPs- Silver nanoparticles; DAT – days after treatment

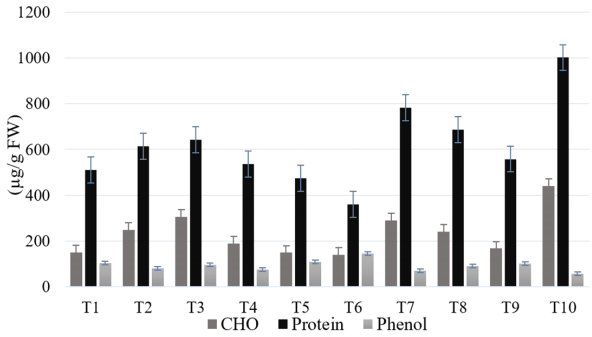

Figure 5. Carbohydrate, protein and phenol content of water hyacinth (µg/g FW) as influenced by different treatments.

T_1- *Lantana camara* aqueous extract at 3 percent, T_2- *Lantana camara* mediated silver nanoparticles at 1 ppm, T_3- *Lantana camara* mediated silver nanoparticles at 10 ppm, T_4- *Parthenium hysterophorus* aqueous extract at 3 %, T_5- *Parthenium hysterophorus* mediated silver nanoparticles at 1 ppm,, T_6- *Parthenium hysterophorus* mediated silver nanoparticles at 10 ppm, T_7- *Coleus amboinicus* aqueous extract at 3 %, T_8- *Coleus amboinicus* mediated silver nanoparticles at 1 ppm,, T_9- *Coleus amboinicus* mediated silver nanoparticles at 10 ppm, T_{10}- Distilled water (control)

the present study, the SOD content increased with the addition of 10 ppm Ph-AgNPs, followed by the addition of 3% aqueous *L. camara* extracts (**Table 3**). An increase in SOD activity in water hyacinth was noted with the use of *L. camara* aqueous extracts at a concentration of 3%. This could be considered as one of the plant's antioxidant responses to phytotoxins present in *L. camara* leaf extract. SOD activity in the leaves of water hyacinth correlated with the accumulation of H_2O_2 and the increase in the degree of membrane peroxidation (Zheng *et al.* 2006).

Conclusion

The 10 ppm *Ph*-AgNPs effectively suppressed photosynthetic rate, stomatal conductance, chlorophyll content, total phenol content, carbohydrate content, protein content and SOD activity and affected water hyacinth growth, *viz.*, number of leaves, length and width of leaves, bud diameter, root length, height of plants, root and shoot fresh weight and dry weight. Thus, AgNPs (10 ppm) biosynthesized using the noxious weed *Parthenium hysterophorus* could be effectively utilized as a component of integrated management of another problematic aquatic weed, water hyacinth.

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