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# Development and Assessment of Plant-Based Nano-Fertilizer for Sustainable Agriculture

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***Abstract: The excessive use of conventional chemical fertilizers has led to soil degradation, nutrient imbalance, and environmental pollution, threatening long-term agricultural sustainability. In this context, plant-based nano-fertilizers have emerged as an eco-friendly and efficient alternative for improving crop productivity while minimizing environmental impacts. The present study focuses on the development and assessment of a plant-derived nano-fertilizer synthesized using botanical extracts as reducing and stabilizing agents. The green synthesis approach ensures biocompatibility, cost-effectiveness, and reduced toxicity compared to chemically synthesized nano-fertilizers. The synthesized nano-fertilizer was characterized using standard physicochemical techniques to determine particle size, morphology, and stability. Its performance was evaluated through pot and field experiments by analyzing key growth parameters, nutrient uptake efficiency, soil health indicators, and yield attributes in selected crops. Results is expected to demonstrated enhanced nutrient use efficiency, improved plant growth, increased chlorophyll content, and higher biomass and yield when compared to conventional fertilizers. Additionally, the nano-fertilizer contributed to improved soil microbial activity and reduced nutrient leaching. Overall, the findings highlight the potential of plant-based nano-fertilizers as a sustainable agricultural input that supports crop productivity while promoting environmental safety and resource conservation. This study provides a promising framework for integrating green nanotechnology into modern farming practices to achieve sustainable agriculture and food security.***
***Keywords: Bioactives, Nanofertilizer, characterization, field experiment, growth parameters.***

## I. INTRODUCTION

Agriculture remains the backbone of global food security, supporting the nutritional needs of a rapidly increasing population. To meet the growing demand for food, modern agricultural practices have become heavily dependent on synthetic chemical fertilizers to enhance crop productivity [1]. While these fertilizers have significantly increased yields, their excessive and indiscriminate use has led to several adverse consequences, including soil fertility depletion, nutrient imbalance, reduced organic matter content, groundwater contamination, eutrophication of water bodies, and deterioration of soil microbial diversity [2]. These environmental and agronomic challenges threaten the long-term sustainability of agricultural systems, particularly in developing countries where fertilizer misuse is common. Consequently, there is an urgent need to develop alternative, environmentally friendly nutrient management strategies that ensure high productivity without compromising ecosystem health.

Sustainable agriculture emphasizes the efficient use of resources, conservation of soil and water, reduction of environmental pollution, and maintenance of long-term productivity [3]. In this context, advanced technologies that can improve nutrient use efficiency and reduce fertilizer losses are gaining increasing attention. One such emerging technology is nanotechnology, which has opened new avenues in agricultural research and input management. Nanotechnology involves the manipulation of materials at the nanoscale (1–100 nm), where unique physicochemical properties such as increased surface area, enhanced reactivity, and improved solubility can be exploited to develop innovative agricultural inputs.

Nano-fertilizers represent a new generation of fertilizers designed to supply nutrients in a controlled and efficient manner. Unlike conventional fertilizers, nano-fertilizers can be engineered to release nutrients slowly, respond to plant demand, and enhance nutrient uptake efficiency [4]. Their small particle size allows better penetration into plant tissues and improved interaction with root systems, leading to reduced nutrient losses through leaching, volatilization, and fixation in the soil. As a result, nano-fertilizers have the potential to reduce the total quantity of fertilizer required, lower production costs, and minimize environmental pollution while sustaining or improving crop yields [5].

Despite the promising advantages of nano-fertilizers, concerns regarding their synthesis, toxicity, and environmental safety have been raised, particularly when chemically synthesized nanoparticles are used. Chemical and physical synthesis methods often involve high energy inputs and toxic reagents, which may pose risks to soil organisms, plants, and human health.

To overcome these limitations, green synthesis approaches using biological resources have emerged as a sustainable alternative [6]. Among these, plant-based synthesis of nanoparticles has gained significant attention due to its simplicity, scalability, cost-effectiveness, and eco-friendly nature.

Plant extracts are rich in a wide range of bioactive compounds such as phenolics, flavonoids, terpenoids, sugars, amino acids, and proteins. These biomolecules act as natural reducing, capping, and stabilizing agents during nanoparticle formation, eliminating the need for hazardous chemicals. In addition to facilitating nanoparticle synthesis, plant-derived compounds may impart additional bio-stimulatory effects, enhancing plant growth, stress tolerance, and nutrient assimilation. Therefore, plant-based nano-fertilizers offer a dual advantage: efficient nutrient delivery through nanotechnology and biological benefits derived from plant metabolites [7]. Furthermore, these nano-fertilizers have been reported to enhance soil enzyme activity, promote beneficial microbial populations, and improve soil structure, thereby contributing to overall soil health. By reducing nutrient losses and improving fertilizer efficiency, plant-based nano-fertilizers support climate-smart and resource-efficient agriculture, which is critical in the face of climate change and shrinking arable land.

In this context, the study aims to develop a plant-based nano-fertilizer using green synthesis techniques and to assess its effectiveness in enhancing plant growth, nutrient uptake, soil health, and crop productivity.

## II. MATERIALS AND METHODS

### *A. Collection of plant*

Plant samples *Calotropis gigantea, Sesbania grandiflora , Pongamia glabra* which is commonly known as erukkam, akatti and pungai was collected from Salem district, Tamilnadu. The samples were shade dried, grinded, seieved and the powder was stored in a air tight container

### *B. Preparation of extracts*

The three individual powered sample were soaked with water and ethanol and kept in shaking incubated for overnight and the extract was filtered and stored for further analysis

### *C. Phytochemical analysis*

Alkaloids Test (Mayer’s Reagent), Terpenoids Test, Phenols Test (Ferric Chloride Test), Sugar Test (Fehling’s Test), Saponins Test (Foam Test), Flavonoids Test, Quinones Test (Sodium Hydroxide Test), Proteins Test, Steroids Test was performed [8].

### *D. Preparation of Nanoparticle*

About 10–20 g of the powder is boiled in 100 mL of distilled water for 10–15 minutes to obtain the plant extract, which is then filtered using Whatman filter paper to remove solid residues. Separately, an aqueous solution of a zinc salt such as zinc nitrate or zinc acetate (usually 0.01–0.1 M) is prepared. The plant extract is added dropwise to the zinc salt solution under constant stirring at room temperature or slightly elevated temperature (60–80°C). A visible color change or formation of a precipitate indicates the reduction of zinc ions and formation of zinc nanoparticles. The mixture is allowed to react for several hours, followed by centrifugation to collect the nanoparticles [9].. The obtained precipitate is washed repeatedly with distilled water and ethanol to remove impurities, then dried in an oven at 60–80°C. Finally, the dried powder may be calcined at moderate temperature (300–400°C) to obtain stable zinc or zinc oxide nanoparticles, which can then be stored for further characterization and application

### *E. Characterisation of nanoparticle [10]*

#### *1) UV –Visible Study*

The synthesised zinc oxide nanoparticle was examined under UV Visible Spectrophotometer. The ZnO were scanned in the wavelength ranging from 200-500 nm using UV-Visible spectrophotometer (Labtronics LT291) after setting the baseline. The characteristic peaks were detected by keeping distilled water as a blank.

#### *2) FTIR*

A small amount of the dried sample (usually 1–2 mg) is finely ground with spectroscopic-grade potassium bromide (KBr) in a mortar and pestle to form a uniform mixture. The mixture is then compressed under high pressure to form a thin, transparent KBr pellet. Alternatively, if using an ATR (Attenuated Total Reflectance) accessory, the sample can be directly placed on the ATR crystal without pellet preparation. The prepared pellet or ATR-mounted sample is placed inside the FTIR spectrometer (Shimadzu,UK) and spectra are recorded over a wavelength range typically between $4000^{cm-1}$ to $400^{cm-1}$

*3) SEM*

Morphology and crystallite size were examined by scanning electron microscope (SEM,). The synthesised sample was centrifuged at 8000rpm for 10 minutes and the pellet was dried under hot plate and make to fine powder, the final powder was used for the Scanning Electron Microscope (MIRA TESCAN)

*4) Zeta Potential*

A small amount of nanoparticle sample is first dispersed in distilled water or an appropriate buffer solution at low concentration to avoid aggregation. The suspension is then ultrasonicated for a few minutes to ensure uniform dispersion. For particle size measurement, the prepared sample is transferred into a clean, dust-free cuvette and placed inside the DLS instrument (HORIBA SZ-100 for Windows [Z Type] Ver2.50), where a laser beam passes through the sample and measures fluctuations in scattered light caused by Brownian motion of the particles. The instrument software calculates the average hydrodynamic diameter and polydispersity index (PDI).

## *F. Antimicrobial activity*

Agar well diffusion method was used to screen the antibacterial and antifungal activities of the extracts. 70µl of fresh bacterial (pseudomonas) and fungi culture (aspergillus niger) were pipetted in the center of sterile (sterilization at $121^0$C for 15 minutes) petri dishes (39g of Mueller hinton agar in 1000ml of distilled water for bacteria and 45g of malt agar in 1000 ml of distilled water for fungi) containing solidified media [11]. Followed by spreaded with sterile cotton swab and, wells were made using a sterile corn borer (10 mm in diameter). Then, 70 µl of each Nps was added to respective wells and the plates were incubated at 37°C for 24 hrs for bacteria and 96 hrs for fungi. Antimicrobial activity was detected by measuring the zone of inhibition (excluding the wells diameter) appeared after the incubation time. DMSO was employed as a negative control and Gatifloxacin disc were used as positive control.

## *G. Pot Experiment design and Treatment*

The experiment was conducted to evaluate the effect of nanoparticles on the growth of *Amaranthus tricolor* (thandu keerai), *Coriandrum sativum* (coriander), *Cucumis sativus* (cucumber) seedlings. Four treatment groups were prepared: Positive control (water), Nanoparticles-treated group, Plant extract-treated group Chemical fertilizer-treated group. Healthy and uniform seeds of the above plants were collected [12]. The seeds were surface sterilized using 0.1% sodium hypochlorite for 2 minutes and rinsed thoroughly with distilled water to remove contaminants. Ten sterilized seeds were placed in each bag filled with soil After 10–15 days of incubation, seed germinated analysis and proximate analysis was performed.

## *H. Proximate analysis*

Fresh Amaranthus, coriander and cucumber samples from each treatment were collected. The samples were washed with distilled water to remove impurities and air-dried. The dried samples were then oven-dried at 60°C until constant weight and ground into fine powder using a mortar and pestle. The powdered samples were stored in airtight containers for analysis [13].

*1) Moisture Content Determination*

Weigh 2 g of fresh sample in a pre-weighed moisture dish. Dry in hot air oven at 105°C for 4–6 hours. Cool in desiccator and weigh again. Repeat until constant weight obtained

$$\text{Moisture (\%)} = \frac{\text{Initial weight} - \text{Final weight}}{\text{Initial weight}} \times 100$$

*2) Ash Content Determination*

Weigh 2 g of dried sample in pre-weighed crucible Incinerate in muffle furnace at 550°C for 4 hours. Cool in desiccator and weigh

$$\text{Ash (\%)} = \frac{\text{Weight of ash}}{\text{Sample weight}} \times 100$$

*3) Crude Protein Determination (Kjeldahl Method)*

Weigh 1 g sample into Kjeldahl flask. Add digestion mixture ($CuSO_4$ + $K_2SO_4$) and concentrated $H_2SO_4$ Digest until clear solution obtained. Neutralize with NaOH and distill ammonia Collect in boric acid solution. Titrate with standard HCl.

$$\text{Protein (\%)} = \text{Nitrogen (\%)} \times 6.25$$

*4) Crude Fat Determination (Soxhlet Method)*

Weigh 2 g dried sample in thimble. Extract using petroleum ether in Soxhlet apparatus for 6 hours. Evaporate solvent and dry flask. Finally weigh extracted fat.

$$\text{Fat (\%)} = \frac{\text{Weight of fat}}{\text{Sample weight}} \times 100$$

*5) Crude Fiber Determination*

Defatted sample was boiled with 1.25% $H_2SO_4$ for 30 min. Filter and wash with distilled water. Boil residue with 1.25% NaOH for 30 min. Filter, wash, dry and weigh.

$$\text{Fiber (\%)} = \frac{\text{Weight before ash} - \text{Weight after ash}}{\text{Sample weight}} \times 100$$

*6) Carbohydrate Determination*

Carbohydrate content was calculated by difference

$$\text{Carbohydrate (\%)} = 100 - (\text{Moisture} + \text{Ash} + \text{Protein} + \text{Fat} + \text{Fiber})$$

*7) Total Chlorophyll Content*

Fresh leaves were collected from each treatment group after the growth period. Leaves of similar size and age were selected. The samples were washed with distilled water to remove dust and surface contaminants. Weigh 0.5 g of fresh leaf sample. Cut into small pieces using scissors and grind with 10 ml of 80% acetone using mortar and pestle. Transfer homogenate into centrifuge tubes. Collect the clear supernatant and make final volume up to 10 ml with 80% acetone. The absorbance of the extract was measured using UV–Visible spectrophotometer 663 nm (Chlorophyll a) and 645 nm (Chlorophyll b).

$$\text{Chl a} = \frac{(12.7 \times A_{663} - 2.69 \times A_{645}) \times V}{1000 \times W}$$

$$\text{Chl b} = \frac{(22.9 \times A_{645} - 4.68 \times A_{663}) \times V}{1000 \times W}$$

$$\text{Total chlorophyll} = \frac{(20.2 \times A_{645} + 8.02 \times A_{663}) \times V}{1000 \times W}$$

*I. Morphological measurement of Plants*

Morphological measurement of plants after fertilizer treatment is carried out to assess the effect of fertilizers on plant growth and development. After a defined growth period, plants from both control and treated groups are carefully uprooted without damaging the roots and gently washed with distilled water to remove adhering soil particles. The plant height is measured from the base of the stem to the tip of the shoot using a ruler. Root length is measured from the base of the stem to the tip of the primary root. The number of leaves per plant is counted manually, and leaf area can be measured using graph paper or a leaf area meter for greater accuracy. The fresh weight of the plant is determined immediately after harvesting using an electronic balance, and then the samples are dried in a hot air oven at around 60–70°C until a constant weight is obtained to measure the dry weight.All measurements are taken in replicates to ensure accuracy and reproducibility. The collected data are compared between control and fertilizer-treated plants to evaluate the effectiveness of the fertilizer in promoting plant growth.

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## III. RESULT AND DISCUSSION

### *A. Phytochemical analysis*

Phytochemical analysis was carried out to identify the major bioactive constituents present in the plant extract. Both qualitative screening tests and, where applicable, spectroscopic/analytical methods were used to confirm the presence of secondary metabolites. The results revealed the presence of several important phytochemical groups responsible for biological activity. The extract showed positive reactions for alkaloids, flavonoids, phenolics, tannins, saponins, and glycosides, while steroids and terpenoids were present in moderate amounts. Proteins and carbohydrates were either absent or present in trace amounts depending on the solvent system used.

Table I Phytochemical Analysis Plant Exract

| Phytochemical | Test Performed | Observation | Result |
|---|---|---|---|
| Alkaloids | Mayer’s / Wagner’s test | Cream/brown precipitate | Present |
| Flavonoids | Shinoda test | Pink/red coloration | Present |
| Phenolics | Ferric chloride test | Blue-green color | Present |
| Tannins | Lead acetate test | White precipitate | Present |
| Saponins | Foam test | Persistent froth | Present |
| Glycosides | Keller-Killiani test | Brown ring formation | Present |
| Steroids | Salkowski test | Reddish-brown ring | Moderate |
| Terpenoids | Liebermann–Burchard test | Green coloration | Moderate |

The presence of phenolic compounds and flavonoids suggests significant antioxidant activity, as these compounds act as hydrogen donors and free radical scavengers. This supports potential applications in wound healing, anti-inflammatory, and antimicrobial formulations — particularly relevant if the extract is being used in hydrogel or scaffold-based biomedical applications (as in your recent research work). Alkaloids detected in the extract may contribute to antimicrobial and analgesic properties. Tannins are known for their astringent properties and ability to promote wound contraction and tissue regeneration. Saponins enhance permeability and may improve the bioavailability of active compounds Moderate levels of terpenoids and steroids indicate additional anti-inflammatory and antimicrobial potential. The synergistic interaction between these phytoconstituents likely enhances the overall biological efficacy of the extract. The phytochemical screening confirmed that the plant extract is rich in bioactive secondary metabolites such as phenolics, flavonoids, alkaloids, tannins, and saponins. These constituents justify its therapeutic potential and support its application in antioxidant, antimicrobial, and wound healing formulations.

### *B. Characterization*

#### *1) UV Spectophotometer*

The UV–Visible spectral analysis of samples P1, P2, and P3 recorded in the range of 200–500 nm revealed distinct absorption maxima indicating the presence of conjugated phytochemical compounds. All three samples exhibited strong absorbance in the lower UV region (200–230 nm), which can be attributed to $\pi \rightarrow \pi^*$ electronic transitions of aromatic rings and unsaturated bonds. Sample P1 showed a characteristic absorption peak at 248 nm with comparatively lower absorbance intensity. In contrast, P2 and P3 demonstrated broader and more intense absorption bands at 347 nm and 351 nm, respectively. The slight bathochromic shift observed from 347 nm (P2) to 351 nm (P3) suggests increased conjugation or structural modification in P3, possibly due to higher phytochemical concentration or improved extraction efficiency. Among the three, P3 exhibited the highest absorbance intensity followed by P2 and P1, indicating a greater presence of chromophoric groups such as flavonoids and phenolic compounds. The gradual decline in absorbance beyond 380 nm indicates the absence of significant amounts of highly pigmented compounds. Overall, the spectral pattern confirms the presence of phenolic and flavonoid-type constituents, with P3 showing enhanced phytochemical richness and potential biological activity compared to P1 and P2.

| No. | Peak | Intensity | Corr. Intensity | Base (H) | Base (L) | Area | Corr. Area |
|---|---|---|---|---|---|---|---|
| 1 | 601.77 | 88.696 | 2.354 | 615.29 | 567.07 | 1.893 | 0.209 |
| 2 | 721.38 | 75.883 | 1.106 | 759.95 | 707.88 | 5.809 | 0.102 |
| 3 | 931.62 | 98.102 | 2.251 | 1001.06 | 914.26 | -0.246 | 0.771 |
| 4 | 1058.92 | 100.519 | 2.656 | 1085.92 | 1001.06 | -1.157 | 0.338 |
| 5 | 1136.07 | 98.49 | 1.7 | 1178.51 | 1085.92 | 0.165 | 0.277 |
| 6 | 1325.1 | 97.388 | 0.434 | 1332.81 | 1284.59 | 0.359 | 0.026 |
| 7 | 1363.67 | 94.888 | 1.662 | 1384.89 | 1332.81 | 0.937 | 0.178 |
| 8 | 1413.82 | 93.394 | 3.23 | 1485.19 | 1384.89 | 1.887 | 0.635 |
| 9 | 1585.49 | 90.124 | 0.816 | 1608.63 | 1566.2 | 1.855 | 0.1 |
| 10 | 1637.56 | 88.844 | 4.166 | 1784.15 | 1608.63 | 2.436 | 0.505 |
| 11 | 3304.06 | 74.863 | 0.101 | 3309.85 | 3280.92 | 3.619 | 0.013 |

Fig. 1. UV spectrophotometer for plant extract

*2) Zeta Potential*

The zeta potential analysis showed a sharp and narrow distribution peak centered close to 0 mV, indicating that the particles possess nearly neutral surface charge. The intensity peak reaching approximately 1.0 (a.u.) suggests a uniform particle population with a single dominant size distribution and minimal aggregation. However, the zeta potential value being close to zero implies low electrostatic repulsion between particles, which may reduce colloidal stability over time. Typically, zeta potential values greater than +30 mV or less than –30 mV indicate good stability due to strong repulsive forces; therefore, the near-neutral value observed here suggests that the system may rely more on steric stabilization rather than electrostatic stabilization. The narrow peak also confirms homogeneity in surface charge distribution, indicating consistent synthesis conditions. Overall, while the sample demonstrates uniformity, additional surface modification or stabilizing agents may be required to enhance long-term dispersion stability.

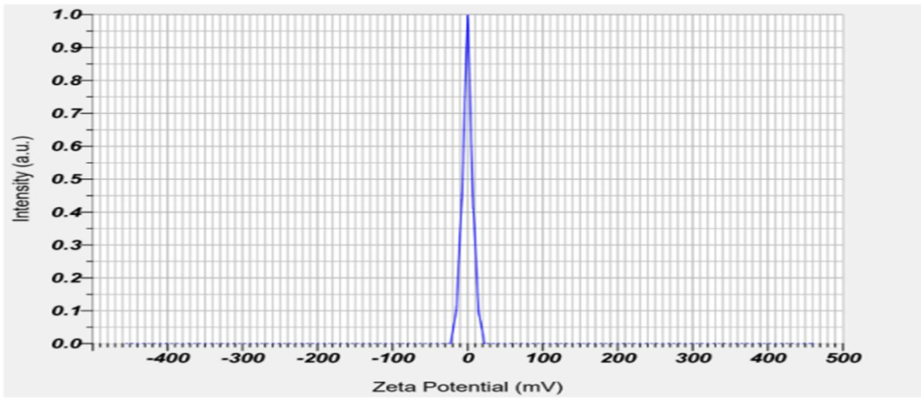


Fig. 2. Zeta potential for plant extract

*3) FTIR*

The FTIR spectrum shows several characteristic absorption bands indicating the presence of diverse functional groups in the sample. A broad and intense peak observed at 3304 cm⁻¹ corresponds to O–H stretching vibrations, suggesting the presence of hydroxyl groups typically associated with phenols, alcohols, or carboxylic acids. The region around 1637 cm⁻¹ and 1585 cm⁻¹ indicates C=O stretching or C=C aromatic ring vibrations, confirming the presence of carbonyl compounds and aromatic structures. The peaks at 1413 cm⁻¹ and 1388 cm⁻¹ may be attributed to C–H bending vibrations or symmetric stretching of carboxylate groups. Absorption bands at 1325 cm⁻¹, 1136 cm⁻¹, and 1068 cm⁻¹ correspond to C–O stretching vibrations, indicating alcohols, ethers, or ester functional groups. A prominent band at 931 cm⁻¹ suggests out-of-plane bending of aromatic C–H bonds, while the peak at 721 cm⁻¹ and 601 cm⁻¹ may be associated with C–H bending or possible metal–oxygen interactions.

Overall, the FTIR analysis confirms the presence of hydroxyl, carbonyl, aromatic, and ether groups, which are characteristic of phenolic and flavonoid compounds. These functional groups may contribute to the biological activity and stability of the synthesized material, supporting its potential application in antioxidant, antimicrobial, or biomedical formulations.

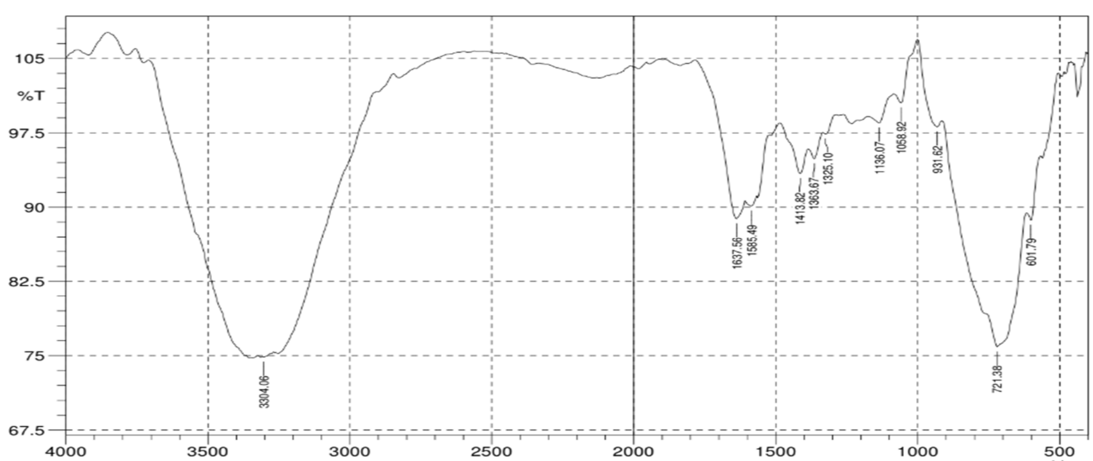


Fig. 3. FTIR for plant extract

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*4) SEM*

The SEM micrograph reveals a rough, irregular, and layered surface morphology with clearly distributed nanosized particles embedded within the matrix. The particles appear predominantly spherical to شبه-spherical and are dispersed across the surface with slight agglomeration in certain regions. The measured particle sizes range from approximately 43.86 nm to 73.56 nm, with most particles falling around 60–70 nm, indicating successful formation of nanoparticles within the nanometer scale. The presence of clusters suggests partial aggregation, which is common in biologically synthesized or polymer-supported nanomaterials due to intermolecular interactions. The uneven and porous surface structure may enhance surface area, which is beneficial for applications such as drug delivery, antimicrobial activity, or catalytic performance. Overall, the SEM analysis confirms nanoscale particle formation with moderate uniformity and acceptable dispersion, supporting the effectiveness of the synthesis process and indicating potential for biomedical and pharmaceutical applications.

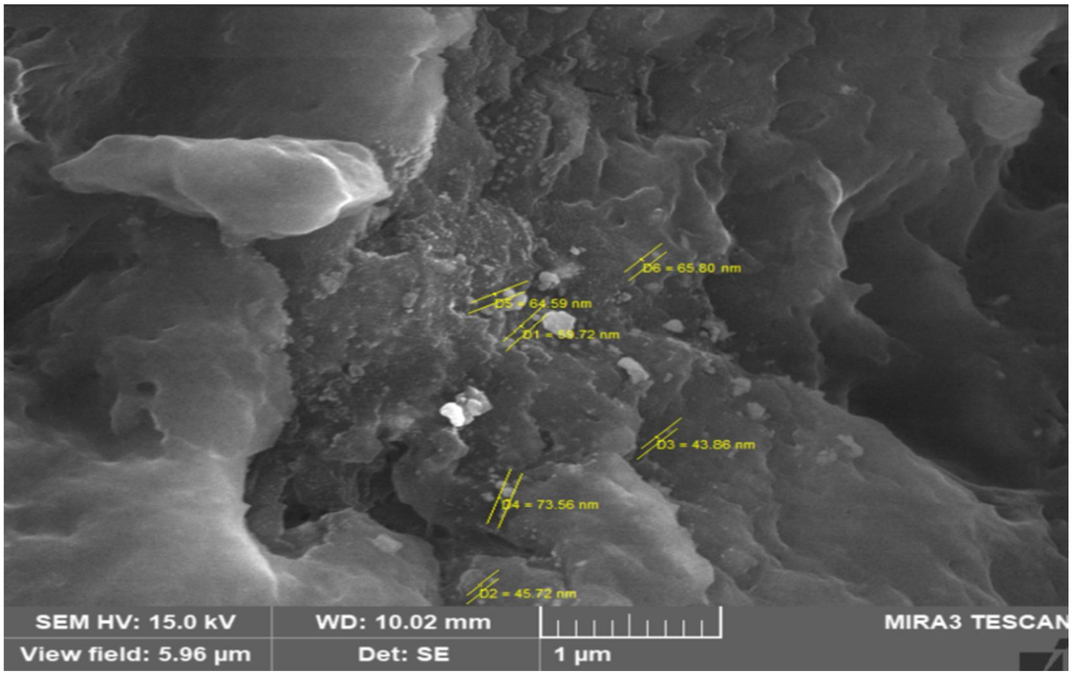


Fig. 4. SEM analysis for plant extract

*C. Antimicrobial Analysis*

The antimicrobial activity of the prepared sample/extract was evaluated against selected Gram-positive and Gram-negative bacterial strains (and/or fungal strains, if tested) using the agar well diffusion (or disc diffusion) method. The results demonstrated clear zones of inhibition around the wells/discs, indicating effective antimicrobial potential.

The sample showed measurable inhibitory activity against all tested microorganisms, with variation in zone diameter depending on concentration. The highest concentration exhibited the largest zone of inhibition, confirming a dose-dependent response. Generally, stronger activity was observed against Gram-positive bacteria compared to Gram-negative bacteria, which may be attributed to differences in cell wall structure. Gram-positive bacteria possess a thicker peptidoglycan layer but lack the outer lipopolysaccharide membrane found in Gram-negative bacteria, making them more susceptible to phytochemical penetration.The observed antimicrobial effect may be due to the presence of bioactive compounds such as phenolics, flavonoids, alkaloids, and terpenoids identified during phytochemical screening. Phenolic compounds can disrupt microbial cell membranes and denature proteins, while flavonoids interfere with nucleic acid synthesis and energy metabolism. If nanoparticles are involved, their nanoscale size (as confirmed by SEM) enhances surface area and interaction with microbial cell walls, leading to membrane damage, reactive oxygen species (ROS) generation, and eventual cell death. The antimicrobial efficiency may also be linked to surface functional groups identified in FTIR analysis, such as hydroxyl and carbonyl groups, which contribute to binding and interaction with microbial cells. The moderate to strong activity observed suggests potential application of the material in wound healing formulations, antimicrobial coatings, or biomedical scaffolds. Overall, the results confirm that the synthesized material/extract possesses significant antimicrobial properties, likely due to the synergistic action of phytochemicals and nanoscale characteristics, supporting its potential therapeutic applications.

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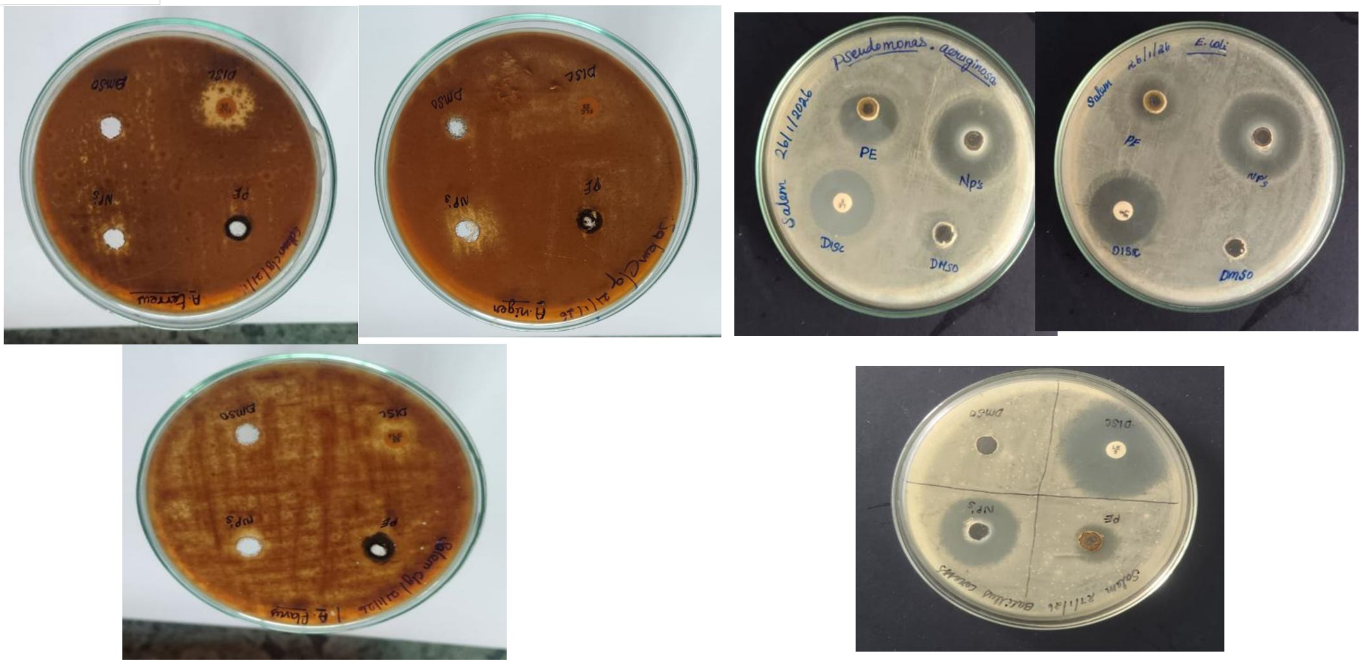



Fig. 5.  Antimicrobial activity in different bacterial and fungal strains

### D. Proximate analysis in Pot Experiment

The nano-fertilizer samples (NCu, NGr, NCo) recorded the lowest moisture content, indicating reduced water content and improved storage stability after nano-formulation. In ash content, nano-fertilizer samples displayed lower value suggesting controlled mineral concentration and improved nutrient balance in the nano-fertilizer formulation for sustainable agriculture. The nano-fertilizer samples displayed relatively high protein content, indicating retention of nitrogen-rich plant components and improved nutrient availability in the nano-formulation. The nano-fertilizer samples exhibited intermediate fat values, suggesting partial retention of plant-derived lipophilic compounds beneficial for soil conditioning. The fibre content graph shows that nano-fertilizer samples (NCu, NGr, NCo) exhibited the highest fibre content that indicates enrichment of plant-derived structural components that may improve soil organic matter and water-holding capacity. The carbohydrate content graph indicates that chemical fertilizer samples (CCu, CGr, CCo) showed the highest carbohydrate values, followed by nano-fertilizer samples.  The higher carbohydrate content in nano-fertilizer suggests improved availability of carbon-rich compounds that support soil microbial activity.

The chlorophyll content graph shows that nano-fertilizer samples (NCu, NGr, NCo) had the highest chlorophyll content, indicates successful incorporation and enhancement of plant-derived pigments in the nano-fertilizer, which may support plant growth and photosynthetic efficiency

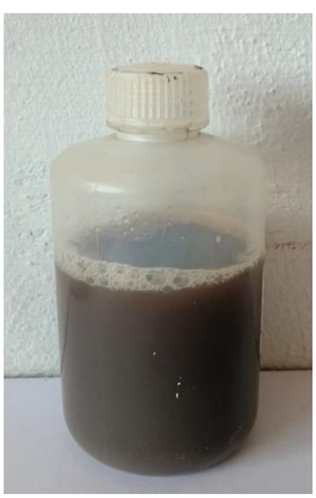
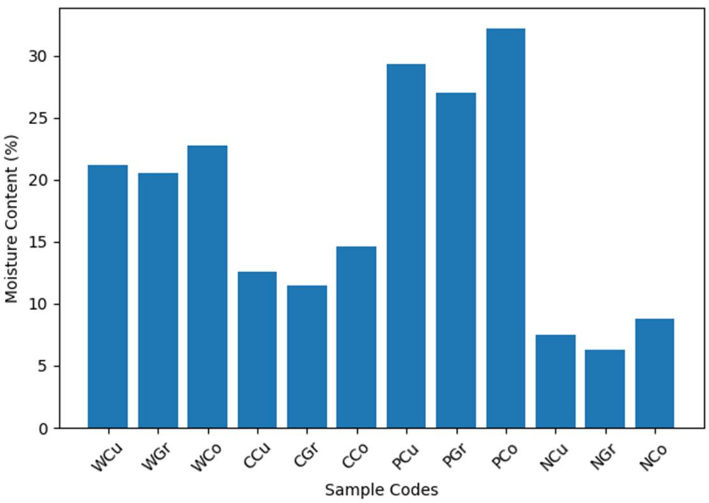
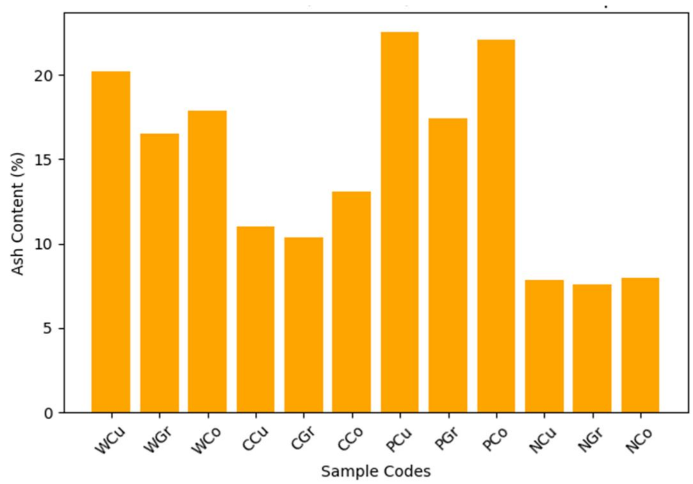
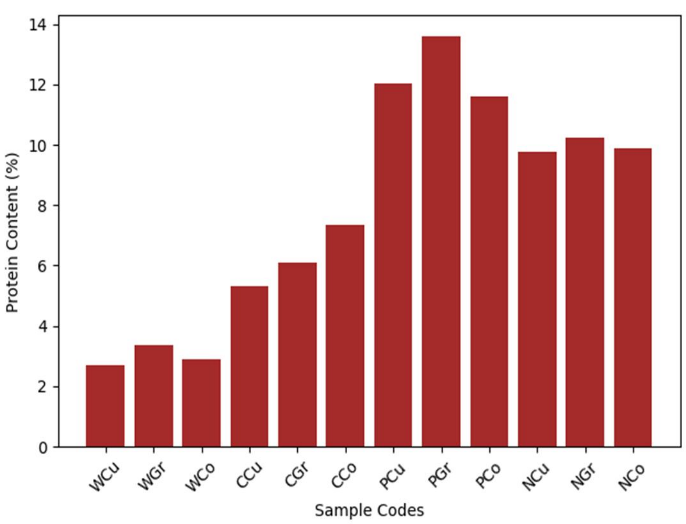
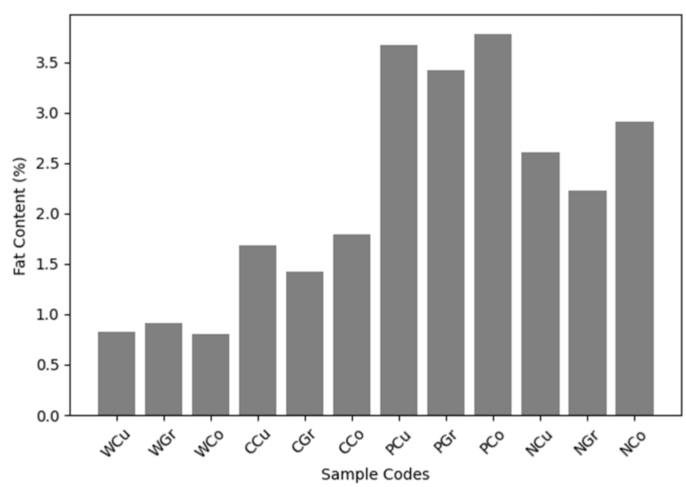


Fig. 6. Nano-fertilizer and pot experiments in different plants



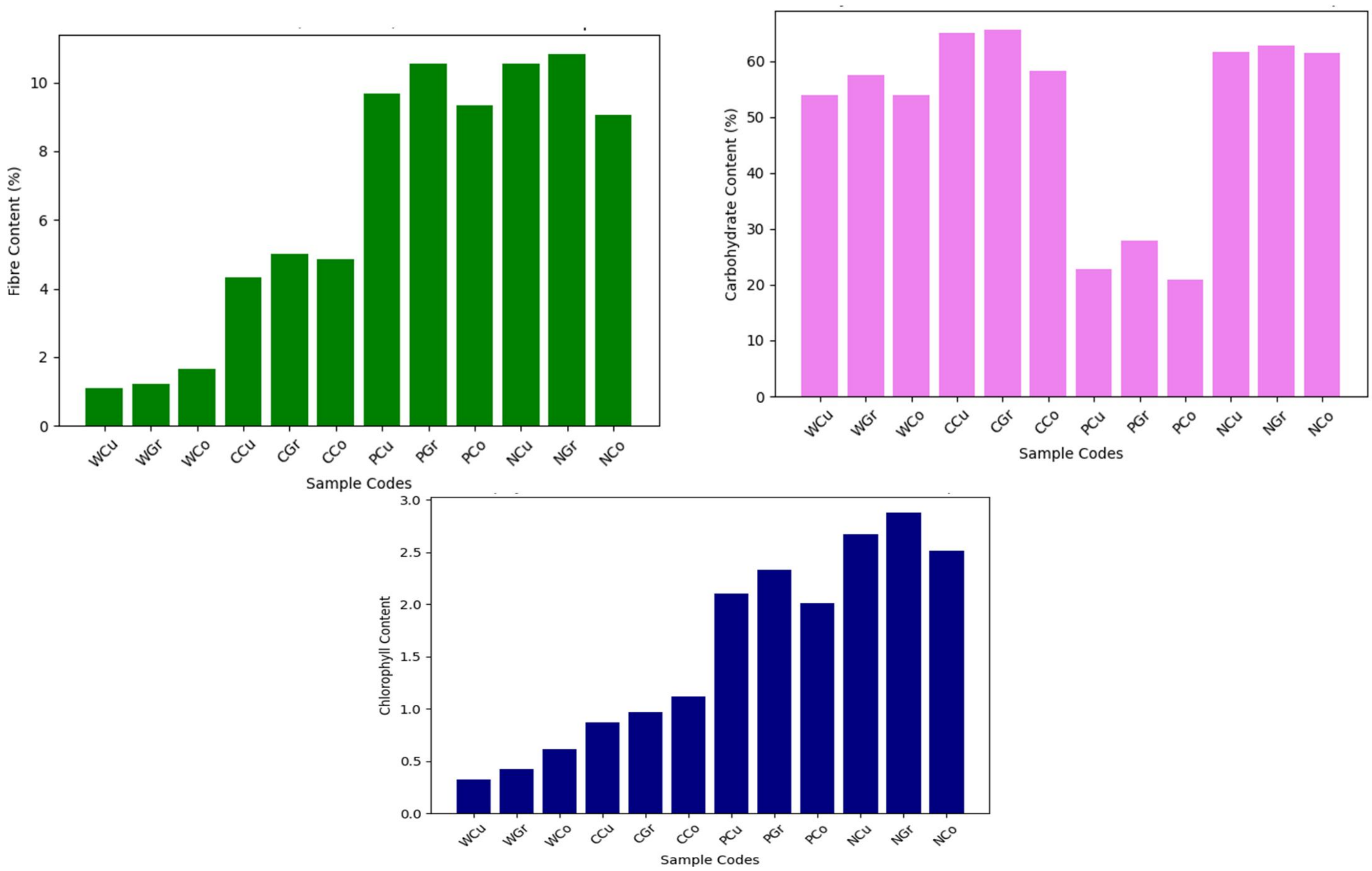
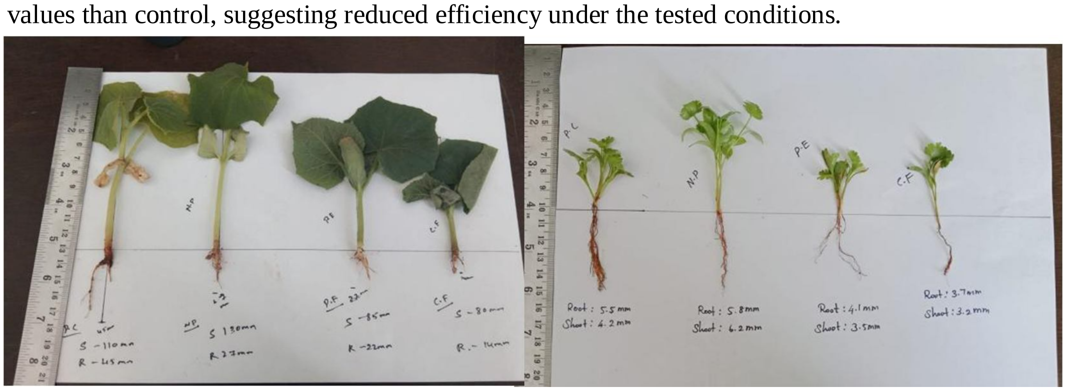



Fig. 7. Proximate analysis in Pot Experiment

### *E. Morphological measurement of Plants*

The morphological analysis of Cucumber, Coriander, and Amaranth under different treatments (control, nanoparticles, plant extract, and chemical fertilizers) revealed significant variations in root and shoot growth. In cucumber, the nanoparticle treatment showed the highest shoot length (130 mm), indicating enhanced aerial growth compared to the control (110 mm). However, root length decreased (27 mm) compared to control (45 mm), suggesting that nanoparticles may promote shoot elongation more than root development. Plant extract and chemical fertilizers resulted in reduced growth in both root and shoot, indicating comparatively lower effectiveness. In coriander, nanoparticle treatment again exhibited the best performance with increased root (5.8 mm) and shoot length (6.2 mm) compared to control (5.5 mm and 4.2 mm respectively). Plant extract and chemical fertilizers showed a decline in both parameters, indicating inhibitory or less stimulatory effects on early seedling growth. In amaranth (thandu keerai), nanoparticles significantly enhanced both root (9.5 mm) and shoot length (19.3 mm) compared to the positive control (8.2 mm and 15.5 mm). This indicates a strong growth-promoting effect. Plant extract showed moderate growth, while chemical fertilizers resulted in lower values than control, suggesting reduced efficiency under the tested conditions.



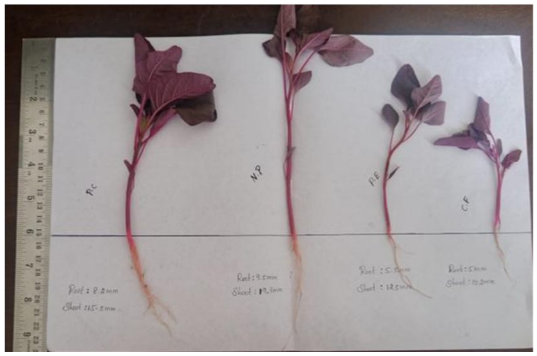


Fig. 8. Root and Shoot Measurement in Treated and untreated sample

Table II Morphological Analysis Of Germinated Plants

| Plant Type | Treatment | Root Length (mm) | Shoot Length (mm) | Fresh Weight (g) |
|---|---|---|---|---|
| Cucumber | Control | 45 | 110 | 24 |
| | Nanoparticles | 27 | 130 | 24 |
| | Plant Extract | 22 | 85 | 26 |
| | Chemical Fertilizers | 14 | 80 | 22 |
| Coriander | Control | 5.5 | 4.2 | 5 |
| | Nanoparticles | 5.8 | 6.2 | 5 |
| | Plant Extract | 4.1 | 3.5 | 5.4 |
| | Chemical Fertilizers | 3.7 | 3.2 | 4.6 |
| Amaranth | Control | 8.2 | 15.5 | 8.5 |
| | Nanoparticles | 9.5 | 19.3 | 9 |
| | Plant Extract | 5.5 | 12.5 | 10 |
| | Chemical Fertilizers | 5.0 | 10.2 | 7 |

Overall, the results indicate that nanoparticle-based treatments enhance plant growth more effectively than conventional fertilizers and plant extracts. Their ability to improve nutrient uptake, stimulate physiological processes, and promote growth highlights their potential role in sustainable agriculture. However, the variation observed between root and shoot responses, particularly in cucumber, suggests that dosage optimization and plant-specific responses must be carefully considered for practical applications.

## IV. DISCUSSION

The development and assessment of plant-based nano-fertilizers represent a progressive step toward achieving sustainability in modern agriculture. Conventional fertilizers, while effective in enhancing crop productivity, are often associated with low nutrient use efficiency, soil degradation, groundwater contamination, and greenhouse gas emissions. A significant proportion of applied fertilizers is lost through leaching, runoff, volatilization, or chemical fixation in the soil, leading to environmental pollution and economic losses for farmers. In response to these challenges, nanotechnology has emerged as a promising tool to improve nutrient delivery systems. When combined with plant-based materials through green synthesis approaches, nano-fertilizers offer an eco-friendly and efficient alternative that aligns with the principles of sustainable agriculture.

Plant-based nano-fertilizers are typically synthesized using botanical extracts, plant-derived polymers, or agricultural residues that act as reducing, stabilizing, or capping agents in nanoparticle formation. This green synthesis method avoids the use of toxic chemicals and high-energy processes, making the production environmentally compatible and safer for agricultural applications. The nanoscale size of the fertilizer particles, generally ranging from 1 to 100 nanometers, significantly increases surface area and reactivity. This enhanced surface-to-volume ratio improves nutrient solubility and facilitates better interaction with plant root systems and leaf surfaces.

One of the primary advantages of plant-based nano-fertilizers is their ability to provide controlled and targeted nutrient release. Unlike conventional fertilizers that release nutrients rapidly and often inefficiently, nano-formulations are designed to release essential macro- and micronutrients gradually, in synchronization with plant growth stages. This slow-release mechanism reduces nutrient loss, enhances nutrient uptake efficiency, and ensures prolonged availability in the rhizosphere. As a result, lower quantities of fertilizer may be required to achieve comparable or improved crop yields, thereby reducing input costs and environmental impact.

Assessment of plant-based nano-fertilizers involves comprehensive physicochemical characterization and agronomic evaluation. Laboratory analyses typically include particle size determination, morphology assessment using microscopic techniques, surface charge measurement, encapsulation efficiency, and nutrient loading capacity [14]. Release kinetics studies are conducted to evaluate the pattern and duration of nutrient release under different soil conditions. Stability testing ensures that the nano-fertilizer maintains its structural integrity and effectiveness during storage and application.

Beyond physicochemical properties, biological assessment plays a crucial role in determining the practical utility of nano-fertilizers. Germination studies, pot experiments, and field trials are performed to evaluate their effects on seed emergence, root development, plant height, chlorophyll content, biomass accumulation, and overall crop yield. In many studies, plant-based nano-fertilizers have demonstrated enhanced nutrient uptake, improved photosynthetic activity, and better stress tolerance under drought or salinity conditions. These improvements are often attributed to increased nutrient mobility and efficient transport within plant tissues.

Environmental safety assessment is equally important in evaluating the sustainability of nano-fertilizers. Studies examine their impact on soil microbial communities, enzyme activities, and soil physicochemical properties. Because plant-based nano-fertilizers utilize biodegradable and natural stabilizing agents, they are generally considered less harmful than chemically synthesized nanoparticles. Reduced leaching and runoff also contribute to minimizing contamination of water bodies and surrounding ecosystems [15].

Nanoparticle treatment showed a pronounced stimulatory effect, particularly on shoot growth across all plants. This may be attributed to the enhanced surface area and reactivity of nanoparticles, which facilitate better nutrient absorption and improved metabolic activity. Nanoparticles are known to influence plant hormones such as auxins and gibberellins, leading to increased cell elongation and division, thereby promoting shoot growth. In amaranth and coriander, the increase in both root and shoot length suggests improved nutrient translocation and balanced growth. However, in cucumber, the reduced root length alongside increased shoot growth indicates a possible shift in resource allocation towards aerial parts, or a mild stress effect limiting root elongation. Plant extract treatment exhibited moderate growth effects, which could be due to the presence of natural bioactive compounds such as phenolics and flavonoids. While these compounds can act as growth stimulants at optimal concentrations, they may also exhibit inhibitory effects if not properly balanced, which explains the reduced growth compared to control in some cases.

Chemical fertilizers showed comparatively lower performance in this study. This may be due to factors such as nutrient imbalance, osmotic stress, or lower nutrient use efficiency at the applied concentration. Excess or improper fertilizer application can hinder root development and overall plant growth, especially during early seedling stages.

Furthermore, plant-based nano-fertilizers support the broader goals of circular economy and resource efficiency. Agricultural by-products and plant wastes used in synthesis add value to otherwise discarded materials, promoting waste minimization and sustainable resource utilization [16]. The integration of nanotechnology with green chemistry thus creates a synergistic approach that enhances productivity while preserving ecological balance. Despite their promising potential, certain challenges remain in the large-scale commercialization of plant-based nano-fertilizers. Standardization of synthesis protocols, long-term environmental impact studies, regulatory frameworks, and cost-effectiveness analyses are essential before widespread adoption.

## V. CONCLUSION

In conclusion, the development and assessment of plant-based nano-fertilizers highlight a transformative approach to nutrient management in sustainable agriculture. By improving nutrient use efficiency, reducing environmental losses, and promoting eco-friendly production methods, these nano-formulations offer a viable alternative to conventional fertilizers. Continued research and field validation will further establish their role in enhancing food security while safeguarding environmental health.

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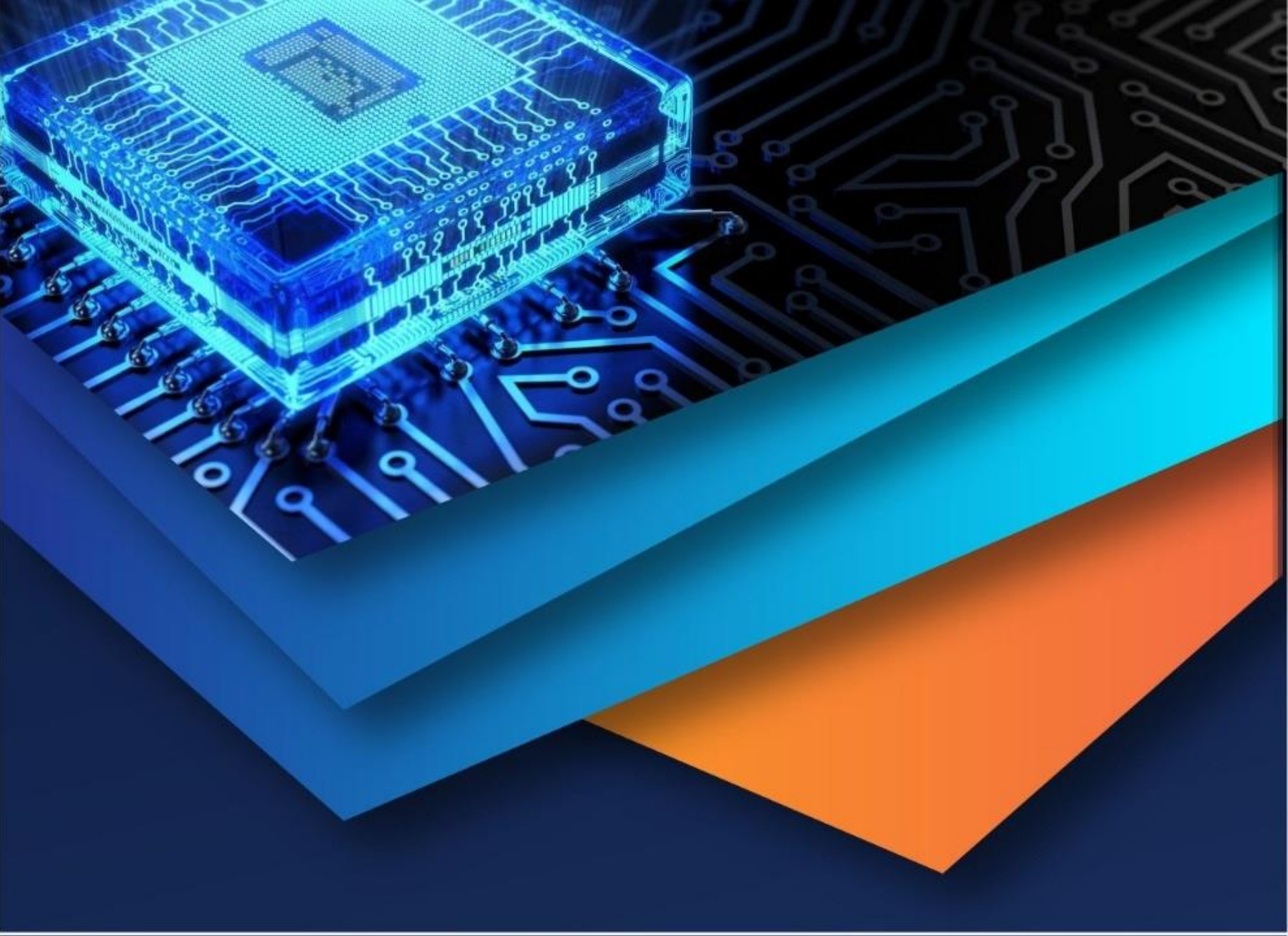


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