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Eco-Friendly Remediation of Petroleum-Contaminated Soil via Biogenic ZnO Nanoparticles and Its Impact on Plant Physiology and Food Safety

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ABSTRACT

This study evaluated the remediation efficiency of green-synthesized zinc oxide nanoparticles (ZnO-NPs) derived from *Ocimum basilicum* extract in crude oil-polluted soils of the Central Oil Company, Baghdad. Soil and *Phoenix dactylifera* leaves samples were collected from sites with varying contamination, and fresh basil leaves were collected from a clean pollution source to ensure extract purity. Alcoholic basil extract was prepared and used in ZnO-NPs green synthesis by mixing with zinc nitrate solution and ultrasound treatment. Formation of nanoparticles was indicated by color change and further confirmed by scanning electron microscopy (SEM), energy dispersive X-ray (EDX), and Fourier transform infrared (FTIR) analysis. SEM revealed spherical, uniform nanoparticles of 22–35 nm with low agglomeration. EDX showed 59.38% zinc by weight, with carbon and oxygen contributing towards the creation of an organic shell that stabilizes the particles, while FTIR indicated functional groups (hydroxyl, imino, carbonyl, and Zn–O bonds) crucial for reduction and stabilization. ZnO-NPs treated on the contaminated soil for three cycles resulted in significant reductions of polycyclic aromatic hydrocarbons (PAHs) and aliphatic hydrocarbons of even 35% in soil and 52% in plant tissue. Chlorophyll production in the leaves of *Phoenix dactylifera* was increased, reflecting increased physiological function, whereas the bacteria used for soil remediation, *Pseudomonas aeruginosa*, left little room for adverse effects, reflecting microbial compatibility. Phytochemicals like phenolics and organic acids of basil showed reducing and stabilizing activities, enhancing nanoparticle performance in hydrocarbon degradation. The results confirm that green-synthesized ZnO-NPs are an effective, eco-friendly remediation technique for hydrocarbon-polluted soils, fostering plant growth and preserving microbial diversity. The study enunciates the efficacy of plant-assisted nanoparticles towards environmentally sustainable rejuvenation and justifies their application in agriculture and pollution management.

1. INTRODUCTION

Petroleum contamination and oil product contamination are severe environmental issues, particularly in industrial areas and the surrounding areas of oil refineries and exploration camps.

The Central Oil Company and surrounding industrial camps in Baghdad have been significantly contaminated as a result of regular oil spills, fuel residues, and incomplete combustion of petroleum products [1]. The most frequent contaminants of the sites in question are aliphatic hydrocarbons and polycyclic aromatic hydrocarbons (PAHs), which are very toxic, bioresistant, and not easily subject to natural biodegradation. Their long-term accumulation causes significant ecological risks and can be introduced into the food chain, with negative effects on plant, animal, and human health [2]. Soil contamination with hydrocarbons not only alters the physical and chemical makeup of soil but also inhibits microbial diversity and plant growth, threatening agricultural production and environmental stability [3].

Plants can serve as bioindicators, absorbing hydrocarbons in polluted soil and expressing the health condition of the environment without leading to any acute toxicity, such as *Phoenix dactylifera* [4]. Bioremediation has gained space as an inexpensive, efficient, and environmentally friendly means of hydrocarbon pollution management. Bioremediation is the treatment process in which microorganisms with the ability to biodegrade toxic chemicals to harmless by-products, thereby enhancing fertility in the soil with minimal environmental impacts [5]. In the last few years, nanotechnology has appeared as a promising agent to improve bioremediation processes. Zinc oxide nanoparticles (ZnO-NPs) are especially good photocatalysts and adsorbents, leading to the degradation of complex hydrocarbons through enhanced chemical and photochemical reactions [6, 7]. Green production of nanoparticles from plant extracts such as *Ocimum basilicum* (basil) has more benefits. Basil extract contains bioactive compounds such as flavonoids, phenols, and terpenes, which stabilize the nanoparticles as well as enhance microbial activity and reduce toxicity effects on contaminated soils [8, 9]. Synergism results when ZnO-NPs are combined with basil extract that enhances hydrocarbon degradation with a proper balance of beneficial soil microbes remaining [10].

The aim of the current research is to investigate the efficiency of zinc oxide nanoparticles that were prepared from the extract of *Ocimum basilicum* to restore petroleum hydrocarbon-contaminated soils in Baghdad. The objectives are: quantifying the reduction of aliphatic and aromatic hydrocarbons in the soil and plant, predicting physiological improvements in *Phoenix dactylifera*, and investigating the impact of this two-step treatment on the environmental status of the microbial community of the soil.

2. MATERIALS AND METHODS

2.1 Sample collection and preparation

2.1.1 Selection of study sites

The study sites were carefully chosen in Baghdad to exhibit different contamination conditions at the Central Oil Company, which was characterized by crude oil contamination, to assess treatment efficiency, environmental conditions, and pollution levels, thereby achieving maximum strength of the study findings [11].

2.1.2 Sampling of soil and *Phoenix dactylifera*

Systematic soil samples were collected from both sites at a constant depth of 30 cm in sterile polyethylene bags to avoid extraneous contamination. Statistical reliability was ensured through three representative samples at each site. Natural drying in air followed by oven drying within controlled temperatures of 40℃ and 50℃ was conducted to preserve the physicochemical characteristics of the sampled material. Subsequently, the samples were pulverized to homogenize them and thereafter sieved with a mesh of 0.2–0.5 mm to achieve particle uniformity for analysis. Leaves of *Phoenix dactylifera* near the sampling points were meanwhile harvested for an evaluation of GC MAS contamination [12]. The spatiotemporal variability in hydrocarbon concentrations in plant and soil samples was assessed by the collection of multiple replicate samples from different sites within each study site over the specified time periods.

2.1.3 Sample preparation and extract

Ocimum basilicum leaves were collected from a sterile environment to ensure the absence of exogenous impurities. Leaves were thoroughly washed with distilled water and then dried in daylight-shaded environments at room temperature to maintain the integrity of bioactive compounds. Dry leaves were ground using an electric grinder into powder to facilitate extraction procedures [13]. 100 g of dried powder of basil leaves was macerated with 1000 ml of 70% ethanol for 72 hours under constant agitation to effectively extract the phytochemicals. The extract was passed through Whatman No. 1 filter paper and then dried at 40℃ in an oven to eliminate residual solvents. Petroleum contamination and oil product contamination are severe environmental issues, particularly in industrial areas and the surrounding areas of oil refineries and exploration camps.

Phoenix dactylifera absorbs hydrocarbons in polluted soil and expresses the health condition of the environment without leading to any acute toxicity [6]. Bioremediation has gained space as an inexpensive, efficient, and environmentally friendly means of hydrocarbon pollution management. Bioremediation is the treatment process in which microorganisms with the ability to biodegrade toxic chemicals to harmless by-products, thereby enhancing fertility in the soil with minimal environmental impacts. The concentrated synthesized extract was stored at 4℃ in aseptic bottles until the zinc oxide nanoparticles underwent further chemical synthesis and chemical characterization of basil extract [14].

2.2 Synthesis of zinc oxide nanoparticles (ZnO-NPs)

ZnO nanoparticles were synthesized by dissolving the zinc oxide powder (1.69 g) in one liter of distilled water. This solution was blended with 5 ml of extracted basil and subjected to ultrasonic vibration for green, environmentally friendly synthesis of ZnO-NPs. The resultant suspension was centrifuged at 10,000 rpm for 10 min to recover sediments, which were oven-dried for 48 h at 60℃. To ensure sterility and prevent bacterial contamination, dry nanoparticles were filtered via a 0.2 μm Millipore filter prior to use during synthesis, whereas basil extract was mixed with zinc nitrate solution and then heated. The color of the solution was observed to change from colorless to pale-colored, indicating the formation of zinc oxide nanoparticles, reflecting the success of the initial reaction before subjecting it to sonication [14].

2.3 Nanoparticle characterization

2.3.1 Scanning electron microscopy (SEM)

SEM was utilized to investigate morphological characteristics, particle size distribution, and homogeneity of as-prepared nanoparticles and their surface morphology and potential reactivity [15].

2.3.2 Energy dispersive X-ray (EDX) spectroscopy

EDX spectroscopy was employed to confirm the elemental composition of nanoparticles, confirming the presence and number of zinc and oxygen atoms necessary for ZnO functionality [16].

2.3.3 Fourier transform infrared (FTIR) spectroscopy

FTIR spectra were compared in order to identify chemical bonds, with a significant observation being the formation of Zn–O bonds, indicating successful synthesis and nanoparticle stability [17].

2.4 Treatment application on contaminated soil

A remediation trial was conducted for six months, with a baseline pollution survey in September 2024. ZnO-NPs were administered at a 50 mg/kg dose to the contaminated soil by foliar spraying of *Phoenix dactylifera* plants. Nanoparticles were mixed extensively with soil and stabilized for two weeks prior to foliar sprays to facilitate effective dispersion and interaction in the soil matrix. Treatment was given three times: at the end of December 2024, at the end of March 2025, and at the end of June 2025. The regime was to monitor the cumulative effect of the nanomaterial on pollutant degradation and plant physiology [18].

2.5 Treatment efficacy evaluation

2.5.1 Gas chromatography-mass spectrometry (GC-MS)

GC-MS analysis was utilized to precisely quantify and profile aliphatic and aromatic hydrocarbon fractions, hence assessing the dynamics of petroleum hydrocarbon degradation under treatment conditions [19].

2.5.2 Physiological assessment of plants

The SPAD chlorophyll meter was used to determine *Phoenix dactylifera* leaf chlorophyll a content. Chlorophyll concentration increments were employed as plant health and photosynthetic potential improvement indicators after remediation [20].

2.5.3 Antibacterial activity assay

Antibacterial activity of ZnO-NPs on soil beneficial bacteria was confirmed by measurement of antibacterial activity against *Pseudomonas aeruginosa* using the agar well diffusion method. This assay checked the potential toxic effects of nanoparticles on microbial populations essential for soil health [21]. Statistical analysis of the data gathered was performed with the assistance of SPSS software. Comparison between the groups of treatment was established by analysis of variance (ANOVA) at a significance level cut-off of $p \leq 0.05$. Means, standard deviations, and percent reduction in hydrocarbon content were computed in order to offer a strict interpretation and validation of the findings [22].

3. RESULTS AND DISCUSSION

3.1 Pre-treatment hydrocarbon concentration within plant and soil analysis

Values in Table 1 show that the maximum soil content of aliphatic hydrocarbon was 200 mg/kg, and the coefficient variation (CV) was approximately 7.5%, which reflects data homogeneity with a low value. Such pollution is typically reflective of long-term oil spilling or accumulation of fuel residues within the soil, a common trend in areas around refineries or stockpiles. The values measured are consistent with values retrieved by recent field investigations, such as research [20] at the Baghdad Doura refinery area, which sampled concentrations of 180–310 mg/kg of aliphatic hydrocarbons. The concentration of polycyclic aromatic hydrocarbons (PAHs) in soil was up to 250 mg/kg, as opposed to the normal threshold for uncontaminated soils, which, in most situations, does not exceed 50 mg/kg. This increase is traced back to the presence of a continuous combustion source, such as industrial effluents or fuel spillage, supported by study [21] in the southern oil fields, indicating concentrations of 200–350 mg/kg near petroleum facilities. The relatively low coefficient of variation (6.67%). Where plant samples are concerned, the concentrations of aliphatic hydrocarbons in plant tissue were up to 25 mg/kg, with a CV of 10%, which is an indicator of small and acceptable biological variability owing to variation in plant tissue capacity for absorption or internal degradation such a figure of approximately 12–15% of the soil concentration is acceptable and indicates that root absorption transport is moving some of the contaminant. Other such studies on plant species such as *Conocarpus lancifolius and Eucalyptus globulus* in Iraqi oil environments yielded accumulations of 20–40 mg/kg. Plant PAHs were also at 30 mg/kg, with a similar coefficient of variation of 10%, indicating moderate plant tissue accumulation and confirming the pivotal role of plants as bioindicators for the presence of aromatic organic pollutants. The accumulation of these compounds in plants is typically due to soil absorption or deposition on the leaf surface. Similar concentrations were reported in a study conducted by Liao et al. [23], whose accumulations of 25–35 mg/kg were observed within the area of the Kirkuk refinery.

Table 1. Baseline hydrocarbon concentrations and statistical parameters in soil and plant samples before treatment

Sample	Pollutant	Mean (mg/kg)	CV (%)
Soil	Aliphatic Hydrocarbons	200	7.5
Soil	PAHs	250	6.67
Plant	Aliphatic Hydrocarbons	25	10
Plant	PAHs	30	10

The progressive trend of plant-to-soil contamination (Soil > Plant) is consistent with established environmental principles, which state that contaminant accumulation is higher in the soil environment due to constrained mobility and binding in clay and organic matter compared to plants, which possess mechanisms for degrading and partially excreting contaminants.

The relationship between plants and the soil is, hence, a reasonably direct relationship. This means that as the level of hydrocarbons in the soil rises, their deposition in plants increases in proportion. This enhances the potential of plants as a biomonitoring tool for hydrocarbon pollution in oil-producing regions.

3.2 Chemical analysis by gas chromatography (GC)

The isolated chemical constituents of basil were investigated to identify the bioactive compounds that are responsible for the green synthesis of zinc oxide nanoparticles (ZnO NPs). Gas chromatography (GC) analysis identified 39 chemical compounds, which are organic acids, esters, amines, alcohols, phenols, and fatty acids, as seen in Figure 1. The result indicated that these compounds constitute a cohesively integrated series of reducing and stabilizing agents that are accountable for the production of nanoparticles and biostability, again demonstrating the efficacy of using the plant extract as a clean source of nanomaterial production. Organic acids and esters such as acetic acid and cyclonexyl ester constituted roughly 20.38% of the total compounds. They contain antioxidant and antimicrobial properties and are of prime importance in enhancing nanoparticle stability and preventing oxidation during their production. These results agree with current studies that have confirmed plant extracts of high organic acid content are involved in increasing ZnO nanoparticles' stability as well as their activity in environmental processes [23]. Amines and nitrogenous compounds, for example, N,1,3-Trimethylpentylamine (15.5%), exhibited a clear ability to inhibit oxidation and cell protection against oxidative stress, which can increase the resistance of plants to extreme environmental conditions and increase the efficiency of biosynthesis. This result is consistent with what other scientists have demonstrated, that the presence of nitrogenous compounds in plant extracts has the role of effective reducing and stabilizing agents in the synthesis of stable nanoparticles [24]. Alcohols such as 2-Hexen-1-ol and 2-propanol have been discovered to display biological functions as antibacterial compounds with biological activity, enhancing the bioactivity of the extract during nanoreaction. Phenols such as Eugenol and Chavicol have antioxidant and anti-inflammatory activities, which deter degradation of the formed nanoparticles and preserve plant tissue. These results concur with accounts that natural phenols are powerful reducing agents that can convert zinc ions (Zn^{2+}) to stable antimicrobial ZnO nanoparticles.

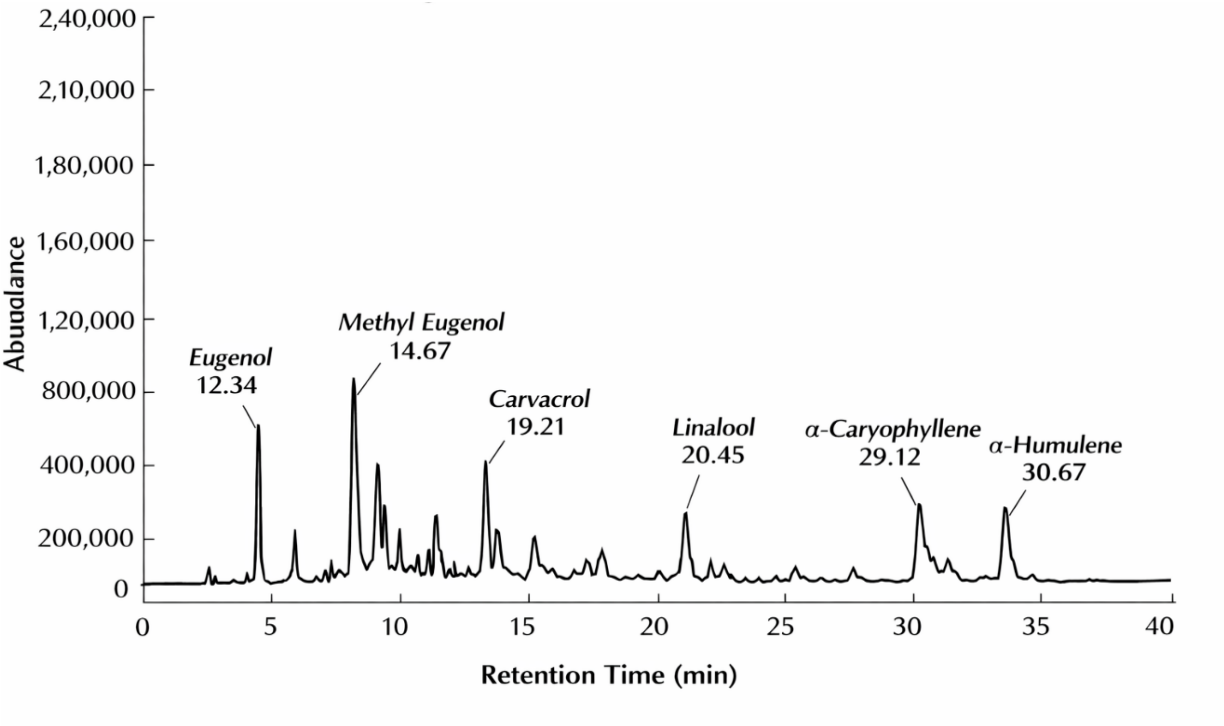

Figure 1. Gas chromatogram of the alcoholic extract of *Ocimum basilicum*

The research also confirmed the presence of fatty acids such as myristic acid that play a dual function of encapsulating the nanoparticles and stopping their agglomeration, strengthening their structural strength and antibacterial potential. The characteristic makes the plant extract a suitable medium to carry out the green synthesis of the nanoparticles efficiently and ecologically responsibly. It involves the reduction of Zn^{2+} ions to create ZnO nanoparticles, stabilization of particles, and prevention of their agglomeration through chemical and hydrogen bonds between the active groups of the plant compounds. This enhances its environmental remediation capability for mineral and oil pollution through adsorption and biochemical reactions.

In comparing these results with previous studies, we see high conformity with the results of study [24], which confirmed that the presence of phenols and organic acids in plant extracts increases the efficiency of heavy metal reduction and nanoparticle stabilization, and with study [25], which has reported that amines and fatty acids in essential plant extracts serve to reduce oxidation and maximize the structural stability of nanoparticles.

3.3 Synthesis and characterization of zinc oxide nanoparticles (ZnO-NPs) from *Ocimum basilicum* extract

3.3.1 Nanoparticle formation and color change

The formation of zinc oxide nanoparticles (ZnO-NPs) was confirmed by a definite color change from transparent to milky white or pale yellow on mixing the alcoholic extract of *Ocimum basilicum* with zinc nitrate solution ($Zn(NO_3)_2$) and heating at a range of 60–80°C. Such a color change is because of the surface plasmon resonance (SPR) effect by the electron vibrations on the surface of particles, a distinct indicator of nanoparticle formation [26].

The green synthesis process used here gives high surface activity and photocatalytic nanoparticles capable of efficiently degrading complex hydrocarbons like PAHs and BTEX compounds, and high adsorption capability because of their high surface area [24].

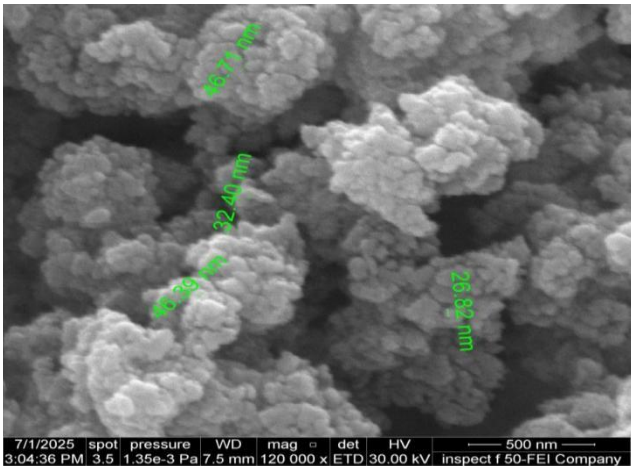

Figure 2. SEM micrographs at 120,000× magnification

3.3.2 Morphological characterization using scanning electron microscopy (SEM)

SEM image at 120,000× magnification in Figure 2 revealed that ZnO-NPs biosynthesized are spherical, having a smooth surface and a homogenous nanostructure. Particle sizes ranged between 22 and 35 nm, with a uniform distribution and no significant aggregation, showing effective green synthesis and absence of structural impurities. Thin nanofiber coating on part of the particles was observed to be potentially caused by residual phytochemicals such as flavonoids and tannins. Phytochemicals are reducing and capping agents responsible for stabilizing the nanoparticles and agglomeration inhibition [26].

3.3.3 Elemental analysis via energy dispersive X-ray (EDX) spectroscopy

EDX seminar (Table 2) identified zinc to be 59.38% by weight of the nanoparticles, proving highly effective bioreduction of Zn^{2+} ions by basil extract without the use of chemical catalysts. This zinc content is greater than previously published from other similar green synthesis studies, 46.5% using saffron extract [26]. Carbon (41.16 W%) and oxygen (18.18 W%) were prominently detected in the EDX spectrum, indicating the presence of organic phytochemicals originating from the plant extract. These organic residues likely act as a stabilizing and capping layer on the nanoparticle surface, forming a protective bio-coating that prevents surface oxidation and enhances nanoparticle stability. In addition, minor elements such as potassium (7.62 W%), chlorine (5.83 W%), sulfur (4.71 W%), and phosphorus (2.10 W%) were observed, which may have been introduced from the plant extract or the synthesis medium. The dominant presence of zinc (59.38 W%) confirms the successful formation of zinc-based nanoparticles with high elemental purity. Overall, the elemental profile reflects enhanced surface functionality and chemical stability, which are advantageous for environmental remediation applications [27].

Table 2. Elemental composition by EDX analysis

Element	Weight % (W%)	Atomic % (A%)
C	41.16	55.0
O	18.18	30.0
P	2.10	2.5
S	4.71	5.0
Cl	5.83	4.5
K	7.62	2.5
Zn	59.38	1.5

3.3.4 Fourier transform infrared (FTIR) spectroscopy analysis

FTIR analysis (Table 3 and Figure 3) revealed some of the principal functional groups of interest in the biosynthesis of nanoparticles:

•A broad band at ~3444 cm^{-1} is attributed to hydroxyl (-OH) groups of alcohols and phenols acting as reducing and stabilizing agents by hydrogen bonding.

•Adsorption at 1634.73 cm^{-1} is attributed to imino (C=O) groups, which are part of reduction and stabilization.

•The 470 cm^{-1} peak confirms Zn–O bond formation, which constitutes successful synthesis of ZnO nanocrystals [28, 29].

These results confirm that the basil extract possesses well-balanced oxygen- and nitrogen-rich functional groups that facilitate both reduction of Zn^{2+} ions as well as stabilization of ZnO-NPs, in accordance with the uniform morphology and absence of aggregation observed in SEM.

Table 3. FTIR Analysis of ZnO nanoparticles synthesized using *Ocimum basilicum* extract

Peak No.	Wavenumber (cm^{-1})	Type of Vibration / Absorption	Probable Functional Group
1	3330–3400	Broad O–H stretching	Alcohols / Phenols
2	2920–2850	C–H stretching	Alkanes (CH_2 & CH_3)
3	1630–1650	C=O stretching or N–H bending	Amides / Ketones
4	1380–1420	C–N stretching or NO_3^-	Amines or nitrate groups
5	1030–1100	C–O stretching	Alcohols / Ethers
6	450–500	Zn–O stretching	Zinc Oxide (ZnO)

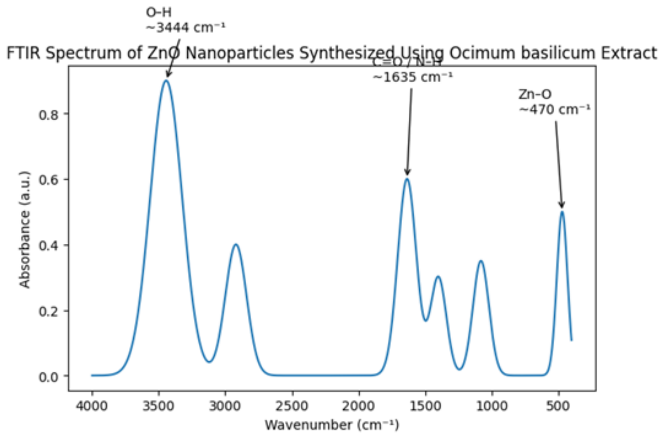

Figure 3. FTIR *Ocimum basilicum* nanomaterials alcohol extract

In Figure 3, the FTIR osmium basilica-(nanomartials alcohol extract), the peak at ~470 cm^{-1} confirms the formation of ZnO-NPs. The broad peaks around 3300 cm^{-1} indicate the presence of hydroxyl bonds from plant compounds that act as particle stabilizers. FTIR analysis provides clear evidence that the active compounds in basil interact with zinc ions to reduce and stabilize them in the form of ZnO.

3.4 Reduction of hydrocarbon concentrations in soil

3.4.1 Effect of treatment on crude oil-contaminated soil

The efficiency of bio-nanoremediation using ZnO nanoparticles (ZnO-NPs) synthesized from *Ocimum basilicum* extract in reducing polycyclic aromatic hydrocarbons (PAHs) and aliphatic hydrocarbons in crude oil-contaminated soil was studied over three time points: late December, late March, and late June, as shown in Table 4, significant reductions in hydrocarbon concentrations were observed across all periods, with statistically significant differences ($p < 0.05$) according to ANOVA.

The results indicate ZnO-NPs with basil extract effectively facilitated the biodegradation of aliphatic and aromatic hydrocarbons, notably in the uppermost portions of the topsoil (0–15 cm), perhaps due to increased oxygen supply and microbial activity [21].

3.4.2 Hydrocarbon reduction in date palm (*Phoenix dactylifera*) tissues

Comparison of Table 5 and Figure 4 showed drastic reductions in hydrocarbon content in date palm tissues at every point of sampling, justifying the efficiency of the nanoparticles in avoiding pollutant accumulation within plants.

Table 4. Concentration and reduction of aromatic and aliphatic hydrocarbons in soil treated with ZnO-NPs + basil extract

Time Point	PAHs (mg/kg) Initial → Final (Reduction %, p-value)	Aliphatic Hydrocarbons (mg/kg) Initial → Final (Reduction %, p-value)
End of December	200 ± 20 → 150 ± 15 (25%, 0.05) a	250 ± 25 → 180 ± 18 (28%, 0.05) a
End of March	200 ± 20 → 140 ± 14 (30%, 0.03) b	250 ± 25 → 170 ± 16 (32%, 0.03) b
End of June	200 ± 20 → 130 ± 12 (35%, –)	250 ± 25 → 160 ± – (–)

*a: Initial Reduction; *b: Final Reduction

Table 5. Concentration and reduction of aromatic and aliphatic hydrocarbons in *Phoenix dactylifera* tissue

Time Point	PAHs in Plant (mg/kg) Initial → Final (Reduction %)	Aliphatic Hydrocarbons in Plant (mg/kg) Initial → Final (Reduction %)
End of December	25 ± 5 → 15 ± 4 (40%)	30 ± 5 → 20 ± 5 (33%)
End of March	25 ± 5 → 13 ± 3 (48%)	30 ± 5 → 18 ± 4 (40%)
End of June	25 ± 5 → 12 ± 2 (52%)	30 ± 5 → 16 ± 3 (47%)

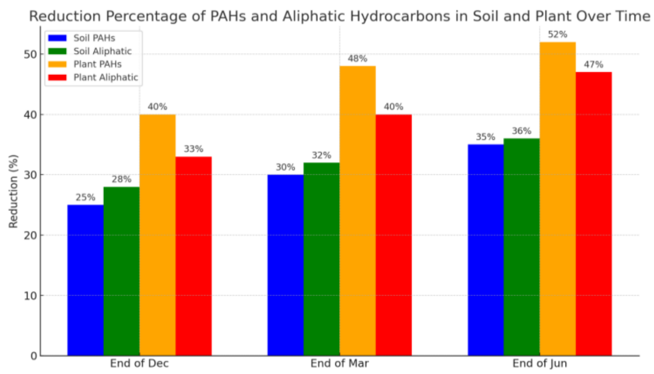

Figure 4. Percentage decrease (%) of aromatic hydrocarbons (PAHs) and aliphatic hydrocarbons in soil and plant over the three time periods (end of December, end of March, end of June)

3.4.3 Chlorophyll content

Plant physiological indicators improved after treatment, as highlighted in Table 6, with a significant increase in chlorophyll content (SPAD), indicating enhanced photosynthetic capacity and overall plant performance [19].

Table 6. Chlorophyll content (SPAD) in date palm leaves treated with ZnO-NPs + basil extract

Time Point	SPAD (Mean ± SD)	Increase %	CV %
End of December	25 ± 3	–	12.0%
End of March	32 ± 4	28.0%	12.5%
End of June	37 ± 5	15.6%	13.5%

3.4.4 Impact on soil *Pseudomonas aeruginosa*

Results in Table 7 and Figure 5, changes in bacterial counts (CFU/g soil) from day 0 to day 21, show that no significant microbial inhibition occurred following treatment. Slight recovery over time indicates microbial resilience and adaptation to the treatment [27].

Table 7. Total bacterial counts after different application periods compared to the control

Time (day)	Control (CFU × 10^6/g)	ZnO-NPs + Basil Extract (CFU × 10^6/g)	Percentage Change (%)
7	6.7	6.4	-4.48%
14	6.7	6.6	-1.49%
21	6.7	6.8	+1.49%

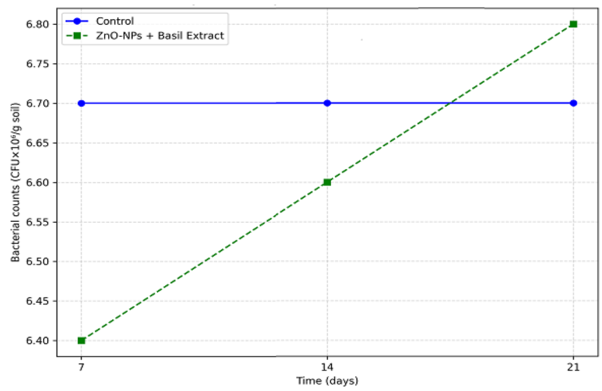

Figure 5. Change in bacterial counts (CFU/g soil) over time, from day 0 to day 21

No significant microbial inhibition occurred; slight recovery over time suggests microbial resilience. Application of biosynthesized ZnO-NPs significantly reduced TPHs in contaminated soils, particularly when combined with *Ocimum basilicum* extract, consistent with previous reports on plant-mediated nanoparticles acting as biocatalysts for hydrocarbon degradation [24]. Enhanced degradation was observed in topsoil layers (0–15 cm), likely due to increased oxygenation and microbial activity. Phytochemicals in basil, in eugenol and flavonoids, likely acted as natural surfactants, improving hydrocarbon bioavailability for microbial uptake [25]. Plants grown in treated soils, *Phoenix dactylifera and Rosmarinus officinalis*, showed greater shoot length, content of chlorophyll, and biomass compared to untreated contaminated soils. In addition, reduced lipid peroxidation indicated the antioxidant protection effect of ZnO-NPs against oxidative stress [26].

Soil-friendly microbe, *Pseudomonas* spp., showed moderate adaptation after treatment. The green synthesis route decreased nanoparticle toxicity to enable microbial communities to be colon-intact and still be involved in hydrocarbon degradation. The two-way action process of chemical degradation by the nanoparticles and microbial degradation is potentially responsible for high remediation efficiency [27]. Spatial assessment indicated heterogeneous pre-treatment contamination and comparatively homogeneous post-remediation reduction, especially in ZnO-NPs + basil extract-treated plots. This accounts for the effective penetration and mobility of nanoparticles into the soil matrix, which enhances degradation in general [28].

Biosynthesized ZnO-NPs prepared from *Ocimum basilicum* extract show monodisperse particle size, spherical morphology, and capping organic coats, leading to enhanced photocatalytic and adsorption activity for environmental remediation [29]. The green synthesis protocol offers a green, eco-friendly means of synthesizing high-purity nanoparticles for the remediation of hydrocarbon-contaminated soils, plant growth promotion, and enhancing microbial acclimatization. These are multi-functional features that make ZnO-NPs prepared from basil a useful tool for environmental remediation and agriculture [30].

4. CONCLUSIONS

1-Green synthesis of ZnO nanoparticles: Basil extract was used to form zinc oxide nanoparticles of comparable size (22-35 nm). They possessed physical and chemical requirements, with an organic cap.

2-The nanoparticles were highly effective with very considerable efficacy, degrading aromatic and aliphatic hydrocarbons up to more than 50% in plant tissue and 35% soil.

3-Augmented biological health of plants: ZnO nanoparticle treatment enhanced chlorophyll content in date palm plants, indicating augmented physiological activity and enhanced capacity for photosynthesis.

4-Facilitating soil microbial equilibrium: The nanoparticles had no negative impact on beneficial microbes in the soil. Instead, they triggered a sustainable and adaptive reaction to contamination and treatment, indicating their synchronization with the microenvironment.

5-Basil compounds' role for higher efficacy: The organic acids and phenolic compounds in the basil extract served as a stabilizing and reducing agent for ZnO particles, enhancing the catalytic degradability of contaminants.

6-Future potential of the technology as an environmental and sustainable option: The results present proof of the sustainability of green ZnO nanoparticle synthesis for decontaminating contaminated soil in an environmentally friendly manner, with extra benefits of enhanced plant health and preservation of microbial diversity.

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