Green Synthesis of Silver Nanoparticles from Black Tea Residue and Their Allelopathic Influence on Crop and Weed Seedlings

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Abstract

The utilization of agricultural and food waste materials for sustainable nanotechnology applications has gained significant interest in recent years. This study investigates the impact of silver nanoparticles (AgNPs) synthesized from black tea residue and applying on seed germination and seedling growth. Black tea residues, rich in polyphenols, caffeine, and essential minerals, were processed into nanoparticles and applied to seeds of selected plant species. The experiment was conducted under controlled laboratory conditions using 5 mL of each treatment in petri dishes at 20°C for 10 days. The tested seeds included *Hordeum vulgare* (wild barley), *Triticum aestivum* (wheat), *Vigna radiata* (mung bean), and *Brassica nigra* (black mustard), with treatments at five concentrations (control, 0.4%, 0.8%, 1.2%, and 1.6%).

Data analysis revealed that the $AgNO_3$ black tea residue nanoparticles exerted a concentration-dependent phytotoxic effect, significantly inhibiting germination and early growth at higher concentrations (1.2% and 1.6%). Some species, such as *B. nigra*, showed sensitivity even at lower levels, while shoot dry weight at 0.4% suggested a possible hormetic effect. These results suggest that the combined action of allelochemicals and AgNPs may disrupt hormonal signaling and induce oxidative stress via reactive oxygen species (ROS), leading to growth suppression. This bioactivity highlights their potential use as an eco-friendly alternative to chemical herbicides.

Moreover, the use of black tea waste as a nanoparticle stabilizer supports sustainable agriculture by converting waste into value-added, biodegradable herbicidal agents. These findings demonstrate that AgNPs derived from black tea residues can serve as an effective, natural weed management tool while reducing environmental risks such as herbicide resistance and soil contamination.

Keywords: Allelopathy, black tea residue, nanoparticles, weed control.

1. Introduction

The phenomenon known as allelopathy occurs when plants emit secondary metabolites, or allelochemicals, into the environment to either directly or indirectly affect the growth of nearby plants [1]. Allelochemicals can directly disrupt target plant respiration, photosynthesis, enzyme synthesis, and metabolism [2] or indirectly through beneficial soil microbes and soil fertility that impact plant communities [3]. Root exudation and the breakdown of plant leftovers are the main ways that E. jolkinii distributes different chemical compounds into the soil [4]. Rain leaching distributes these substances throughout the soil, including phenolic acids, amino acids, lipids, flavonoids, alkaloids, and terpenoids [5]. Theophrastus was the first to examine the problem of plants influencing other plants through chemical release in 370 BC [6]. Molisch used the term Allelopathy for the first time in 1937. The Czech-Austrian botanist Hans Molisch (1937) first used the term "allelopathy" in his book The Influence of One Plant on Another: Allelopathy. Molisch gave numerous examples of how chemicals emitted into the environment by plants can have both stimulatory and inhibitory effects on one another [7].

Nanotechnology, a nanometer is one billionth of a meter, and the word "nano" is a Greek noun that means "dwarf." Nanomaterials (NM) are used in a wide range of industries and fields, including energy, agriculture, medical, and industry, because of their small size and larger surface area, which provide distinct physical and chemical properties that set them apart from bulk materials with the same composition [8]. There is Plenty of Room at the Bottom" was the title of a talk given by American physicist Richard Feynman, who was designated the father of nanotechnology on December 29, 1959, at a meeting of the American Physical Society at Caltech. New developments in electronics, energy, health, and environmental science are made possible by this technology, which makes use of unique physical, chemical, and biological characteristics that manifest at the nanoscale. In recent years, the green production of metallic nanoparticles has become a promising field of study. This method has become more popular since it is easy to use, economical, takes less time, produces non-toxic byproducts, is environmentally friendly, and can be scaled up for large-scale production [9]. The primary reaction that takes place throughout the bottom-up process of biosynthesis of nanoparticles is reduction/oxidation [10]. Plant extracts' reducing or antioxidant qualities are often what cause metal compounds to be reduced into their corresponding nanoparticles. Because it is less expensive, more environmentally friendly, easier to scale up for large-scale synthesis, and does not require the use of hazardous chemicals or high pressure, energy, or temperature, green synthesis offers advantages over chemical and physical methods [11]. Better manipulation, control over crystal formation, and stabilization are provided by green synthesis [12]. Because plants include a wide variety of phytochemicals, including flavonoids, glycosides, polyphenols, terpenoids, and enzymes, they play a key role among these biological sources for the creation of nanostructures [13].

With 70–80% of all tea consumed, black tea is the most widely produced tea in the world. Green tea comes in second with 20% and oolong tea with 2%. [14]. The fresh leaves of *C. sinensis* are primarily withered, rolled, fermented, and dried during the black tea manufacturing process. Withering and fermentation are essential processes for the formation of black tea's flavor and aroma. Cell sap from harvested shoots concentrates during withering, causing the leaves to become floppy and lose moisture [15]. The fermentation stage of black tea is a crucial processing step in which oxidative enzymes including polyphenol oxidase (PPO) and peroxidase (PO) oxidize the majority of the polyphenols, including catechins, to generate quinones, which are then oxidized and condensed to form theaflavins (TFs). Theabrownins, thearubigins (TRs), and other polymerization products [16].*Camellia sinensis* is the source of tea, one of the most important strategic beverages in the world [17].During the manufacturing process, tea is divided into three primary types based on the degree of oxidation: unoxidized (green tea), semi-oxidized (Oolong tea), and fully oxidized (black tea) [18].The classification of tea is also influenced by the varietal varieties, such as assamica for black tea, hibiscus for red tea, and sinensis for green tea [19]. When making tea, the young top leaves—which are distinguished by an unopened leaf bud with a coil—are frequently harvested [20]. Around the world, tea (Camellia sinensis) is grown, especially in China, India, and a few other Asian nations. The southern region of Yunnan Province, which is situated in southwest China, is where tea first appeared. Camellia sinensis var. sinensis, which is a bush-like plant with small leaves that originated in China and grows in some Asian countries with mild cold climates, and Camellia sinensis var. Two-thirds of the world's population drinks tea infusions made from the leaves of a particular kind of plant called Camellia sinensis [21]. Allelopathy offers a promising ecological approach to weed management, particularly in response to the limitations of synthetic herbicides. Herbicides, while effective, often lead to environmental contamination, herbicide-resistant weed populations, and negative impacts on non-target organisms. Simultaneously, unchecked weed growth can significantly reduce crop yield by competing for water, nutrients, and light. In this context, the use of allelopathic plants or their extracts provides a natural alternative by suppressing weed germination and growth through the release of bioactive secondary metabolites [51].

The aim of this study is to evaluate the allelopathic effects of silver nanoparticles synthesized from black tea residue on the germination and early growth of selected monocot and dicot crop and weed species.

2-MATERIAL AND METHODS

2. Experimental

2.1. Preparation of tea residue extracts

In this study, commercially available black tea (brand name: *Butterfly*) was purchased from local markets in Erbil, within the Kurdistan Region of Iraq. Tea residue was selected as a raw material due to its richness in bioactive compounds when prepared under appropriate conditions. The preparation involved boiling the required volume of water, removing it from heat, and then steeping black tea leaves (*Camellia sinensis*) for 3–5 minutes before collecting and shade-drying the residue [43]. Given the high daily consumption of black tea in Iraq and particularly in the Kurdistan Region, substantial quantities of tea residue are generated, presenting an opportunity for value-added applications. In this context, silver nanoparticles were synthesized from black tea residue for potential use as an eco-friendly herbicide. The synthesis involved mixing 10 g of dried tea residue with 100 mL of distilled water, stirring the mixture at 50 °C for 30 minutes using a magnetic stirrer, allowing it to cool, and then filtering the solution [22].

A Shimadzu UV-2600i spectrophotometer was used to assess the potential for nanoparticle formation from the plant extract. The extract was prepared according to the established method, then diluted at a 1:5 ratio and transferred into quartz cuvettes with a 1 cm path length [49]. A characteristic absorption peak within the 200–400 nm range indicates the feasibility of synthesizing nanoparticles from the extract.

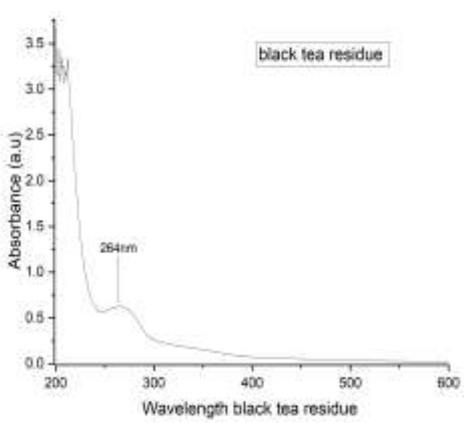

Figure (2.1) UV–Vis spectrum of black tea residue extract.

2.2. Synthesis of Ag NPs

Preparation of $AgNO_3$ Dissolve 1gm of $AgNO_3$ in 100ml of distilled water. Heat the filtered tea residue for 30 minutes at 50°C. Add the tea residue to the $AgNO_3$ solution until it turns dark brown or black and centrifuge for 6000 cycles for 1 minute Repeat the process, rinse with water and alcohol and place it in the oven at 80 degrees for 16 hours. in figure 2.2. show the Synthesis of $AgNO_3$ NPs black tea residue [50].

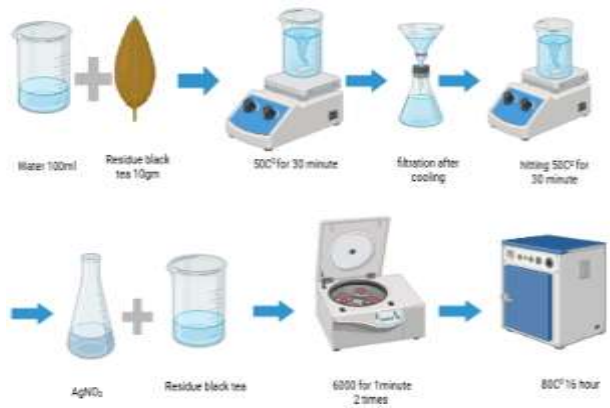

Figure 2.2 Synthesis process of $AgNO_3$ nanoparticles using black tea residue extract.

2.3. Bioassay

In this study, the effects of silver nitrate ($AgNO_3$) nanoparticles on seed germination and seedling growth were evaluated for four plant species: wheat, mung bean, brassica, and barley weed. A stock solution was prepared by dissolving 0.1 g of $AgNO_3$ in 100 mL of distilled water under continuous stirring. From this, working concentrations of 0, 0.4, 0.8, 1.2, and 1.6 mM were prepared. Petri dishes (9 cm diameter) lined with 9 cm filter papers were used for the germination tests. Seeds were surface-sterilized prior to placement, with 10 seeds added per dish and 5 mL of the respective treatment solution applied to each. The dishes were incubated at 20 °C for 10 days. After the incubation period, measurements were taken for seed germination percentage, shoot and root lengths, and seedling dry weight [23].

2.6. Experimental design and statistical analysis

The ANOVA general linear model was used to analyze the experiment's results (Minitab software, version 20). Totally three replications of a randomized design (CRD) were selected. Means were compared for significant differences using Duncan's test ($P \leq 0.05$).

3. Characterization of Silver Nanoparticles

The size, shape, surface area, and dispersion of nanoparticles are all directly related to their unique characteristics. The task of identifying the structural properties of these nanoparticles is completed by analytical methods like energy-dispersive spectroscopy (EDS), scanning electron microscopy (SEM), Fourier transform infrared spectroscopy (FT–IR), and ultraviolet–visible spectroscopy, among others. The synthesis of nanoparticles has advanced thanks in large part to these techniques, which enable precise evaluation of their structural and physicochemical characteristics as well as thorough visualization. These techniques offered thorough understanding of the optical, size distribution, elemental composition, and morphological properties of the nanoparticles [24].

3.1. Ultraviolet–Visible (UV–Vis) Spectroscopy

Determining the optical properties, manufacturing, and stability of nanoparticles are only a few of the many uses for the crucial ultraviolet–visible (UV–Vis) spectroscopy technique [25].

This method is advantageous since it is simple, easy to use, sensitive, selective, and rapidly assessed. UV-V is spectroscopy quantifies the amount of visible or ultraviolet light that various compounds in solution absorb [26]. When a sample solution containing only a crude plant extract was analyzed, no noticeable peak was found. On the other hand, the botanically generated nanoparticle sample had distinct peaks at various wavelengths. In particular, according to [27], the absorption band for silver nanoparticles (Ag NPs) normally lies between 417 and 448 nm. Ag NPs' UV–vis spectra were captured at various points in time. At 439 nm, the UV-vis spectra displayed the highest absorption. Increased absorbance is seen in the curve at different time intervals (0–30 minutes), with maxima observed around 439 nm, which is very selective for silver nanoparticles. After 24 hours, the UV-vis spectra revealed that

A Shimadzu UV-2600i UV device was used to detect and form nanoparticles after the nanoparticles are formed or after adding the $AgNO_3$ solution, the measurement is taken from the solution again. Dilute the plant solution in a ratio of 1:5 and place it in quartz cuvettes (1 cm path length). If it reads above 400, it means that the nanoparticle is completely formed. The example in Figure 3.1. shows that black tea residues can be used to make nanoparticles.

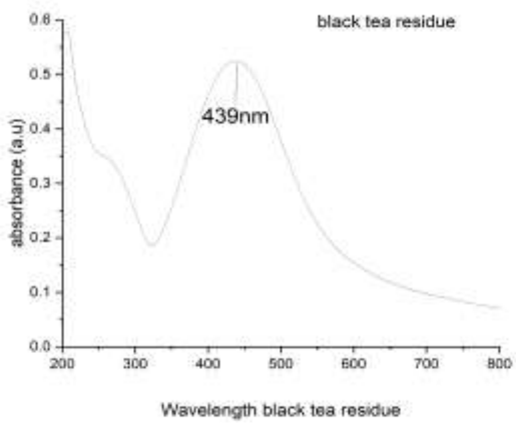

Figure (3.1.) UV- Visible spectra of black tea residue nanoparticle extract

3.2. Fourier Transform Infrared (FT-IR)

One useful method for examining the surface chemistry of nanoparticles is Fourier Transform Infrared (FT-IR) Spectroscopy. By creating a molecular fingerprint of the sample by its absorption and transmission spectra, this method is used to evaluate biomolecules in order to identify their functional groups involved in the creation of nanoparticles [28]. To illustrate the presence of important biomolecules involved in the nanoparticle formation process, the authors of [29]. found several functional groups on the surface of silver nanoparticles (Ag NPs) made from the extract of black tea residue (*Camellia sinensis*) [30].

The existence of functional groups involved in the biogenic synthesis and stability of nanoparticles was indicated by different peaks in the black tea residue extract's FTIR spectrum. The presence of phenolic or alcoholic substances, such as flavonoids and tannins, is suggested by a large peak at 3275 cm^{-1} that corresponds to O–H stretching vibrations. C≡C (alkyne) groups, which are rare but can originate from unsaturated plant-derived chemicals, are responsible for a peak at 2108 cm^{-1}.The carbonyl groups (C=O) present in ketones, aldehydes, or carboxylic acids are indicated by the peak at 1633 cm^{-1}. Additionally, the existence of complex phytochemicals such as saponins or polyphenolic ethers is confirmed by peaks at 642 and 594 cm^{-1}, which correspond to C=C bending (aromatic rings) and C–O–C ether connections, respectively. These results show that bioactive chemicals found in black tea residue can efficiently stabilize nanoparticles and reduce metal ions.

Wavenumber (cm^{-1}) Potential Functional Group Stretch from O to H: 3275cm Alcohols or phenols are signs of polyphenolic substances such as tannins or flavonoids. 2108 cm^{-1} C≡C stretch Alkyne groups are rare but can arise from unsaturated chemicals produced from plants. The carbonyl group, which is 1633 cm^{-1}, is probably derived from ketones, aldehydes, or carboxylic acids (such as flavonoids and tannins). 642 cm^{-1} C=C bend Alkenes—possibly from polyphenols' aromatic ring structures. Stretch 594 cm^{-1} C–O–C Ether linkage may be a sign of glycosidic linkages found in polyphenolic ethers or saponins. Polyphenolic compounds, which are known to reduce metal ions and cap/stabilize nanoparticles, are confirmed by the presence of O–H, C=O, and C–O–C groups. This backs up the use of leftover black tea as a green capping and reducing agent for the manufacture of nanoparticles. $AgNO_3$ as shown in(Figure .3.2)

Application of (Shimadzu ATR-FTIR) to liquid nanoparticle samples for functional group determination, first clean the crystal surface with ethanol and a lint-free tissue.

Make sure it is completely dry before small droplet (e.g., 1-3 µL) of nanoparticle suspension directly onto the ATR crystal. applying the sample. Use a pipette to place a Cover evenly Scan sample close lid to reduce atmospheric mixing.

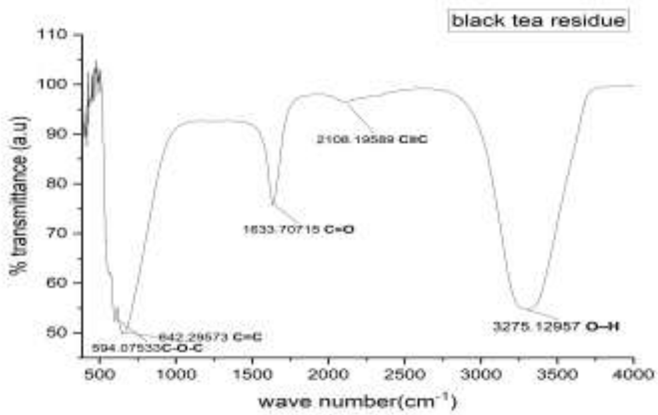

Figure 3.2 FTIR spectrum of tea black residue nanoparticle extract.

3.3. Scanning Electron Microscopy

One crucial method for analyzing the two-dimensional surface morphology of nanoparticles is scanning electron microscopy, or SEM. Although AFM can generate accurate three-dimensional pictures [31]. SEM provides a potent tool for examining the dimensions, form, and surface characteristics of biosynthesized nanoparticles. The SEM examination helps researchers better understand the structural variation of nanoparticles. A variety of morphologies were seen, including spherical, cubical, and rectangular shapes. as shown in Figure (3.3).

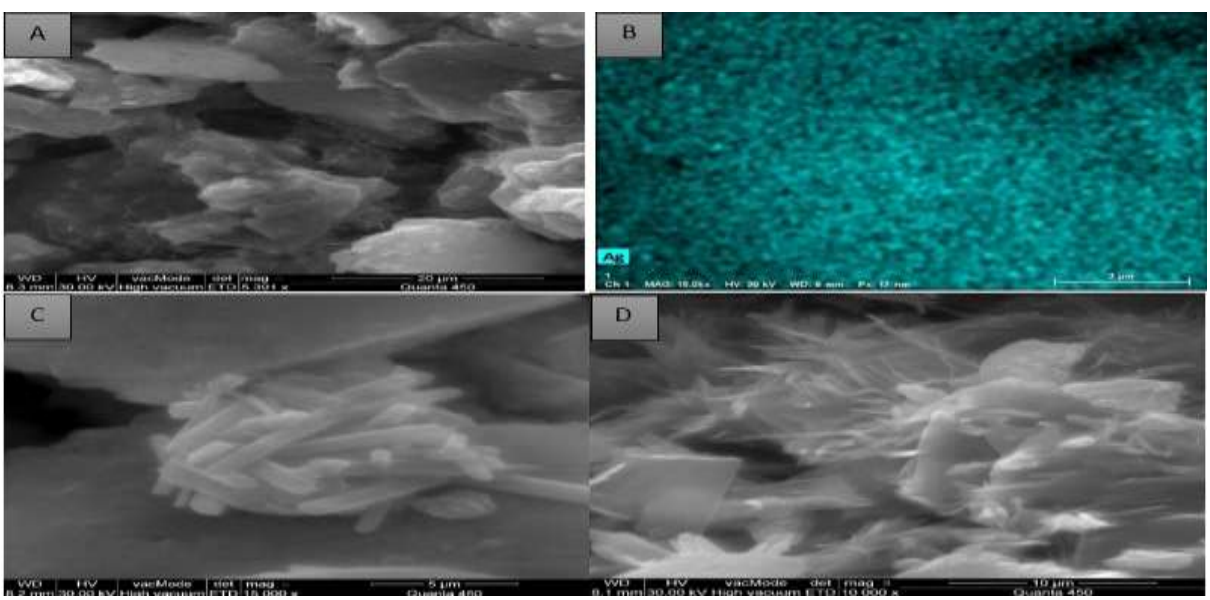

Figure (3.3) Scanning electron micrographs (A–D) of silver nitrate nanoparticles synthesized using black tea residue extract.

3.4.X- Ray Diffraction (XRD)

An important technique for assessing the structure of crystals and crystal planes as well as figuring out the size of nanomaterial crystallites is X-ray diffraction (XRD). This

technique depends on X-rays' capacity to penetrate materials deeply and provide detailed information about the interior structure of crystals [32]. According to [33], XRD investigation of crystalline materials will show diffraction peaks at particular

angles that correlate to the arrangement of atoms within the crystal lattice. In the XRD investigation, several researchers found distinctive diffraction peaks at 5.53◦,37.44◦,43.51◦,45.59◦, and 63.86◦, (FCC) structure [34]. The Debye Scherrer equation ($D= k\lambda \ \beta\cos\theta$) was used to determine the average size of the silver nanoparticles. D= is the crystal size (Cite). where λ is the wavelength of the X-ray incident on the crystal and k is the constant 0.96. The software origin 64 Bit computed the FWHM using the Gaussian function, and the average size of the generated the extract-generated silver (Ag) nanoparticles have a face-centered cubic nanoparticles was 21.83 nm.

Table3.4. Average size analysis of $AgNO_3$ NPs from XRD analysis.

Average D(nm)	D(nm)	FWHM β (°)	Peak position 2θ (°)
21.83	8.794258	0.9446	5.5348
	27.82112	0.3149	37.4415
	18.91532	0.4723	43.5118
	38.10491	0.2362	45.5918
	15.52359	0.6298	63.8626

which, respectively, correspond to the crystal planes (111), (200), (220), (311), and (222). The findings of this investigation show that

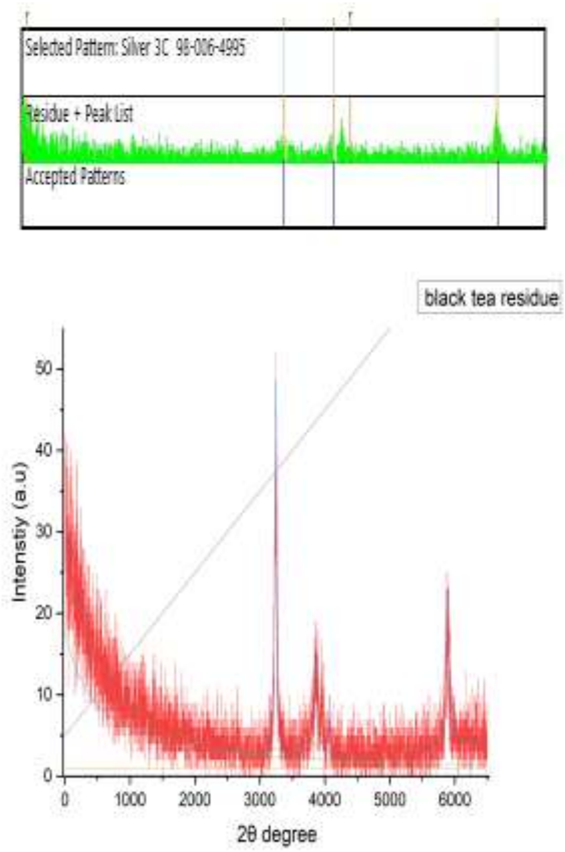

Figure (3.4.) XRD analysis of Ag NPs using tea black residue nanoparticle extract

3.5. Energy dispersive X-ray (EDX)

This EDS (EDX) spectrum shows that the nanoparticle contains silver (Ag) based on the identified peaks. Strong Peaks of Silver (Ag)The Ag Lα emission, which is at ~3 keV, is the peak with the highest intensity Most likely, the Ag Mα emission is a smaller peak at about 0.3 keV. Absence of Important Impurities The absence of noticeable peaks for other elements in the spectrum indicates that silver makes up the majority of the sample. Additional peaks at their distinctive energy levels would be visible if other elements (such as oxygen, carbon, or other metals) were present.

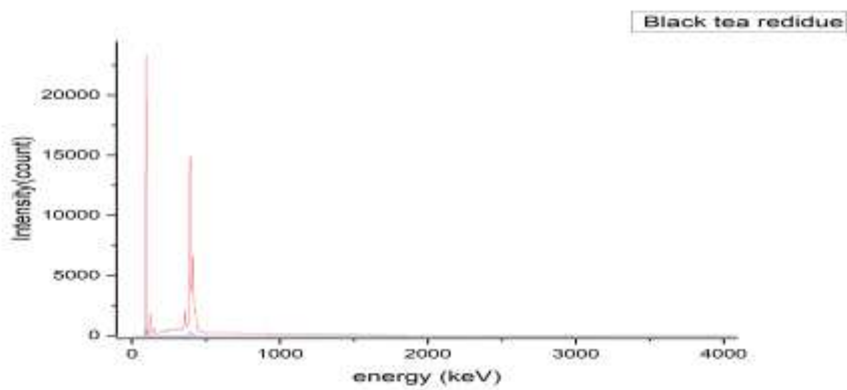

Figure 3.5. EDX spectra image of $AgNO_3$NPs

Results

Seed Germination

This study evaluated the effects of silver nanoparticles synthesized from black tea residue on the seed germination rates of *Vigna radiata*, *Triticum aestivum*, *Hordeum vulgare*, and *Brassica nigra*. High germination rates were observed in the control group and at lower nanoparticle concentrations (0.4% and 0.8%). However, germination rates declined significantly at 1.2% and 1.6% concentrations. The control group consistently showed the highest germination across all species. Notably, *Hordeum vulgare* exhibited a sharp reduction in germination at higher concentrations, and *Brassica nigra* experienced the most pronounced decline between 0.4% and 0.8%. These findings indicate that even relatively low concentrations of $AgNO_3$ nanoparticles from black tea residue can adversely affect seed germination, with effects becoming more severe as concentrations increase.

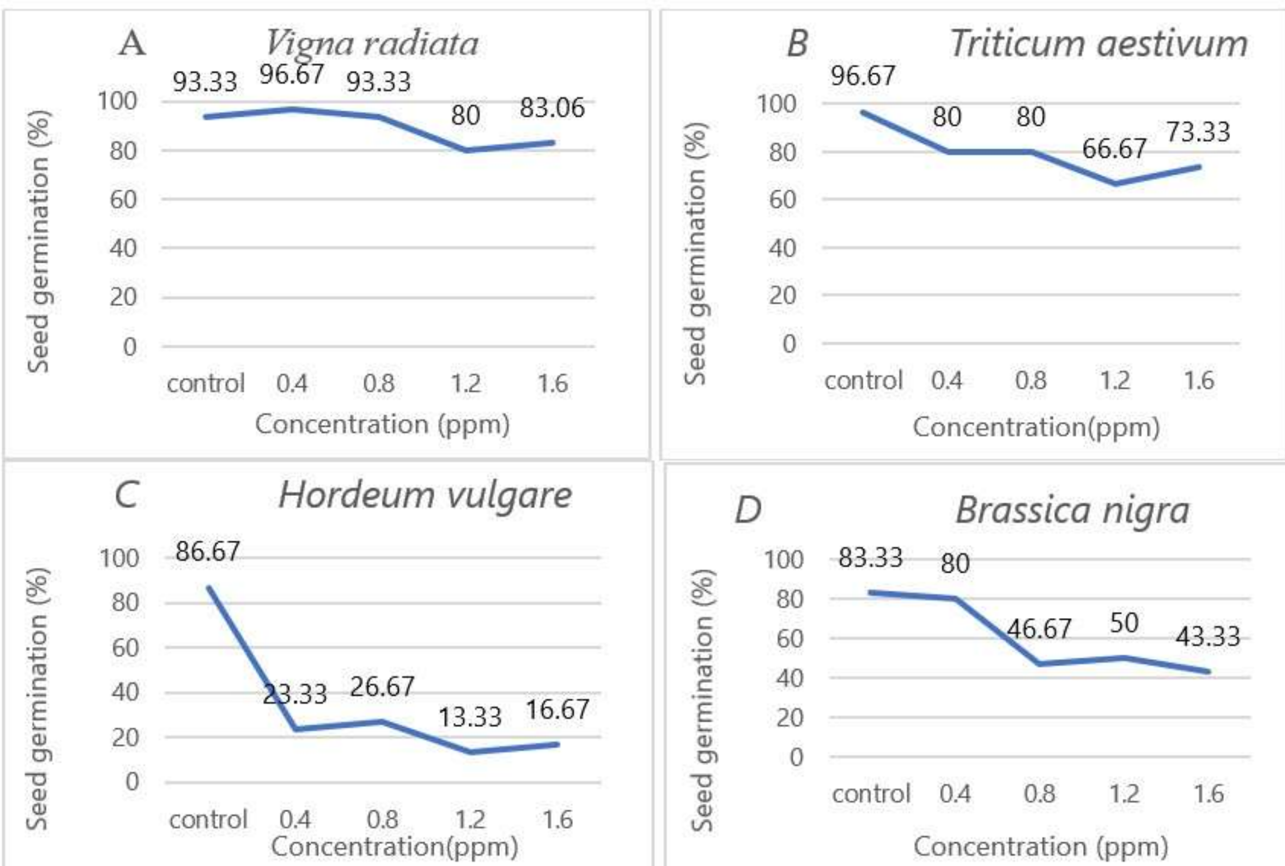

Figure (4.1) Effect of silver nanoparticles synthesized from black tea residue on seed germination (A–D).

Shoot length

The study analyzed the shoot length of plants treated with different concentrations of a $AgNO_3$ NPs black tea residue(0.4, 0.8, 1.2, 1.6 ppm) (Figure 4.2). The control group had the highest shoot length, while treatment groups (0.4% to 1.6%) showed a decrease. The control group had the highest shoot length, while treatment groups showed moderate reductions. The control group had the highest shoot length, while treatment groups showed partial recovery but still significantly lower. The results suggest that the $AgNO_3$ NPs black tea residue treatment may have a significant impact on plant growth. The y-axis shows shoot length per plant, while the x-axis shows treatment groups. Shoot length remains consistent across all treatments, with no statistically significant difference.

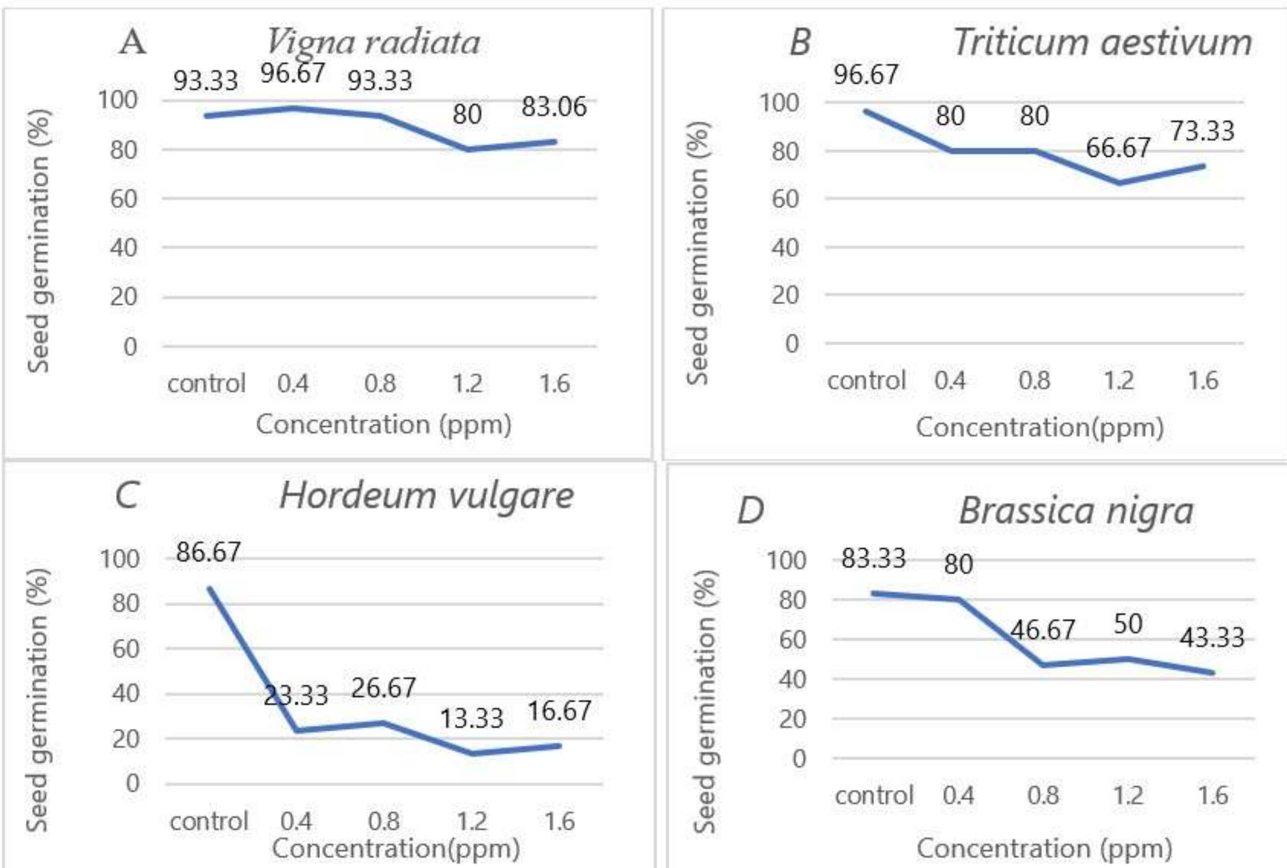

Figure (4.2) Effect of silver nanoparticles synthesized from black tea residue on shoot length (A–D).

Root length

Figure 4.3 presents the impact of silver nanoparticles derived from black tea residue on the root length of *Vigna radiata*, *Triticum aestivum*, *Hordeum vulgare*, and *Brassica nigra*. In general, the control plants maintained similar root lengths, while those treated with the nanoparticles showed a noticeable decrease. The untreated plants recorded the longest roots, whereas the treated ones exhibited a gradual reduction in length. Interestingly, the 1.2% concentration showed no significant difference from the control, but higher concentrations led to clearly reduced root growth. This pattern suggests that increasing levels of silver nanoparticles may inhibit root development. The results also indicate possible variation among samples, potentially due to biological differences or a small sample size.

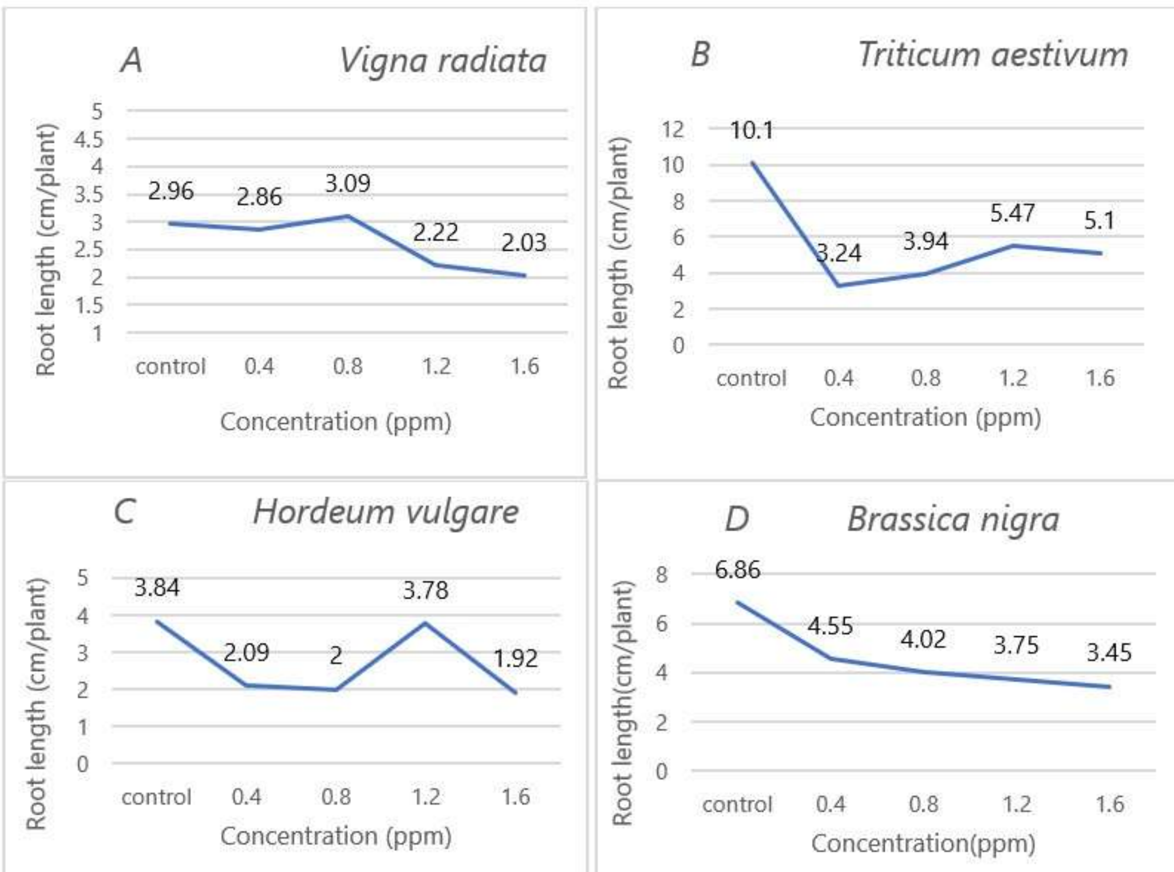

Figure (4.3) Effect of silver nanoparticles synthesized from black tea residue on root length (A–D).

Shoot dry weight

The study analyzed the shoot dry weight of various plants, including *Vigna radiata*, *Triticum aestivum*, *Hordeum vulgare*, and *Brassica nigra*. The control group showed the highest shoot dry weight, suggesting optimal growth conditions. However, varying concentrations of the ubstances led to varying results. The highest shoot dry weight was observed at 0.4% concentration, suggesting a possible stimulatory effect (Figure 4.4). The lowest shoot dry weight was observed at 0.8% concentration, suggesting no statistically significant differences among treatments. The study suggests that the concentration of the substances may have a non-linear response, with some concentrations showing significant improvements and others showing no significant difference.

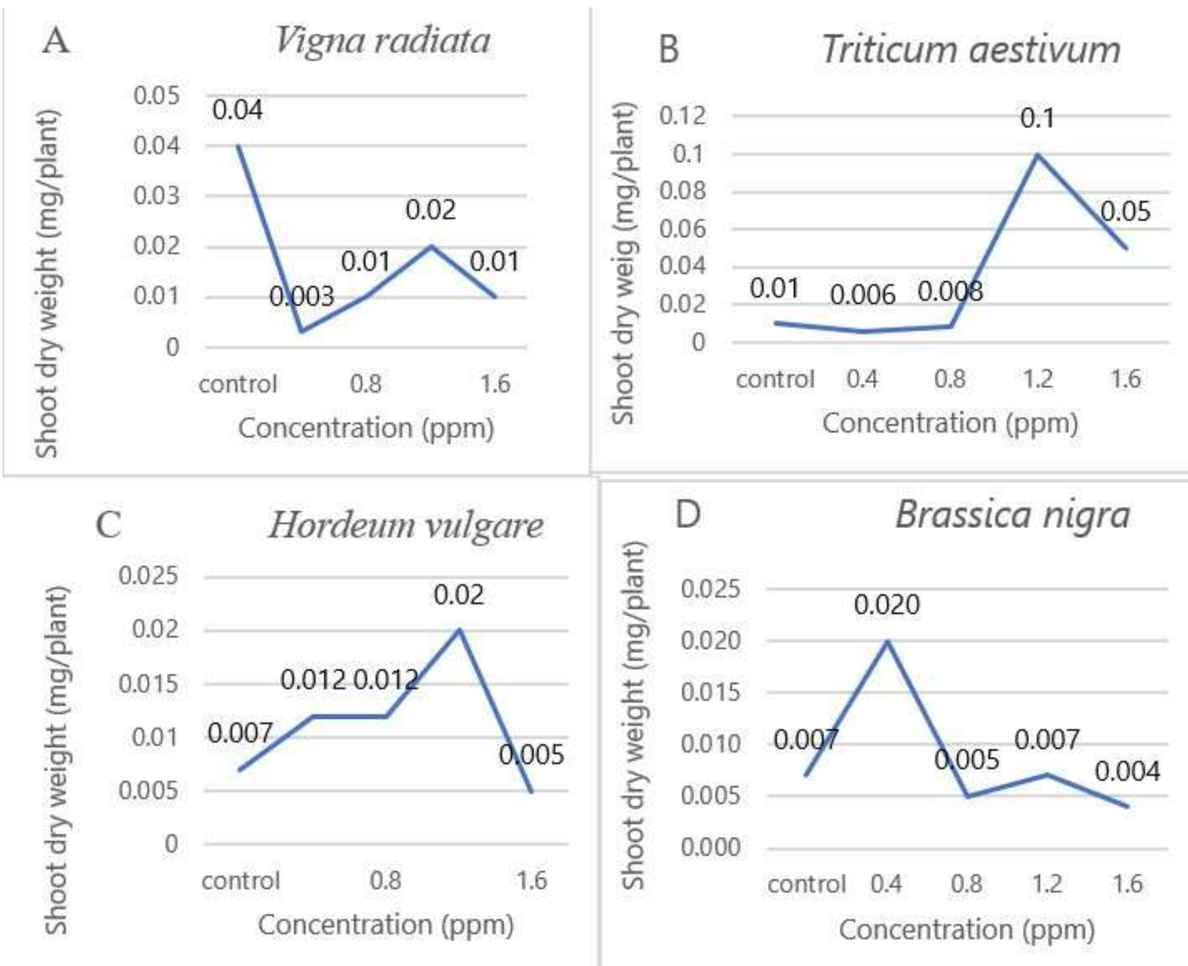

Figure (4.4) Effect of silver nanoparticles synthesized from black tea residue on shoot dry weight (A–D).

Root dry weight

The study examines root dry weight in various plants, including *Vigna radiata*, *Triticum aestivum*, *Hordeum vulgare*, and *Brassica nigra*. The control group has the highest root dry weight, while treatment groups show reduced weight. The lowest value is observed at 0.4% concentration, and from 0.4% to 1.6%, the weight slightly increases but remains significantly lower. The control group has the highest root dry weight, while treatment $AgNO_3$ NPs black tea residue groups show a gradual decline. The control group has the highest root dry weight, and all treatment concentrations show a marked decrease in root dry weight (Figure 4.5).

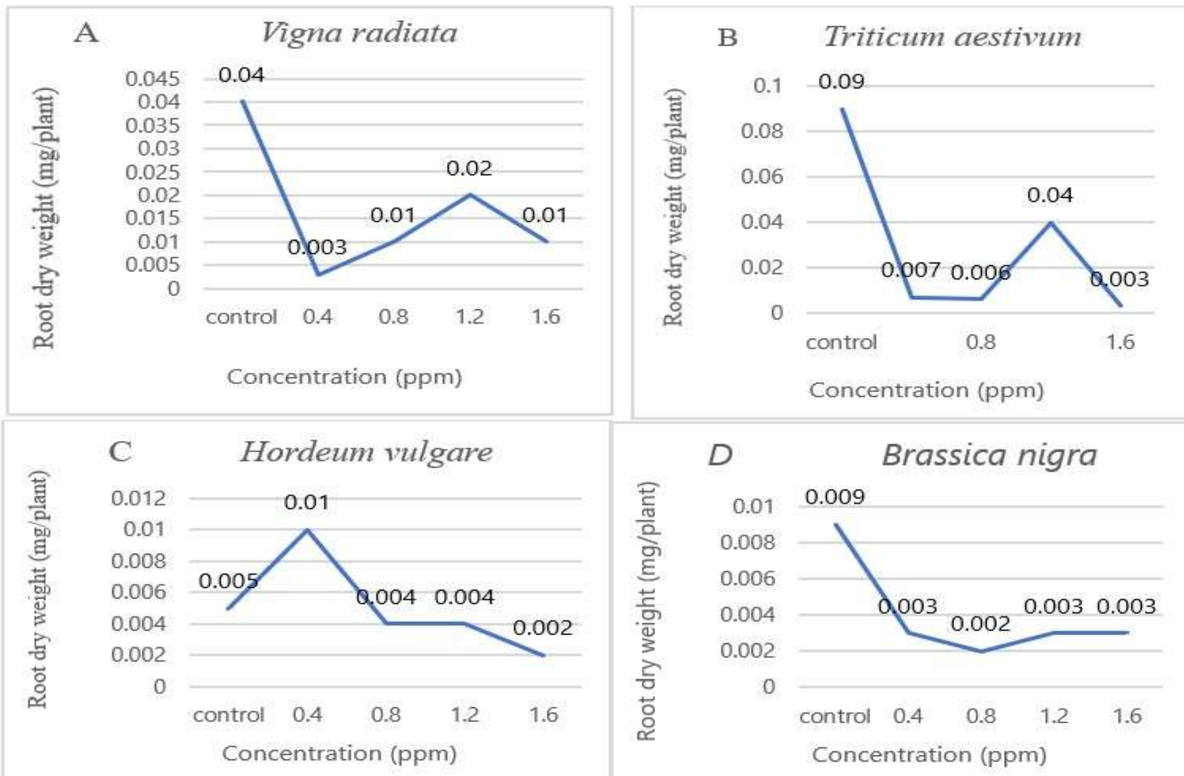

Figure (4.5) Effect of silver nanoparticles synthesized from black tea residue on root dry weight (A–D).

Discussion

Allelopathy has been extensively studied over the past five decades as a natural mechanism for weed suppression and ecological crop management [35]. Its role in sustainable agriculture has grown significantly, especially as a low-cost, organic, and environmentally restorative practice that reduces reliance on synthetic herbicides [36]. However, the complex dynamics of allopathy, particularly its interaction with crop weed competition remain only partially understood [47]. These interactions are largely mediated through allelochemicals, secondary metabolites released into the environment that influence neighboring plant species at physiological and biochemical levels [37].

The findings of the present study contribute to this field by demonstrating that silver nanoparticles (AgNPs) synthesized from black tea residue may amplify allelopathic effects. The observed reductions in germination, shoot and root development, and biomass accumulation across *Vigna radiata*, *Triticum aestivum*, *Hordeum vulgare*, and *Brassica nigra* suggest that AgNPs act as phytotoxic agents, likely through oxidative stress induction. This supports prior evidence that nanoparticles disrupt seed metabolic functions and early development by generating reactive oxygen species (ROS), leading to cell damage [38,39].

Shoot and root growth patterns across treatment concentrations reflect stress-related growth inhibition. While some species exhibited limited recovery at intermediate doses, the overall downward trend aligns with the hypothesis that nanoparticle exposure disrupts hormonal signaling and cellular communication pathways [43]. Root growth, in particular, showed higher sensitivity, which may be attributed to direct contact with nanoparticles in the soil, supporting similar observations in nanoparticle uptake studies [40].

Interestingly, the shoot dry weight exhibited a mild stimulatory response at the 0.4% concentration [36]. This suggests a potential hormetic effect, where low-level stress temporarily enhances growth by activating defense and repair pathways before toxicity prevails at higher concentrations [43, 46]. Such non-linear dose–response behavior has been documented in nanoparticle-plant interaction research and underscores the importance of dose calibration for safe application.

Root biomass, however, showed a more consistent decline across concentrations. The higher sensitivity of roots may reflect their continuous exposure to AgNPs and their role as primary sites for nanoparticle uptake and accumulation. The damage likely involves ROS overproduction, leading to membrane lipid peroxidation, protein denaturation, and compromised organelle integrity. When antioxidant mechanisms are insufficient, this cascade can trigger programmed cell death (PCD), especially in root meristems where cellular division is active [41].

These cellular-level disruptions translate into meaningful physiological outcomes, including impaired water and nutrient uptake, leading to growth retardation. The combined action of allelochemicals and AgNPs may therefore serve as an effective and targeted means of suppressing undesirable plant growth.

From a practical perspective, the use of AgNPs synthesized from black tea residue offers a sustainable bioherbicidal approach, especially during early stages of crop development when competition from weeds is most critical. Enhancing allelopathic potential through nanoparticle delivery could improve efficiency and specificity, aligning with ecological weed management strategies [42].

However, caution is necessary. The phytotoxic effects of AgNPs were found to be concentration-dependent and species-specific. Such variability indicates that blanket applications may pose risks to non-target plants or beneficial organisms. Moreover, the long-term ecological effects of nanoparticle accumulation in the soil remain uncertain. Studies are needed to assess residual toxicity, nanoparticle transformation in the soil, and interactions with soil microbiota [44].

Conclusion

This study highlights the potential of silver nanoparticles synthesized from black tea residue to enhance allelopathic effects and inhibit plant growth parameters such as seed germination, shoot and root length, and biomass. The results showed that even low concentrations can negatively impact plant development, with *Hordeum vulgare* and *Brassica nigra* being particularly sensitive.

The observed responses suggest a synergistic effect between nanoparticles and allelochemicals, offering a sustainable alternative to chemical herbicides. However, due to the variability in plant responses and possible environmental risks, further research is needed to optimize application levels and assess long-term effects.

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