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ORIGINAL PAPER

# Green Synthesis of Ag and Pd Nanoparticles using *Melia azedarach* Leaf Extract: Effects on Carbon Mineralization in Clay and Sandy Textured Soils

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**Abstract**
This study investigated the effects of green-synthesized silver (Ag) and palladium (Pd) nanoparticles (NPs) on soil carbon mineralization under controlled incubation conditions (28 °C and costant moisture for 42 days). AgNPs and PdNPs were synthesized using extracts of *Melia azedarach* L. leaves and characterized by UV-Vis spectroscopy, SEM-EDS, FTIR, and XRD analyses. The nanoparticles were applied to two different soil textures (clay and sandy) at three concentrations (10, 50 and 100 mg $kg^{-1}$) to evaluate their impacts on microbial activity through carbon mineralization measurements over 42 days. The results indicated that carbon mineralization was generally higher in clay soils than in sandy soils, with the highest mineralization rate reaching 15.43% in clay soils compared to 10.21% in sandy soils. AgNPs exhibited stronger inhibitory effects on microbial activity than PdNPs, with the highest AgNP dose (100 mg $kg^{-1}$) reducing carbon mineralization rates to 7.79% in clay soil and 7.16% in sandy soil. Conversely, the addition of *Melia azedarach* leaves and extracts enhanced mineralization, likely due to the presence of easily degradable organic compounds. This study revealed a distinct soil structure dependent pattern, in which clay fractions provide a significant buffering effect against the toxicity of biogenic nanoparticles. These results indicated that the surface coating derived from *Melia azedarach* extract interacted with clay surfaces, potentially reducing the bioavailability of nanoparticles compared with sandy soils.

**Keywords** Silver nanoparticles · Palladium nanoparticles · *Melia azedarach* · Soil microbial activity · Carbon mineralization

## 1 Introduction

The use of nanoparticles (NPs), which play a significant role in nanotechnology and are regarded as a key technology for the future, has increased significantly in recent years due to rapid advancements in various sectors (Kumari et al. 2023; Sedefoğlu 2024). NPs smaller than 100 nm exhibit a large surface area area to volume ratio and high surface energy (Khan et al. 2019; Saleh 2020; Shrestha et al. 2020; Taha et al. 2022; Nassem and Durrani 2023). NPs have been synthesized using physical methods like plasma arc, ball milling, pyrolysis, and laser desorption and chemical methods including sol-gel, chemical vapor deposition, sono-chemical precipitation, and solvothermal techniques, among others for many years (Gleiter 2000; Kumari et al. 2023; Aigbe and Osibote 2024). Physical and chemical synthesis methods have many disadvantages such as being complex and very expensive, requiring the use of toxic substances, and unsuitable for pharmacological and biomedical applications (Abid et al. 2022). More recently, with advancements in technology, biological synthesis of NPs has become feasible, utilizing biological agents in addition to these traditional methods. Biomaterials like plants, fungus, and microorganisms are used in the green synthesis of NPs; these materials serve as capping and reducing agents (Gohil et al. 2024). Green synthesis method has also become the preferred method for the researchers because it is easier to apply, relatively economical, and environmentally friendly (Hong et al. 2016; Singh et al. 2016; Annu and

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Ahmed 2018; Kizildag et al. 2019; Sedefoğlu et al. 2022; Osman et al. 2024; Shah et al. 2025). Though green-synthesized is considered an environmentally friendly approach to producing nanoparticles, it has several disadvantages (Dikshit et al. 2021). Because the chemical composition of biological extracts can vary widely, it becomes challenging to standardize the process and obtain nanoparticles with consistent properties. In addition, controlling factors such as particle size, shape, and distribution is often more difficult than in traditional chemical methods. Green synthesis can also lead to low yields, obstacles in scaling up production, and the need for extra purification steps due to remaining biomolecules. Lastly, since the reaction mechanisms are not yet fully understood, optimizing the process and ensuring reproducibility can be problematic (Fahim et al. 2024).

The increasing use of metal NPs in multiple industrial commodities has elevated the risk of environmental exposure, particularly to air, water, and soil (Collins et al. 2012a; Simonin and Richaume 2015). Among these environmental components, soil is the primary medium where NPs tend to accumulate (Xu et al. 2015; Ahmed et al. 2021). NPs can enter the soil through several pathways, including the application of sewage sludge, landfill disposal, or accidents during industrial production processes (Keller and Lazareva 2013; Keller et al. 2013).

The process by which microorganisms decompose organic matter and release carbon as $CO_2$ is known as soil carbon (C) mineralization. This process is a trustworthy measure of the activity of soil microbial communities since it is directly caused by microbial activity (Pascual et al. 2000; Rodríguez-Albarracín et al. 2025). In order to grow and obtain energy, microorganisms eat organic substrates, and the $CO_2$ they release is a reflection of both their metabolic activity and the functional dynamics of the soil ecosystem (Liang et al. 2024). According to Zhang et al. (2023), measuring carbon mineralization is a commonly used method of assessing microbial activity because it provides insight into the efficiency and rate at which bacteria utilize organic materials. Since it might be challenging to measure microbial numbers or metabolism directly, examining carbon mineralization offers a reliable but indirect approach (Bruni et al. 2025). In summary, measuring soil carbon mineralization provides important information about microbial activity and general ecosystem processes (Rieke et al. 2022). In general, the residual NPs in the soil mainly contaminate the food chain by entering the plant system (Melo et al. 2020). In addition, NPs can be integrated into plant and microbial systems, thus leading to absorption of NPs in the food chain, that subsequently threatens the quality and safety of human health (Ali et al. 2020). Many studies have reported toxic effects of NPs on microbial activity in some soils (Schlich and Hund-Rinke 2015; Zhu et al. 2019; Ali et al. 2020; Saleh 2020; Egbuna et al. 2021; Kumar et al. 2025). However, depending on the soils physicochemical properties, low concentrations of certain nanoparticles have been reported to exert negligible or stimulatory effects on soil enzymes and microbial biomass (Schlich and Hund-Rinke 2015; Shah and Belozerova 2009). These conflicting findings highlighted the need for further extensive and detailed research to elucidate the specific mechanisms and environmental factors, such as soil texture and biogenic coatings, that modulate the magnitude of NPs toxicity in diverse natural ecosystems (Szőllősi et al. 2020; Muzammil et al. 2023). Even though NPs are increasingly being researched in various fields, there is still a lack of scientific data on how NPs impact soil microbial activity (You et al. 2018). Research on soil microbial responses to NPs is increasing, but studies are often focused on specific microbial groups, particular NPs types, or controlled laboratory conditions. Consequently, the broader ecological effects particularly on microbial functions such as decomposition remain poorly understood, highlighting the need for the impacts of Ag and Pd nanoparticles to be systematically investigated in natural soil ecosystems. The response or tolerance of microorganisms in the soil to NPs will provide meaningful and valuable information on the effects of these compounds on the ecological balance. These abilities are important because the decomposition activities of microorganisms ensure the continuity of ecosystems and, therefore, the sustainability of life. In this context, understanding how soil microorganisms respond to green-synthesized Ag and Pd nanoparticles particularly in different soil textures fills an important knowledge gap and provides novel insight into how these NPs may influence key microbial processes such as carbon mineralization.

The accumulation of NPs in soil ecosystems, depending on exposure time, poses a threat to microorganisms living in the soil and may disrupt the ecological balance (Rajput et al. 2018; Kizildag et al. 2019). Texture types and organic matter contents of soils are significant parameters for soil microbial activities and also the toxicity of NPs (Simonin and Richaume 2015; Shao et al. 2022). Although the literature on nanoparticle interactions within different soil textures is limited, recent studies have highlighted the importance of soil properties in nanotoxicity (You et al. 2018; Kizildag et al. 2019; Sharma and Kumar 2024). For instance, Colman et al. (2013) reported that even low doses of AgNPs (0.14 mg $kg^{-1}$) negatively impacted bacterial community composition in sandy loam soils. Regarding metal oxide nanoparticles, You et al. (2018) demonstrated that $CeO_2$, $Fe_3O_4$, $TiO_2$, and ZnO NPs, applied at 100 and 500 mg $kg^{-1}$, significantly altered both bacterial communities and the activities of key enzymes (catalase, invertase, phosphatase, and urease) in saline-alkali and black soils. Similarly, Chai et al. (2015) observed that ZnO and $CeO_2$ NPs tested at 500 mg $kg^{-1}$ reduced thermogenic metabolism, the abundance of Azotobacter and phosphate/potassium-solubilizing bacteria, as well as overall enzymatic activities.

While the toxicity of chemically synthesized nanoparticles is well-documented, there is a significant gap in understanding how green-synthesized NPs capped with phytochemicals behave across different soil textures. Understanding whether soil components (like clay or sand) can buffer the potential toxicity of these biogenic. NPs is crucial for their safe application in agriculture. Green synthesis was selected not only for its environmental sustainability but also for the specific phytochemical coating that governs the NPs surface properties. While the impacts of conventionally synthesized nanoparticles are well documented, the interactions between biogenic surface coatings and complex soil structures remain poorly understood. This study aimed to address this gap by investigating how the interplay between NPs surface properties and soil texture influences microbial responses. Based on this gap, we hypothesized that the physicochemical properties of soil texture significantly modulate the impact of green-synthesized AgNPs and PdNPs on microbial activity. Specifically, we predicted that clay-rich soils would buffer the inhibitory effects on carbon mineralization more effectively than sandy soils, possibly due to the interaction between clay surfaces and the organic capping layer of the NPs. To test this hypothesis, the primary objective of this study was to compare the mineralization rates of C in two contrasting soil textures (clay, sandy) amended with green-synthesized AgNPs and PdNPs, thereby determining the role of soil texture in regulating nanoparticle ecotoxicity.

In the light of all these information, the aim of this study was to determine the carbon mineralization of clay and sandy textured soils at increasing doses (10, 50 and 100 mg $kg^{-1}$) of silver (Ag) and palladium (Pd) nanoparticles (NPs) green-synthesized from extract of *Melia azedarach* L. leaves, and to reveal their potential effects on the ecosystem.

There are almost no studies on the effects of NPs on carbon mineralization in Turkish soils. Since soil characteristics are known to influence the toxicity of NPs, this exploratory work is relevant due to the use of clay and sandy soils commonly found in Türkiye. This study results is significant in terms of adding contributed new data to the existing knowledge about the inhibitory effects of green synthesized AgNPs and PdNPs by monitoring carbon mineralization of microorganisms in two different soil types (clay and sandy), enabling better environmental risk assessment.

## 2 Materials and Methods

This study was carried out with the clay and sandy textured soils collected from agricultural lands of Çukurova University Balcali campus area in Adana, Türkiye. Both soils were taken from 0 to 20 cm depth after upper layer cleaning, and they were air dried and sieved with a 2-mm sieve in the laboratory conditions.

### 2.1 Green Synthesis of AgNPs and PdNPs

For the green synthesis of AgNPs and PdNPs, leaves of *Melia azedarach* L. (Meliaceae) plant naturally growing on the Çukurova University Balcalı campus was used in this study. Plant samples were washed with distilled water and dried in drying oven (60 °C and over night). 5 g of dried leaves were held in 50 ml of distilled water at about 90 °C for 60 min. The extracted materials were then centrifuged for 20 min at 4000 rpm. These extracts were used to produce NPs. Ag and PdNPs were prepared using water-soluble salts of these metals. 1 mM solutions of $AgNO_3$ and $PdCl_2$ were prepared. The NPs were produced by heating 90 mL of metal solution and 10 mL of leaves extract under reflux for 30 min at 80 °C. After then, this solution was left in the dark for 24 h. Several spectroscopic techniques were used to characterize the produced metal NPs after dried.

### 2.2 Characterization of AgNPs and PdNPs

The characterization studies of AgNPs and PdNPs carried out at Çukurova University Central Research Laboratory. The UV-Visible Spectroscopy (UV-Vis) (Agilent Carry 100 UV-Vis) were used to get the absorption spectrum of NPs. The X-ray diffraction was used to determine the crystal structure of the NPs (PANalytical, XRD). Scanning electron microscopy was used to analyze the surface morphology (FEI-SEM). FTIR examinations were used to identify the material surface functional groups. A Jasco FTIR spectrometer was used to record spectra in ATR (Attenuated Total Reflectance) mode within the 4000–400 $cm^{-1}$ range.

### 2.3 Soil Analysis

The soil texture was determined by the Bouyoucos hydrometer (Bouyoucos 1951), field capacity (%) by a vacuum pump at 1/3 atmospheric pressure (Demiralay 1993) and pH with a WTW Inolab 720 pH-meter in 1:2.5 soil-water suspension (Jackson 1958). Total organic carbon (TOC) and total nitrogen (TN) contents of soils (%) were determined by modified Walkley and Black method and Kjeldahl method, respectively (Duchaufour 1970).

### 2.4 Soil Carbon Mineralization

For carbon mineralization; three different doses (10, 50 and 100 mg $kg^{-1}$) of AgNPs and PdNPs green-synthesized from *Melia azedarach* L. leaves were mixed into the clay and sandy soils by 80% of field capacity and incubated at 28 °C for 42 days (Schaefer 1967). The leaves were air-dried, ground into powder, and mixed into the soil. To measure normal soil microbial activity in both soils, the controls

included soil with no addition of AgNPs or PdNPs, soil amended with leaves at a level equivalent to the carbon content of each soil, and soil treated with *Melia* extract.

$CO_2$ produced by microbial activity was captured in 40 ml of saturated $Ba(OH)_2$ solution placed in beakers at the center of the soil samples. The beakers were subsequently transferred to an incubator set at 28 °C for 42 days. The amount of $CO_2$ produced was measured by titration with oxalic acid (Benlot 1977). Empty vessels were used as blank. The carbon mineralization rate (%) was calculated by dividing the cumulative amount of $C(CO_2)$ produced in 42 days into total organic carbon.

### 2.5 Statistical Analysis

A Repeated Measures (General Linear Model) analysis was performed to determine the differences in carbon mineralization between the two different textured soils (clay and sandy), two NPs (AgNPs and PdNPs), and their different doses (10, 50 and 100 mg $kg^{-1}$) (Kleinbaum et al. 1998). Three replicates were used for each combined soil for statistical comparisons. Data were analyzed by a series of analyses of variance. Differences between data were assumed significant at $p<0.05$. All statistical analyses were carried out using SPSS 21.0.

## 3 Results

### 3.1 Characterization of NPs

Spectroscopic methods were used in the characterization of nanoparticles. The comparative UV-VIS spectra of AgNPs and PdNPs green-synthesized using extract of *Melia azedarach* leaves were presented in Fig. 1a. AgNPs were expected to exhibit a peak within the wavelength range of 400–450 nm according to UV-VIS, with the AgNPs showing this peak around 400 nm. The absorption band for Pd ions was generally observed at 415 nm. The absence of this peak for PdNPs provides as proof of the decrease of Pd ions (Fig. 1a).

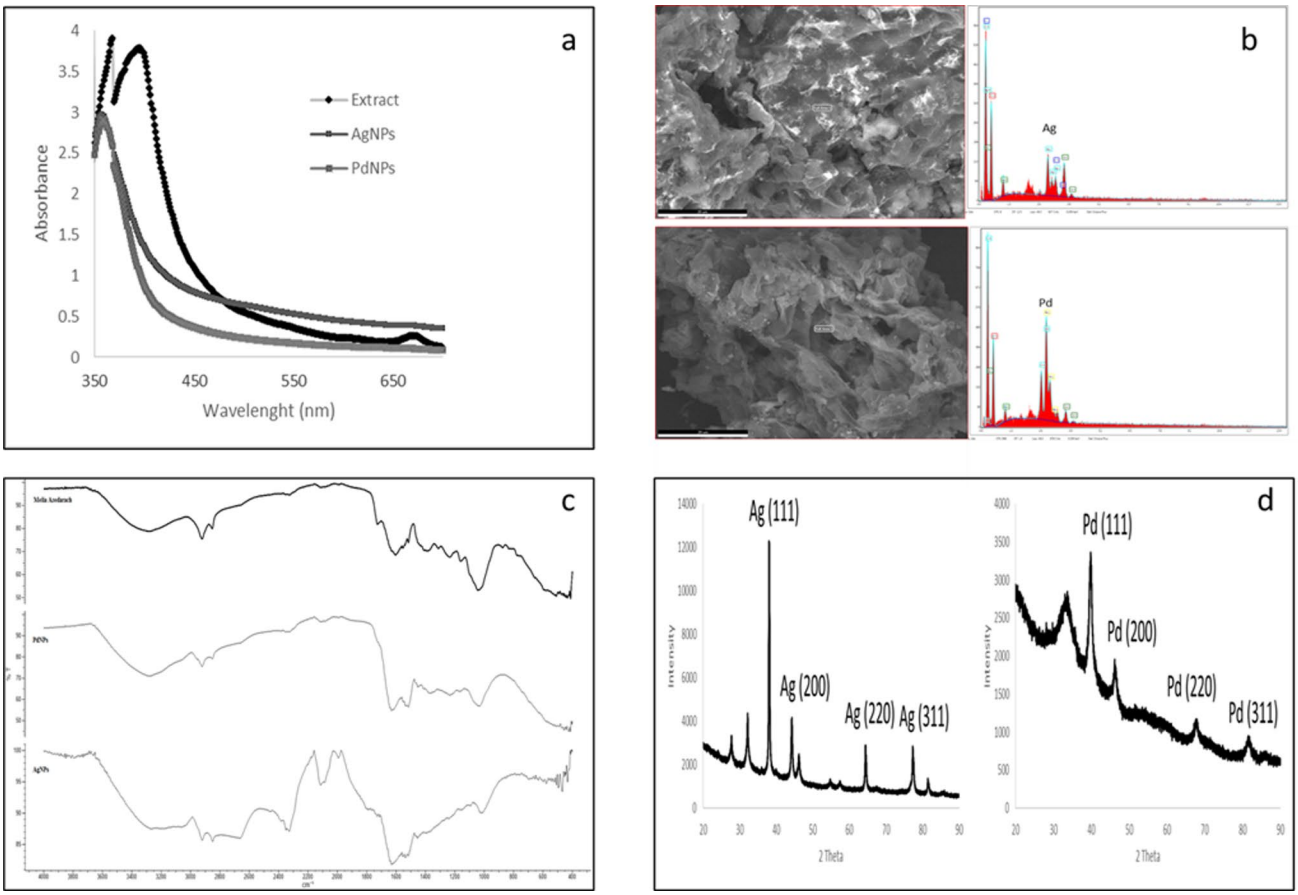



**Fig. 1** Characterization of *Melia azedarach* leaf extract and green-synthesized nanoparticles. **a** UV-Vis absorption spectra of the extract, AgNPs, and PdNPs; **b** Scanning Electron Microscopy (SEM) images with Energy Dispersive X-ray Spectroscopy (EDS) profiles; **c** Fourier Transform Infrared (FT-IR) spectra; **d** X-ray Diffraction (XRD) patterns. Abbreviations: AgNPs: Silver Nanoparticles; PdNPs: Palladium Nanoparticles; UV-Vis: Ultraviolet-Visible; SEM-EDS: Scanning Electron Microscopy-Energy Dispersive X-ray Spectroscopy; FT-IR: Fourier Transform Infrared; XRD: X-ray Diffraction

The morphological characterization of the synthesized AgNPs and PdNPs via SEM analysis confirmed their spherical structure (Hasanzadeh et al. 2021). The presence of AgNPs and PdNPs was confirmed by the presence of intense peaks corresponding to Ag and Pd, respectively, in the elemental composition analysis carried out using EDX, as illustrated in Fig. 1b. Additionally, the detection of minor peaks for elements such as carbon and oxygen was attributed to the presence of phytochemical residues associated with the particles (Patra and Baek 2016; Ramkumar et al. 2017).

The obtained FT-IR spectra exhibited fundamental vibration bands corresponding to organic functional groups (Fig. 1c). These bands include O–H stretching vibrations around 3300 $cm^{-1}$, C–H stretching vibrations associated with alkanes observed at 2917 $cm^{-1}$, and vibration bands encompassing phenolic O–H and C–O bonds around 1300 $cm^{-1}$, as well as stretching bands in the range of 1050–1025 $cm^{-1}$ (Singh et al. 2016).

The XRD pattern of the AgNPs and PdNPs were presented in Fig. 1d. As shown, diffraction peaks corresponding to AgNPs were observed at 38°, 44°, 64°, and 77°. The XRD pattern of the PdNPs exhibited five distinct reflections, typically corresponding to the (111), (200), (220), (311), and (222) planes at 40°, 46°, 68°, 81°, and 78°, respectively. These diffraction planes were clearly evident in the synthesized palladium NPs (Fig. 1d). The sharp peak observed at the Pd (111) plane indicates the high crystallinity of the PdNPs (Narasaiah et al. 2017).

### 3.2 Soil Carbon Mineralization

To investigate the potential use of green-synthesized NPs in soil applications, carbon mineralization was evaluated across two distinct soil textures (clay and sandy). The physicochemical properties of the soils are detailed in Table 1. The clay soil was characterized as a clay loam with a slightly alkaline pH of 7.85 ± 0.07. The carbon and nitrogen contents for this soil were determined as 1.83 ± 0.03 and 0.21 ± 0.01, respectively, which align with typical levels reported in the literature (Loveland and Webb 2003; Poeplau et al. 2018). In contrast, the sandy soil, classified as sandy loam with a pH of 7.55 ± 0.06, exhibited lower carbon (1.32 ± 0.02) and nitrogen (0.18 ± 0.01) contents. Consequently, the C/N ratios were calculated as 8.71 ± 0.22 and 7.33 ± 0.14, respectively.

**Table 1** Physical and chemical properties of the clay and sandy textured soils used in the experiments. Values represent mean ± standard error (SE, $n = 3$)

| | Clay Soil | Sandy Soil |
|---|---|---|
| Sand | 38.55 ± 1.12 | 65.93 ± 1.20 |
| Silt | 30.90 ± 0.82 | 12.70 ± 1.63 |
| Clay | 30.55 ± 1.84 | 22.17 ± 0.28 |
| Texture | **Clay loam** | **Sandy loam** |
| Field Capacity | 32.20 ± 0.71 | 27.20 ± 0.82 |
| pH | 7.85 ± 0.07 | 7.55 ± 0.06 |
| C (%) | 1.83 ± 0.03 | 1.32 ± 0.02 |
| N (%) | 0.21 ± 0.01 | 0.18 ± 0.01 |
| C/N | 8.71 ± 0.22 | 7.33 ± 0.14 |

AgNPs and PdNPs were green-synthesized using extract from leaves of *Melia azedarach* L. naturally grown on the Çukurova University campus in Adana city of Türkiye. The characterization of these NPs was determined, and they were added to clay and sandy soils with different organic matter contents in varying doses to assess their effects on carbon mineralization. Additionally, the leaves and extract of *Melia azedarach* were mixed into both clay and sandy soils based on their carbon-equivalent content to investigate their potential impacts on soil microorganisms.

After a 42-day incubation period, cumulative carbon mineralization was generally higher in clay soils compared to sandy soils. PdNPs application resulted in increased mineralization in both clay and sandy soils. Furthermore, the addition of the leaves and their extracts to the soils as a source of carbon led to increased mineralization in both soils after application of the extract. Higher mineralization was observed in clay control soils and soils mixed with leaves and extract compared to AgNPs treatments (Fig. 2a). Among the soils treated with AgNPs, the highest mineralization occurred in the Ag(50) mixed application (13.29 mg $C(CO_2)$/100 g soil), while the lowest mineralization was observed in the Ag(100) mixed soils (10.47 mg $C(CO_2)$/100 g soil).

It was observed that easily decomposable organic matter was rapidly utilized by microorganisms during the first 7 days, mineralization slowed between days 7–21, and then resumed a faster pace after day 21 (Fig. 2a). A significant difference was found between the control soil and all treatments at the $p < 0.05$ level, with no significant difference observed between the Ag(10) and Ag(50) treatments.

With the exception of the soil mixed with Pd(50), higher cumulative carbon mineralization was observed in the clay control, leaves and extract-amended soils compared to the Pd treatments. Statistically significant differences were found between all treatments, except for the control with Pd(10) and the leaves with Pd(50) applications ($p < 0.001$) (Fig. 2b).

As depicted in Fig. 3, the highest mineralization was observed in soils mixed with leaves (17.87 mg $C(CO_2)$). Upon examining the carbon mineralization in soils mixed with leaves and NPs (Leaves+Ag100, Leaves+Pd100), the 42-day cumulative $C(CO_2)$ values were similar to those of the control soil, with no significant differences observed. However, the differences between Ag100 and Leaves+Ag100, as well as between Pd100 and Leaves+Pd100, were statistically highly significant ($p < 0.001$).

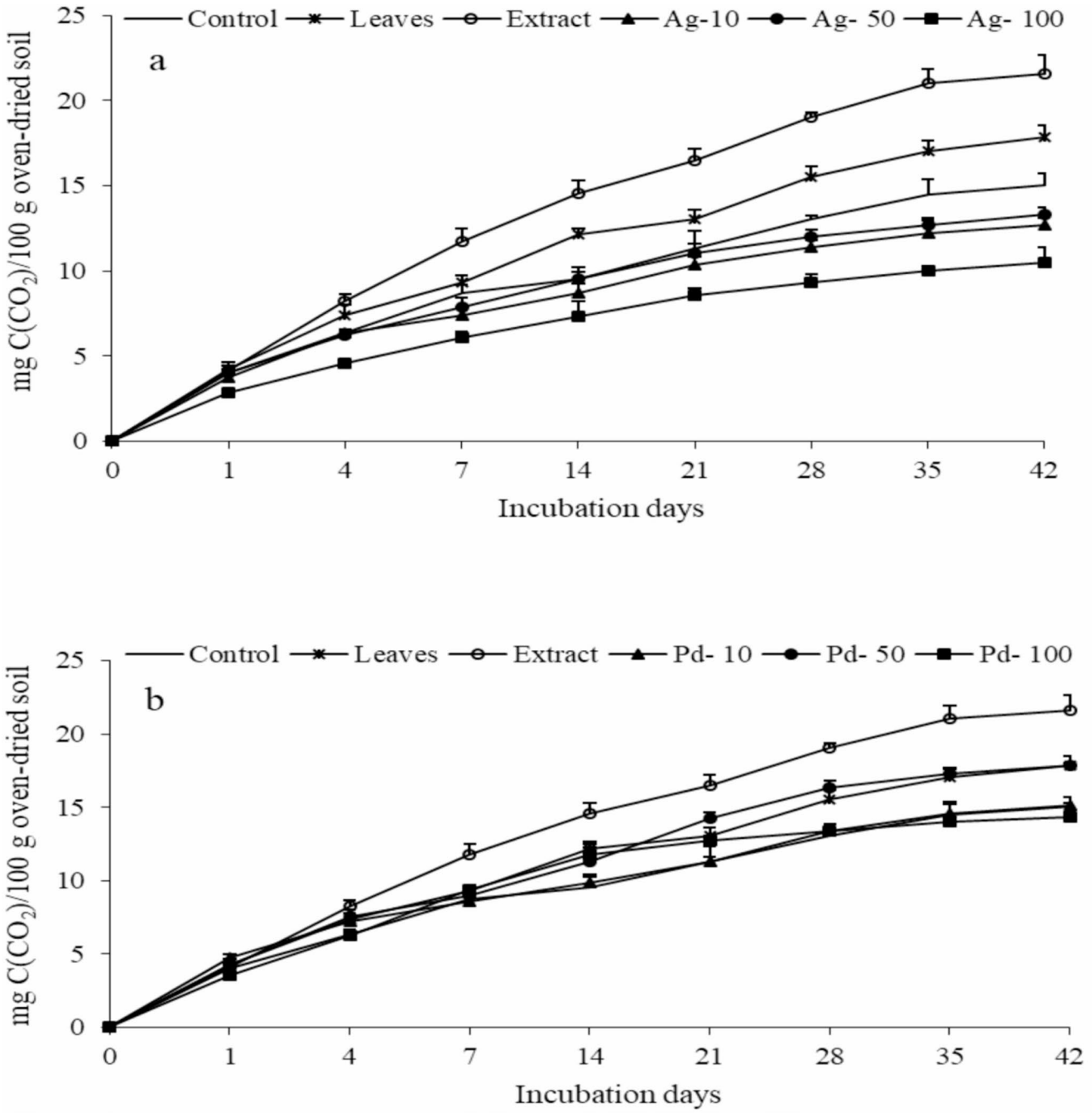



**Fig. 2** Cumulative carbon mineralization [mg $C(CO_2)$/100 g] in clay textured soils treated with *Melia azedarach* leaves, extract, and green-synthesized nanoparticles. a Effects of Silver Nanoparticles (AgNPs); b Effects of Palladium Nanoparticles (PdNPs) applied at 10, 50, and 100 mg $kg^{-1}$. Values represent mean ± standard error (SE, n = 3). Different lowercase letters above bars indicate significant differences between treatments according to Tukey's HSD test at $p < 0.05$

The highest mineralization in sandy soils (14.30 mg $C(CO_2)$) was observed in soils amended with extract of Melia leaves, while the lowest mineralization (10.04 mg $C(CO_2)$) occurred in soils with the addition of Ag(100). Additionally, higher mineralization was observed in soils mixed with extract and leaves compared to the control soils. The addition of different doses of AgNPs to the soils resulted in a reduction in mineralization, indicating the effect of NPs (Fig. 4a).

The effects of Pd nanoparticle applications on cumulative carbon mineralization in sandy soils were found to be similar, with no statistically significant differences observed between the treatments (Fig. 4b).

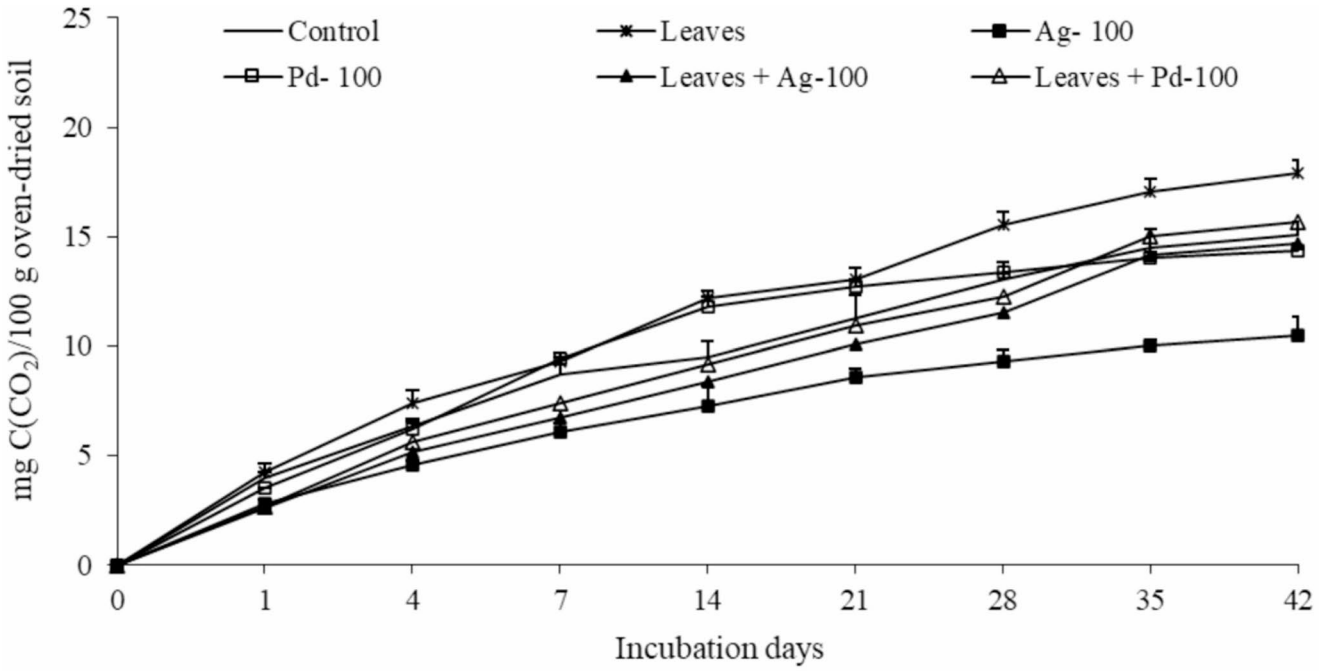



**Fig. 3** Cumulative carbon mineralization [mg $C(CO_2)$/100 g] in clay textured soils. The figure displays the comparative effects of Control, *Melia azedarach* leaves alone, nanoparticles alone (100 mg $kg^{-1}$ AgNPs and PdNPs), and their combined applications (Leaves + AgNPs; Leaves + PdNPs). Values represent mean ± standard error (SE, $n = 3$). Different lowercase letters above bars indicate significant differences between treatments according to Tukey's HSD test at $p < 0.05$

As shown in Fig. 5, higher mineralization was observed in sandy soils mixed with leaves compared to the other treatments, with a significant difference only observed between the Ag(100) application ($p < 0.01$). Additionally, no statistically significant difference was observed between the Melia leaves plus Ag(100) and Melia leaves plus Pd(100) treatments.

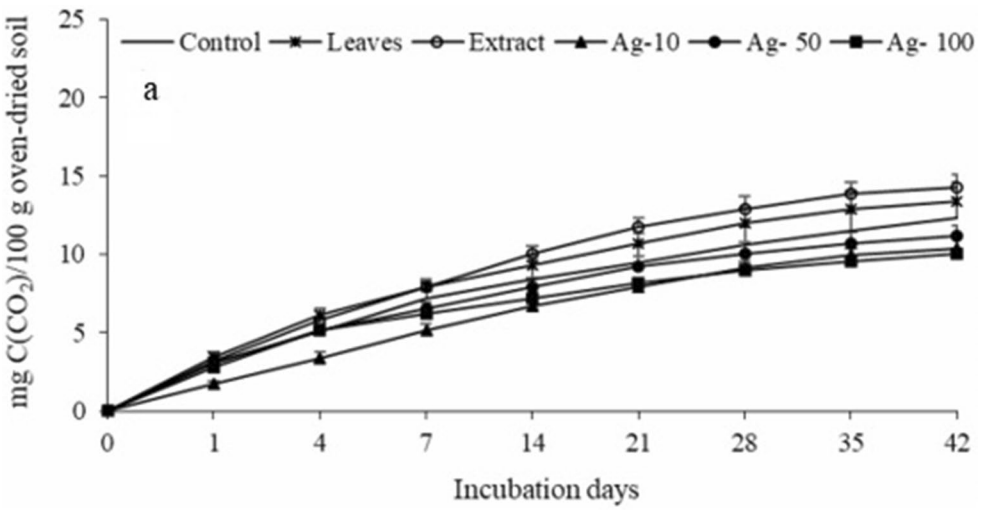
The carbon mineralization ratios of clay soils were highest in the soil amended with extract of Melia leaves (15.43%) and lowest in the Ag(100) application (7.79%) (Fig. 6a). Statistically significant differences were observed between the control soil and all other treatments, except for Pd(10), Leaves + Ag(100), and Leaves + Pd(100) ($P < 0.005$). A highly significant difference ($p < 0.001$) was found between the soil mixed with leaves and the other soils amended with extract and NPs.

When evaluating the carbon mineralization rates of Ag nanoparticle applications, a significant difference was observed between Ag(10) and Ag(100) ($P < 0.05$), whereas no statistically significant difference was found between Ag(10) and Ag(50) nanoparticle treatments. In contrast, a different pattern was observed for Pd nanoparticle applications. A significant difference was detected between soils treated with Pd(10) and Pd(50) ($P < 0.001$), while no significant difference was found in soils treated with Pd(100).

The Leaves+Ag100 application exhibited highly significant differences when compared to both the leaves and Ag(100) treatments ($p < 0.001$). Similarly, the Leaves+Pd100 application showed significant differences when compared to both the leaves and Pd(100) treatments ($p < 0.005$) (Fig. 6a). When the ratios of carbon mineralization in sandy soils were examined (Fig. 6b), the soil modified with extract showed the highest mineralization rate (10.21%), whereas the Ag(100) treatment showed the lowest rate (7.16%). No significant differences were detected among the various AgNPs concentrations (Ag(10), Ag(50), and Ag(100)). In contrast, when evaluating the PdNPs applications, a statistically significant difference was found between Pd(10) and both Pd(50) and Pd(100) treatments ($p < 0.05$) (Fig. 6b).

## 4 Discussion

The AgNPs and PdNPs used in this study were obtained by green synthesis method using *Melia azedarach* leaf extract. The investigation of the analysis performed in this context revealed that the UV results were in accordance with those of NPs produced from plant extracts that reported in the literature (Sasikala et al. 2014; Sinha et al. 2014). *Melia azedarach* leaves are rich in phenolic compounds and contain a significant number of hydroxyl, carbonyl, and carboxyl groups in their structure. According to FT-IR results, the formation of NPs led to changes in the absorption bands at 1375 $cm^{-1}$ and 3300 $cm^{-1}$, depending on the concentration



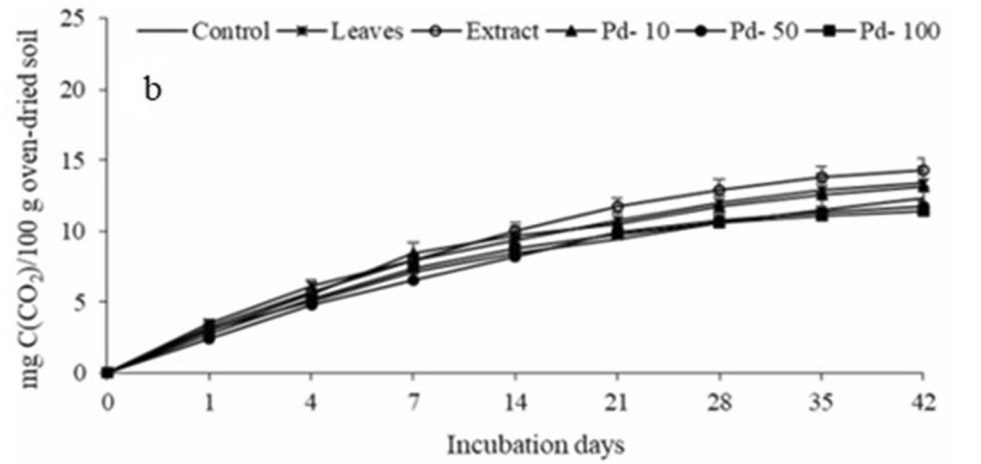




**Fig. 4** Cumulative carbon mineralization [mg $C(CO_2)$/100 g] in sandy textured soils treated with *Melia azedarach* leaves, extract, and green-synthesized nanoparticles. **a** Effects of Silver Nanoparticles (AgNPs); **b** Effects of Palladium Nanoparticles (PdNPs) applied at 10, 50, and 100 mg $kg^{-1}$. Values represent mean ± standard error (SE, $n = 3$). Different lowercase letters above bars indicate significant differences between treatments according to Tukey's HSD test at $p < 0.05$

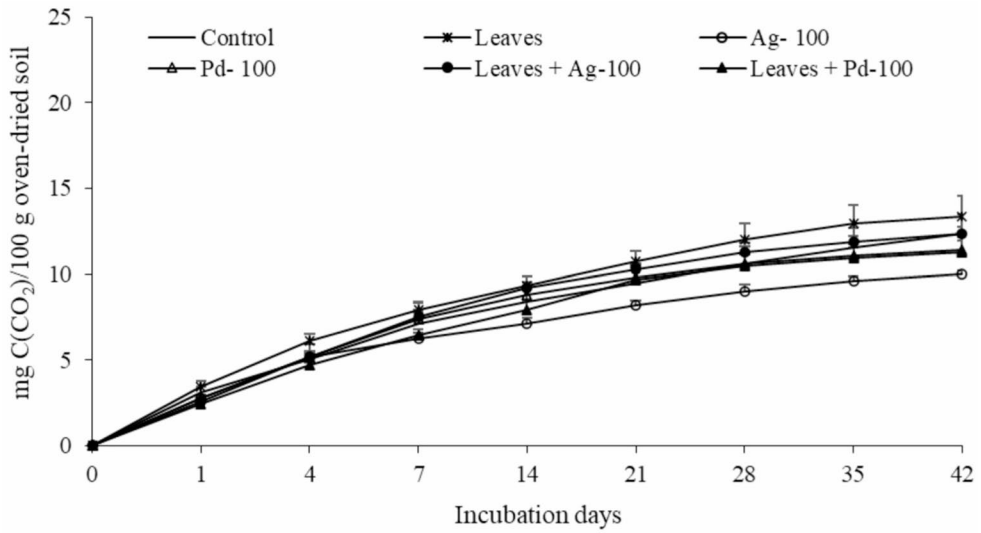



**Fig. 5** Cumulative carbon mineralization [mg $C(CO_2)$/100 g] in sandy textured soils. The figure displays the comparative effects of Control, *Melia azedarach* leaves alone, nanoparticles alone (100 mg $kg^{-1}$ AgNPs and PdNPs), and their combined applications (Leaves + AgNPs; Leaves + PdNPs). Values represent mean ± standard error (SE, $n = 3$). Different lowercase letters above bars indicate significant differences between treatments according to Tukey's HSD test at $p < 0.05$

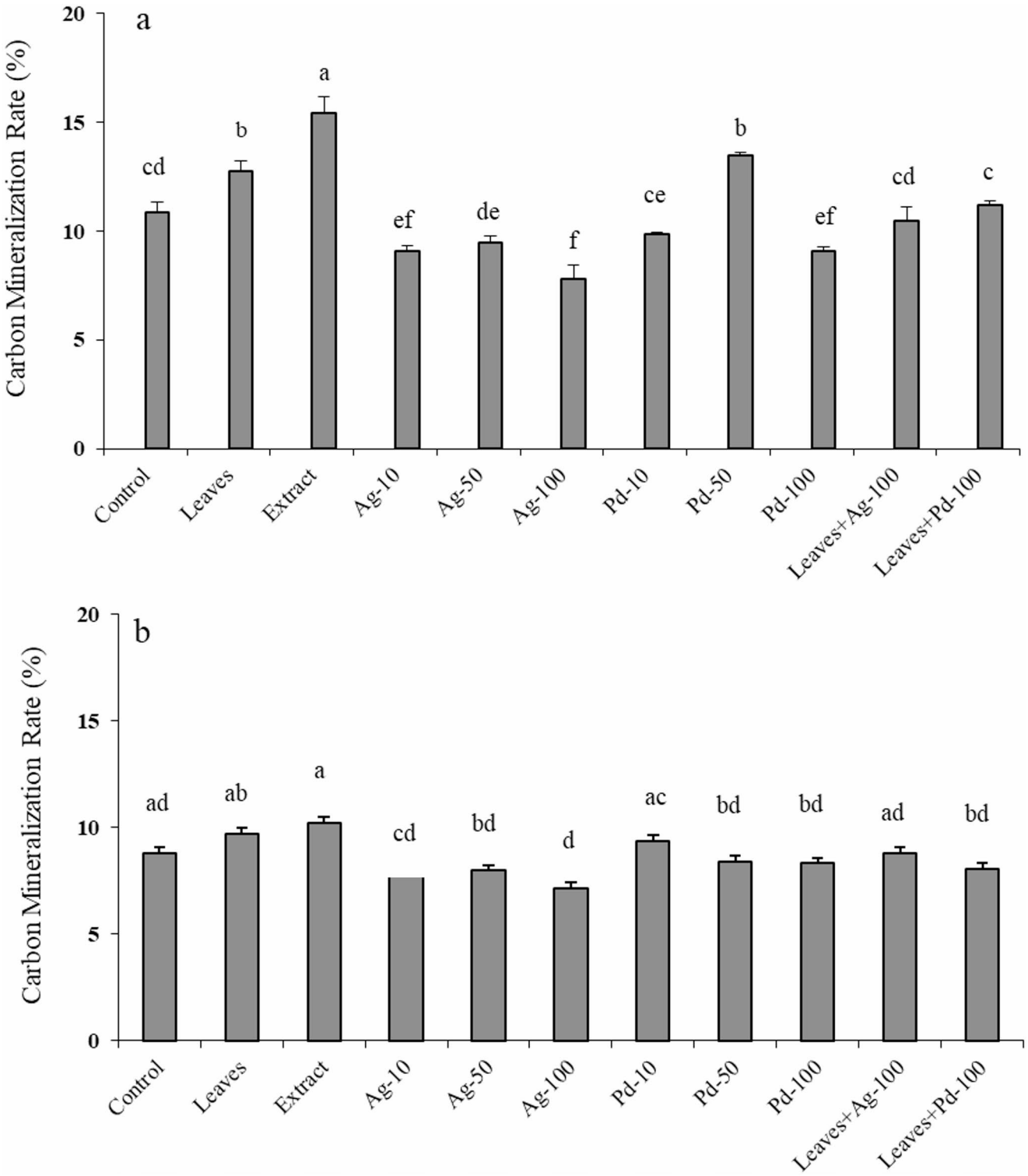



**Fig. 6** Carbon mineralization ratios in (**a**) clay and (**b**) sandy textured soils treated with *Melia azedarach* leaves, extract, and green-synthesized nanoparticles. Treatments include Control, Leaves, Extract, and varying doses (10, 50, and 100 mg $kg^{-1}$) of AgNPs and PdNPs. Values represent mean ± standard error (SE, $n = 3$). Different lowercase letters indicate significant differences between treatments according to Tukey's HSD test at $p < 0.05$

of Ag and Pd. The decrease in peak intensity at 3300 $cm^{-1}$, corresponding to O–H stretching vibrations, indicated that the hydroxyl groups of the plant extract contribute to metal ion reduction and stabilization (Akturk et al. 2019; Thakur and Gupta 2025). The high similarity between the spectra of the synthesized NPs and the plant extract suggests that the NPs were stabilized by biomolecules present in the plant, such as phenolics and carbohydrate derivatives with high hydroxyl group content (Eker et al. 2025).

The XRD results were compared with previous studies in the literature, and the findings were found to be consistent. In a previous study, it was reported that AgNPs exhibit a face-centered cubic (FCC) structure, with the diffraction peaks at 38°, 44°, 64°, and 78° corresponding to the (111), (200), (220), and (311) crystal planes, respectively (Veisi et al. 2018; Raj et al. 2018).

Numerous studies have demonstrated that NPs exhibit different physicochemical and, consequently, toxicological behaviors depending on the soil type (Cornelis et al. 2014; Schlich and Hund Rinke 2015). Factors such as pH, soil moisture, soil temperature, organic matter, and microorganism count were some of the parameters influenced by NPs. Similarly, in a study by Rahmatpour et al. (2017), NPs applied to clay soils exhibited lower toxicity than those applied to sandy soils, which was attributed to the immobilization of NPs through heteroaggregation with clay particles (Rahmatpour et al. 2017).

The PdNPs and AgNPs were added to clay and sandy soils. The application of PdNPs caused both clay and sandy soils to become more mineralized. Additionally, after the extract was applied to the soil, both soils showed increased mineralization as a result of the addition of leaves and their extracts as a carbon source. This is because the extract was in a more easily decomposable state, which makes it easier for soil microorganisms to utilize it as a source of carbon. Results indicate that copiotrophic microorganisms most likely caused a rapid carbon mineralization phase to occur during the first week of incubation, which was followed by a slower phase that was mostly carried out by an oligotrophic microbial community. While oligotrophic (autochthonous) microorganisms are largely in charge of the breakdown of more resistant organic matter when C depletion occurs due to competition among microorganisms, copiotrophic (zygomorphic) microorganisms have a tendency to multiply when readily accessible organic matter is added to the soil (Dilly 2002; Yarwood 2021; Medina et al. 2025). Unlike conventional chemically synthesized NPs which often show direct toxicity, the green-synthesized NPs used in this study exhibited a texture-dependent impact pattern. This suggests that the organic corona derived from the plant extract may interact with clay surfaces differently than bare chemical NPs, a finding that adds a new dimension to the current understanding of nanoparticle-soil interactions. Our results suggested that the natural organic coating of NPs were a key determinant of their interactions with soils of differing structure. In clay-rich soils, this layer likely enhanced interactions with clay minerals, thereby regulating nanoparticle bioavailability and potentially mitigating their toxicity. These findings underscored that surface modifications from green synthesis are a critical determinant of NPs behavior in soils and should be carefully considered in environmental risk assessments. Some studies have shown that the microbial communities responsible for decomposition were significantly susceptible to NPs (Collins et al. 2012b; Batista et al. 2017; Grün et al. 2019). Pradhan et al. (2011) studied the effects of AgNPs on leaf microbial decomposition and demonstrated that exposure to these NPs resulted in a reduction in the rate of leaf decomposition (Pradhan et al. 2011). It was known that the interaction of NPs with organic compounds, such as leaves, can limit the bioavailability of essential nutrients to microorganisms, which in turn can reduce microbial activity (Simonet and Valcárcel 2009). In this study, both NPs added to the soil with leaves were found to restrict soil microbial activity. Moreover, AgNPs toxicity in soil microorganisms was reduced by increasing the soil pH, clay content and types; however, it was not affected significantly by organic content of soil (Schlich and Hund-Rinke 2015; Zou et al. 2016; Wang et al. 2020).

## 5 Conclusions

This study confirms the hypothesis that soil texture acts as a decisive factor in modulating the toxicity of green-synthesized nanomaterials. The findings demonstrate that both silver nanoparticles (AgNPs) and palladium nanoparticles (PdNPs) exert a negative impact on soil microbial activity; however, this effect is significantly more pronounced in sandy soils compared to clay soils. The differences in carbon mineralization between soils with distinct textures may be associated with the potential of clay minerals to mitigate nanoparticle toxicity through physicochemical interactions, such as reduced bioavailability, as opposed to the sandy soil where such interactions are limited. Additionally, the toxicity of AgNPs was found to be higher than that of PdNPs, likely due to their potent antibacterial characteristics. Furthermore, soils enriched with the plant leaf extract maintained higher rates of mineralization, indicating that the biochemical composition of the synthesis medium can support microbial recovery. This study contributes to the state of the art by providing comparative evidence that soil texture is a decisive factor in modulating the toxicity of green-synthesized nanoparticles. Our findings highlight that clay fractions provide a buffering effect against biogenic NPs, a critical parameter that must be considered in future environmental risk assessments of green nanomaterials.

**Authors Contribution** Nacide Kizildag Ozdal: Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Writing – original draft, Writing – review & editing. Bahar Meryemoglu: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing. Husniye Aka Sagliker: Writing – original draft, Writing – review & editing.

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## Declarations

**Competing interests** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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