**Impacts of Nano Zinc Oxide (n-ZnO) on Soil Physicochemical Properties, Micronutrient Dynamics, and the Growth Performance of Ficus benjamina**

**ABSTRACT**

**Aims:** The study aims at investigating the impacts of nano zinc oxide (n-ZnO) on soil physicochemical properties, micronutrient dynamics, and the growth performance of *Ficus benjamina*.

**STUDY DESIGN:**  tThe study employed a completely randomized design (CRD).

**Place and Duration of Study:** Screen house experiment was set up in Institute of Ecology and Environmental Studies, Obafemi Awolowo University, Ile Ife, Nigeria. Ten concentrations of n-ZnO (0, 10, 25, 50, 75, 100, 150, 200, 250, and 300 ppm) were applied to sandy loam soils and allowed to equilibrate for two weeks. Three-week-old *Ficus benjamina* seedlings were then transplanted into the amended soils, and growth parameters were monitored biweekly over twelve weeks. Post-harvest soil samples were analyzed for pH, electrical conductivity (EC), total nitrogen (TN), organic carbon (OC), available phosphorus (P), moisture content, cation exchange capacity (CEC), and micronutrients (Fe, Mn, Cu, Zn) using standard methods.

**Results:** Results showed significant dose-dependent effects of n-ZnO on soil chemistry and plant performance. Soil pH declined from 6.5 (control) to 5.3 at 300 ppm, indicating progressive acidification. EC increased from 0.20 dS/m to 1.12 dS/m at the highest dose, suggesting ionic enrichment. TN and OC slightly increased at 10–50 ppm but declined markedly at ≥150 ppm, indicating microbial suppression. Available P peaked at 50 ppm (35 mg/kg) before falling to 7.3 mg/kg at 300 ppm. Moisture retention improved at moderate levels but declined at higher concentrations. CEC and exchangeable bases decreased at high n-ZnO doses, likely due to cation displacement. Micronutrient trends were inconsistent, with elevated Zn causing nutrient imbalances. *Ficus benjamina* showed improved growth at 10–50 ppm but experienced phytotoxicity and biomass reduction at ≥150 ppm, culminating in plant mortality at 250 ppm.

**Conclusion:** The study concludes that while moderate n-ZnO levels enhances soil fertility and plant growth, higher concentrations adversely affect soil health, nutrient dynamics and plant performance. The study recommends regulation and threshold-specific application of n\_ZnO to avoid ecological toxicity.

Key Words: **Nano Zinc Oxide,** **Soil Physicochemical Properties,** **Micronutrient Dynamics,** **Phytotoxicity,** ***Ficus benjamina***

1.0 INTRODUCTION

Nanotechnology is an emerging technology in the field of environmental management, manipulating materials at the nanoscale, with at least one dimension less than 100 nanometers for diverse applications and these engineered nanoparticles (ENPs) are increasingly used in agriculture and environmental management (Lin and Xing, 2007). Emerging research indicates that nanotechnology can support sustainable agriculture through targeted interventions that maintain soil health and improve plant resilience (Sharma *et al.*, 2016). However, their expanding and increasing usage has raised ecological concerns about their behavior, fate, and potential ecotoxicological impacts (Espinasse *et al*., 2007).

Among ENPs, nano zinc oxide (n-ZnO) is mostly used due to its distinctive physicochemical attributes, making it valuable in precision agriculture for its antimicrobial properties and as a micronutrient supplement (Sharifan and Ma, 2017; Deka, 2019). Zinc plays a crucial role in plant physiology and metal homeostasis, yet zinc deficiency remains a widespread issue, justifying zinc-based interventions (Alloway, 2004; Hansch and Mendel, 2009). Despite its agronomic promise, the ecological effects of n-ZnO in soil remain underexplored. Soils are complex and dynamic systems, and nanoparticle interactions can influence nutrient cycling, microbial communities, and micronutrient availability, potentially causing imbalances or toxicity (Huang *et al*., 2012; Khanna, 2021). Notably, most existing studies on n-ZnO focus on food crops, leaving a gap in understanding n-ZnO's impact on non-edible plants and soil micronutrient dynamics (Alsuwayyid *et al*., 2022; Akanbi-Gada *et al*., 2019),This study was therefore designed to assess the ecological effects of varying concentrations of nano zinc oxide on soil physicochemical properties, micronutrient dynamics, and the growth performance of *Ficus benjamina*, , an ornamental species with known phytoremediation potential.

2.0 MATERIALS AND METHODS

Nano Zinc Oxide (ZnO) Water Dispersion was purchased from LIWEI Nano tech Co., Ltd,. Kaohsiung City, Taiwan (mean particle size of 30 nm) and *Ficus benjamina* was used as test plant for this study and the seedling were raised at Parks and Garden Unit, Obafemi Awolowo University, Ile Ife, Nigeria (OAU). Screen-house experiment was carried-out at the Institute of Ecology and Environmental Studies, OAU. Thirty pot (Size??) were filled with 5 kg of air-dried samples soil from a relatively undisturbed natural vegetation. Ten different concentrations (0, 10, 25, 50, 75, 100, 150, 200, 250 and 300 ppm) of n-ZnO were applied to the soil samples. The soil samples were watered and left for two weeks for equilibration. Three weeks old seedlings of *Ficus benjamina* were transplanted into the pot containing different treatments in triplicates and arranged in the screenhouse using a complete randomised design. Growth parameters (height and number of leaves) were monitored fortnightly for twelve weeks. At the end of twelve weeks after planting, plants were harvested while soil analysis carried out.

All soil samples were air-dried at 20 °C before being ground and sieved through a 2 mm stainless steel sieve for determination of various parameters. Soil samples from each treatment were analyzed for their physicochemical properties. Soil pH was determined using the ASTM D 4972 method (ASTM, 2013) using a calibrated pH meter. Soil Electrical Conductivity was estimated in 1:2.5 soil: water suspension with EC meter (Jackson, 1973). Soil particle size distribution was determined using the Bouyoucos hydrometer method (Rowell, 2014). Cation Exchange Capacity (CEC) was determined following the USEPA (2000) method. Exchangeable cation was analyzed using a flame atomic absorption spectrometer. Total nitrogen was analyzed using the alkaline permanganate method (Subbiah & Asija, 1956). Organic carbon was determined using the Walkley and Black (1934) wet oxidation method. Soil moisture content was determined using the gravimetric method (ASTM, 2016). Available phosphorus was measured using the Olsen *et al*. (1954) method. The transmittance was measured at 660 nm using a spectrophotometer. Micronutrient (Fe, Mn, Cu, Zn) determination was done by the DTPA extraction method (Lindsay & Norvell, 1978; Verma *et al.,* 2022)

3.0 STATISTICAL ANALYSIS

All data collected were subjected to normality testing using the Shapiro-Wilk test. Data sets that met the assumptions of normality were analyzed using one-way analysis of variance (ANOVA). Differences between treatment means were assessed using Duncan’s Multiple Range Test (DMRT) at a significance level of p ≤ 0.05 while visualization was done using Microsoft excel (2010)

4.0 RESULTS AND DISCUSSION

4.1 SOIL PHYSICO-CHEMICAL PARAMETERS AND MICRO-NUTRIENTS BEFORE EXPERIMENT

Baseline soil properties were assessed before the experiment to establish reference values (Table 1). The soil was classified as sandy loam, consistent with earlier studies (Nwite and Alu, 2015). Key parameters included pH 6.5, organic carbon 2.6%, available phosphorus 30 mg/kg, total nitrogen 0.26%, electrical conductivity 0.22 dS/m, and moisture content 10.66%. CEC was 11.12 Cmol/kg, with exchangeable cations: K (0.31), Mg (3.73), Na (0.81), and Ca (6.9) cmol/kg. These values are typical of relatively unpolluted, fertile soils (Sesan *et al*., 2013). The high phosphorus level (>10 mg/kg) reflects good fertility status, aligning with Enwezor *et al*. (1982) and FAO (1976). Calcium and magnesium dominated the exchange complex, supporting soil fertility. Organic carbon and total nitrogen were comparatively low, as observed in similar agro-ecological settings (Landon, 1991; Nwite and Alu, 2015). Similar soils have been used in related experiments (Amin, 2011; Sesan *et al*., 2013), affirming its suitability for this study.

Micronutrient concentrations (mg/kg) were Fe (26), Mn (10.5), Cu (2.3), and Zn (0.5) (Table 1). These trace elements are essential for plant function and ecosystem health. Iron and manganese levels were within adequate ranges, supporting photosynthesis and nitrogen metabolism. (Ning *et al*., 2022; Barman *et al*., 2023). Copper supports lignin formation and enzymatic activity but may become phytotoxic at high concentrations or under poor drainage (Clemens, 2001; Wenshan *et al*., 2007).

Zinc, however, was deficient (0.5 mg/kg), falling below plant nutritional requirements (Zimmerman *et al*., 2002). Zinc is vital for auxin metabolism, enzyme regulation, and root development. Its deficiency may limit plant growth and stress resilience (Hamzah Saleem *et al*., 2022; Dhaliwal *et al*., 2022), indicating the need for Zn supplementation in the soil to sustain ecological and agronomic balance.

4.2 SOIL PHYSICO-CHEMICAL PARAMETERS AND MICRO-NUTRIENTS AFTER EXPERIMENT

Table 2 presents the soil physico-chemical parameters and soil micro-nutrients following 12 weeks of exposure to varying concentrations of nano zinc oxide (n-ZnO). The baseline (pre-experiment) properties provides a reference point for assessing shifts in soil quality due to n-ZnO treatments.

Table 1: Soil Physico-chemical properties and micro-nutrients before the Experiment

|  |  |
| --- | --- |
| Soil Physico-chemical parameters | Values |
| Ph | 6.5±0.10 |
| OC (%) | 2.6±0.30 |
| AP \*(mg/kg) | 30±0.00 |
| TN \*(%) | 0.26±0.00 |
| EC (dS m-1) | 0.22 ±0.02 |
| MOISTURE (%) | 10.6±0.00 |
| K (cmol/kg) | 0.31±0.0 |
| Mg(cmol/kg) | 3.73±0.03 |
| Ca(cmol/kg) | 6.9±0.35 |
| Na(cmol/kg) | 0.18±0.00 |
| Sand (%) | 73±0.00 |
| Silt(%) | 11±0.00 |
| Clay(%) | 16±0.00 |
|  |  |
| Soil Micro-nutrients (mg/kg) |  |
| Fe | 26±0.00 |
| Mn | 10.5±0.25 |
| Cu | 2.3±0.00 |
| Zn | 0.5±0.00 |

\*abbreviation

The particle size distribution (sand: 70–73%, silt: 11–14%, clay: 15–17%) remained largely unchanged across all n-ZnO concentrations (0–300 ppm), indicating that soil texture—mainly influenced by parent material—was not affected by short-term n-ZnO exposure. The consistent sandy loam texture across treatments suggests stable porosity, permeability, and aeration, according to Okonnokhua *et al.* (2007), soil textures are not affected by amendments. Soil pH declined significantly (p < 0.05) with increasing n-ZnO levels, from 6.5 in the control to 5.3 at 300 ppm. This acidification aligns with findings from Verma *et al*. (2022) and is attributed to Zn²⁺ release through nanoparticle oxidation and proton exchange, which increases H⁺ activity in the soil. Acidification below pH 5.5 can suppress microbial diversity and enzymatic functions critical to nutrient cycling and organic matter decomposition. Total nitrogen slightly increased at 10–50 ppm (peak: 0.27%), likely due to microbial stimulation at low doses (Al-Momani *et al*., 2024), but declined significantly (p < 0.05) at higher concentrations, dropping to 0.11% at 300 ppm, likely due to microbial suppression, particularly nitrogen-fixing organisms (Shah *et al*., 2022). Organic carbon also declined markedly from 2.7% to 1.3%, indicating reduced microbial activity and organic matter turnover. Verma *et al*. (2022) and Garcia-Gomez *et al*. (2015) similarly reported that ZnO nanoparticles disrupt microbial consortia and suppress carbon mineralization, reducing soil fertility. Available phosphorus exhibited a unimodal trend, peaking slightly at 10–50 ppm (32–35 mg/kg) before declining significantly (p < 0.05) at 75 ppm (30 mg/kg) and further at 300 ppm (7.3 mg/kg). This pattern aligns with Tarafdar & Claassen (2003) and Verma *et al*. (2022), who linked the initial increase to enhanced P mobilization at low n-ZnO levels. According to the authors, Zinc is a key structural component of phosphatase and phytase enzymes, it promotes P-mobilizing enzyme activity at low concentrations of n-ZnO, thus increasing AP. The subsequent decline at higher concentrations may result from the formation of insoluble zinc-phosphate complexes and inhibition of microbial phosphorus cycling due to excess zinc (Shemawar *et al*., 2021). Accordingly, elevated Zn levels may cause phosphate to bind with Zn²⁺, forming insoluble complexes, while also suppressing microbial activity and acidifying the soil. According to Lv *et al*. (2022) and Bala *et al*. (2019), Zn–P interactions reduce P bioavailability through ion competition and complexation. Additionally, acidification enhances P fixation with Fe and Al oxides, limiting plant P uptake and reducing biomass and root development (Huang *et al*., 2023). According to the results, n-ZnO influenced soil moisture content. Moisture increased significantly (p < 0.05) from 12.5% at 10 ppm to 13.4% at 75 ppm but declined at higher concentrations, with a marked reduction at 300 ppm, indicatin that low n-ZnO levels enhance soil structure and water retention, while higher doses cause degradation and moisture loss (Daraei *et al*., 2024). The increase may result from enhanced microbial aggregation, while the decline at 150–300 ppm likely reflects microbial inhibition and nanoparticle-induced pore space collapse (Dayo-Olagbende *et al*., 2024; Lehmann *et al*., 2020).

Changes in CEC and EC were significant (p < 0.05). EC increased from 0.20 dS/m (control) to 1.1 dS/m at 300 ppm n-ZnO, indicating enhanced ionic activity due to Zn²⁺ release and displacement of native cations (Verma *et al*., 2021). While values below 1 dS/m are not critical, levels ≥250 ppm exceeding this threshold may lead to salinization, reduced productivity, biodiversity loss, and osmotic stress in plants (Rengasamy, 2010). CEC initially increased at lower n-ZnO concentrations, consistent with Liu and Dong (2020), likely due to enhanced nutrient dynamics facilitated by the nanoparticles’ high surface area and reactivity. However, from 100 ppm upward, CEC declined, notably for Ca (6.5 to 3.8 cmol/kg), K (slight decrease), and Mg (3.5 to 2.0 cmol/kg), while Na remained stable. This suggests Zn²⁺-induced displacement of base cations, reducing nutrient availability (Verma *et al*., 2022). The overall decline in CEC reflects competitive cation exchange, weakening soil structure, buffering capacity, and fertility, while also altering microbial communities and nutrient cycling. As noted by Jones and Jacobsen (2001), CEC is a key indicator of a soil’s nutrient-holding capacity and fertility potential.

A distinct trend was observed in the concentrations of four essential soil micronutrients—Fe, Mn, Cu, and Zn—after 12 weeks of exposure to varying n-ZnO levels (Table 2). All were significantly affected by n-ZnO application (p < 0.05). Iron levels increased at lower concentrations, peaking at 75 ppm, likely due to Zn-induced rhizosphere acidification or enhanced root exudation (Rengel, 2015), but declined sharply beyond 100 ppm, dropping by 89% at 300 ppm. This pattern, consistent with Bala *et al*. (2019), may result from Zn²⁺ outcompeting Fe for binding sites, disrupting redox cycling, or altering pH, thereby reducing Fe bioavailability. Mn and Cu followed similar trends. Mn declined from 9.6 to 1.3 kg/kg and Cu from 2.0 to 1.0 kg/kg with increasing n-ZnO. The 72.9% drop in Mn and 50% drop in Cu reflect nutrient imbalances induced by excess Zn. While Cu was less affected—possibly due to its lower mobility and stronger retention—its reduction still suggests competitive interactions. As Mn and Cu are critical for oxidative stress management and enzyme activity, their depletion may impair plant metabolism and soil enzymatic function (Verma *et al*., 2001; Marschner, 2012). Soil Zn levels increased significantly (p < 0.05) from 0.35 ppm (control) to 6.9 ppm at 300 ppm n-ZnO, indicating high solubility and mobility due to the nanoparticles' large surface area and reactivity (Milani and McLaughlin, 2012; Verma *et al*., 2022; Mazhar *et al.,* 2023; ). While Zn is essential, at n-ZnO concentrations above 75 ppm exceeded agronomic thresholds, posing risks of phytotoxicity, disrupted nutrient uptake, and altered microbial activity. Nevertheless, at optimal levels, n-ZnO can enhance micronutrient availability and plant uptake (Moghaddasi *et al.,*2017; Thirugnanasambandan, 2021).

4.3 GROWTH PERFORMANCE OF *Ficus benjamina*

Figures 1 to 5 illustrate the growth response (plant height and leaf number) of *Ficus benjamina* to varying concentrations of n-ZnO over a 12-week period. All plants were transplanted from the nursery to the screen-house with similar baseline values (11 cm height, 4 leaves). By week 3, a slight increase in growth

Table 2: Soil Physico-chemical parameters at harvest

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| CONC OF n-ZnO (ppm) | Particle size (%) | | | pH | N (%) | OC(%) | AP (mg/kg) | MOISTURE(%) | EC  (dS m-1) | CEC Cmol/kg | | | | Soil micro-nutrients (mg/kg) | | | |
| Sand | Silt | Clay | - | - | - | - | - | - | Ca | K | Mg | Na | Fe | Mn | Cu | Zn |
| 0 | 72.0a | 12.0a | 16.0a | 5.55a | 0.24b | 2.75e | 27.0e | 10.95c | 0.20a | 6.55e | 0.35a | 3.55e | 0.16a | 24.90g | 9.60i | 2.00a | 0.36a |
| 10 | 72.0a | 12.0a | 16.0a | 6.5a | 0.26b | 2.70e | 32.0g | 12.75e | 0.26ab | 7.55g | 0.40a | 3.40e | 0.15a | 24.45fg | 9.55i | 2.25a | 0.74b |
| 25 | 71.0a | 13.0a | 16.0a | 6.3a | 0.25b | 2.40d | 32.0g | 12.70e | 0.29b | 7.0f | 0.40a | 3.30d | 0.15a | 24.0f | 9.30h | 2.20a | 0.95c |
| 50 | 70.0a | 13.0a | 17.0b | 6.3a | 0.27b | 2.75e | 35.0h | 12.95f | 0.36c | 6.90f | 0.55a | 3.40e | 0.16a | 26.30h | 8.70g | 2.05a | 1.40d |
| 75 | 70.0a | 14.0a | 16.0a | 6.1a | 0.24b | 2.20cd | 30.0f | 13.40g | 0.38cd | 6.30e | 0.5a | 3.55e | 0.13a | 28.15i | 6.70f | 1.60a | 1.85e |
| 100 | 70.0a | 14.0a | 16.0a | 6.0a | 0.22b | 2.0c | 28.0e | 13.0f | 0.40cd | 5.95d | 0.60a | 3.55e | 0.15a | 18.0e | 5.30e | 7.75a | 2.50f |
| 150 | 71.0a | 13.0a | 16.0a | 5.8a | 0.16a | 1.70b | 18.0d | 12.0d | 0.44d | 5.65c | 3.0a | 3.10c | 0.15a | 11.30d | 2.55d | 1.30a | 3.30g |
| 200 | 73.0a | 11.0a | 16.0a | 5.8a | 0.13a | 1.60b | 13.0c | 12.0d | 0.87e | 4.40b | 0.40a | 2.80b | 0.15a | 5.80c | 2.05c | 1.20a | 4.70h |
| 250 | 73.0a | 11.0a | 16.0a | 5.55a | 0.12a | 1.30a | 10.0b | 9.70b | 1.0f | 4.0a | 0.30a | 2.10a | 0.15a | 3.80b | 1.70b | 1.20a | 5.80i |
| 300 | 73.0a | 12.0a | 15.5a | 5.30a | 0.12a | 1.30a | 7.30a | 8.0a | 1.15g | 3.80a | 0.30a | 2.0a | 0.15a | 3.05a | 1.35a | 1.0a | 6.95j |

*Means of replicates (§ SE) followed by different letters in the same row are significantly different (p < .05) according to Duncan’s new multiple range test.*

was observed across all treatments. Maximum height (14.9 cm) occurred at 50 and 100 ppm, while the highest leaf number (8) was seen at 10–50 ppm. Growth began to decline at concentrations ≥150 ppm, indicating early signs of toxicity and suggesting that low to moderate n-ZnO levels can stimulate growth (Sun *et al*., 2022). By week 5, growth patterns diverged. Peak values (21.5 cm height, 24 leaves) were recorded at 50 ppm, with 75–150 ppm showing stable but reduced growth. In contrast, 200–300 ppm suppressed growth significantly, leading to plant mortality at 300 ppm, marking a toxic threshold (Azarin *et al*., 2022). At week 7, the growth-promoting effect of 50 ppm became more prominent, yielding the highest height (33.9 cm) and leaf count (32). Concentrations above 150 ppm showed marked inhibition, with complete mortality at 250 and 300 ppm, reaffirming 50 ppm as optimal for plant vigor. Week 9 emphasized these trends, with 50 ppm maintaining peak growth (40.8 cm, 46 leaves). Moderate growth was observed at 10–25 ppm, while concentrations above 150 ppm showed progressive decline. By week 11 (maturity stage), the 50 ppm treatment reached 50.4 cm and 56 leaves, while 25 and 75 ppm showed enhanced but lesser growth. Control plants (33.8 cm, 35 leaves) lagged behind, indicating that moderate n-ZnO supplementation improves growth over natural conditions. In week 12, signs of senescence began, with slight reductions in height across treatments, except at 50 ppm (53 cm, 64 leaves), which maintained superior growth. This supports findings by Khan and Bano (2016) and Pillai and Kottekottil (2016) that nanoparticles enhance plant development, stress tolerance, and nutrient uptake. Toxic effects persisted at 250–300 ppm with continued mortality. The study clearly shows a dose-dependent effect of n-ZnO on *Ficus benjamina*, with optimal results at 50 ppm and a beneficial range of 10–75 ppm. These findings align with those of Varma and Khanuja (2017), Raliya and Tarafdar (2013), and Srivastav *et al*. (2021), who noted that low n-ZnO levels enhance photosynthesis and soil fertility. However, concentrations ≥150 ppm inhibit growth, and ≥250 ppm result in mortality, corroborating reports by Aiken *et al. (*2011);; Liu *et al.* (2015); Dastjerdi *et al.* (2016) and Akanbi-Gada *et al*. (2019) on n-ZnO toxicity. This highlights the critical need for dose optimization in nanomaterial use in plant systems. While low to moderate levels stimulate growth, higher concentrations are phytotoxic. Priyanka *et al*. (2021) emphasized that plant response to n-ZnO depends on dose, exposure duration, and genotype.

Fig 1: Height and no of leaves at week 1 Fig 2:Height and no of leaves at week 3

Fig 3 Height and no of leaves at week 5 Fig 4 Height and no of leaves at week 7

Fig 5 Height and no of leaves at week 9 Fig 6 Height and no of leaves at week 11

Fig 7: Height and no of leaves at week 12

5.0 CONCLUSION

This study assessed the multifaceted impacts and dual roles of n-ZnO on soil quality and the growth performance of *Ficus benjamina* growth. Low concentrations (10–50 ppm) improved nutrient dynamics, while higher levels (≥100 ppm) impaired soil fertility, acidified soil, reduced CEC and organic carbon, and disrupted micronutrient balance and microbial processes. Zinc's antagonism with Fe, Mn, and Cu suggests competitive inhibition. These study also revealed that n-ZnO at lower concentration improved plant growth while at higher concentration became toxic to *F. benjamina,* highlighting that ornamental plants are also vulnerable and can serve as sensitive indicators of nanoparticle toxicity. The study emphasizes the need for a “nano-safe” threshold and sustainable nanoparticle use in environmental and agricultural applications to prevent ecological harm.

6.0 Recommendation**s**

Based on the results and conclusion, the following recommendations were drawn:

1. for sustainable soil fertility and plant productivity, n-ZnO should be applied optimum concentrations at concentrations to optimizes nutrient availability and plant response without compromising soil health.
2. applications of n-ZnO in agriculture and landscaping must incorporate ecotoxicological surveillance, risk assessments and soil monitoring protocols to mitigate toxicity.
3. targeted and judicious use of n-ZnO in agroecosystems characterized by zinc deficiency can be a strategic micronutrient intervention. However, site-specific calibration is essential.
4. There should be regulations of the use of nanoparticles to sustain environmental integrity
5. Extended studies are needed to evaluate the cumulative and residual impacts of n-ZnO on soil microbial communities, enzymatic activity, and trophic interactions under field conditions. This will better inform guidelines for its safe use in agroecology and environmental remediation.
6. *Ficus benjamina* demonstrates resilience and responsiveness to low-dose n-ZnO, therefore, urban green infrastructure developers can consider such applications application of n-ZnO ornamental horticulture, however, this must be accompanied by protocols to ensuring ecological safety.

DISCLAIMER (ARTIFICIAL INTELLIGENCE) Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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