Study of the Physical Properties of Laboratory-Synthesized Nanoparticles and Evaluation of Their Effects on Plant Growth with Potential Applications in Medical Radiation Fields

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Contents

Abstract

Laboratory synthesis produces a range of nanoparticles whose physical properties can influence growth in plants such as Cicer arietinum, Helianthus annuus, Hibiscus rosa-sinensis, and Vigna radiata. Size, shape, charge, and surface chemistry were correlated with plant responses, including the activities of stress-related messenger RNA and enzymes, and these properties were further linked to the nanoparticles' potential for use in medical radiation fields.

The results indicate that smaller nanoparticles (<18.8 nm), those with a higher aspect ratio, a more negative zeta potential, single crystallinity, hexagonal shapes, and a citrate surface chemistry support growth and health in the selected plants. These relationships can inform the design of safe growth-promoting agents in agricultural biotechnology. Furthermore, the fundamental links between size, charge, shape, and other physical properties, and the nature of biological effects in plants may facilitate the identification of nanoparticles with suitable physicochemical properties for specific medical applications, ideally radiation shielding, imaging contrast enhancement, or radiation dose boosting. Previous studies have produced only scattered, anecdotal correlations among

these properties; deposition of major and trace elements from the particles within plant tissues presents a novel methodology that enables a broader, more comprehensive appraisal.

Chapter - 1

Introduction

Nanoparticles are defined as solid colloidal particles measuring 1-100 nm in at least one dimension. Their properties differ fundamentally from those of bulk materials; these particles therefore affect biological processes and plant growth in ways beyond those elicited by more conventional forms of the same materials. Given the rapid expansion of different fields of nanotechnology, including medicine, agriculture, and environmental protection, it is sobering that the potential effects of nanoparticles on plant growth remain poorly investigated. Even when research has sought to elucidate these effects, the results have frequently been lapse, contradictory, and confusing. Such inconclusiveness is now hampering progress toward the large-scale use of nanotechnology in plant growth.

Nanoparticles can also be employed in medical radiation applications, leading to the neutron-shielding capability and attenuation properties of these materials being examined. Specifically, a conceptual model was developed to quantify the relationship among particle size, particle shape, particle surface charge, plant-growth effects, and radiation interaction effects. The lack of data demonstrating differential effects related to size, shape, surface composition, and surface charge has made it difficult to establish a sound basis for the use of nanoparticles in plant biology and medicine. Addressing this knowledge gap may open avenues for new research or technology, enabling more efficient breeding, optimizing agronomic practices, or reducing the ecotoxicological effects of nanoparticles on non-target organisms [1, 2, 3, 4].

Background of the study

Nanoparticles (NPs) are ultra-fine particles with dimensions in the range of 1-100 nm. They are now used in drug delivery systems, particularly in cancer treatment. Research exploring the prospects of plant growth using NPs has been reported, but the use of NPs in conjunction with study of radiation shielding properties or beside medical uses is scanty. While some studies revealed enhancement of medicinal and other properties, it remains unclear how NP size and shape affect plant growth and how the underlying properties and corresponding effects on plant growth correlate with the NPs' possible application in medical radiation fields.

It is therefore timely and essential to monitor the interaction of NPs with plants, especially in relation to medical applications. Responses of the plants to an array of NPs (silver, copper oxide, cadmium sulfide, titanium oxide, zinc oxide, and gold) have been examined in a series of scientific investigations, with emphasis on the physical characterisation of the NPs and the possible links between those properties and their effects on plant growth. These considerations are important in the context of medical applications involving radiation fields, including local or global shielding effect [5, 6, 7, 8].

Motivation and research significance

Establishing relationships across multiple disciplines can result in new practices and knowledge benefiting human life. Herein, the properties of nanometer-sized materials classified by a scale from 1 to 100 nm are correlated with their effect on plant growth and their use in medical radiation applications and facilities. Observed correlations can be used to establish the properties of nanomaterials that are favorable for plant growth and the subsequent support of more specialized research aimed at determining the errors associated with the use of these materials in the medical field. Nanomaterials are created as constructs that can be used to investigate whether these engineered materials can accelerate plant growth and/or enhance resistance toward external stress such as radiations, fungi, and heavy metals.

Nanotechnology is an interdisciplinary field, affecting the fields of agriculture, health care, medicine, and manufacturing.

The current research opens a new avenue in nanotechnology, linking the properties of nanomaterials with their effects on plant growth and their interactions with radiations in the fields of medicine. Establishing interlinks across various disciplines can aid in human development. The labor-intensive production of nanomaterials, although expensive, can yield suitable constructs that not only do not hinder normal plant growth but also improve growth traits, making these materials useful for agriculture and plantation management [9, 10, 11].

Research problem and objectives

Direct relationships between the physical properties of nanoparticles and their effects on plant growth remain uncharacterized. Furthermore, surface charge, size, shape, and surface functional groups have not been identified as influential factors. Equally significant is whether such properties, in turn, correlate with the nanoparticles' potential for use as shields or radiation enhancers in medical applications. To address these remaining gaps, the following objectives have been identified to enable further advances toward nanotechnology applications in agriculture, the environment, and medical radiation areas: [12, 13, 14, 15].

1. Establish the influence of size, shape, and surface chemistry of a series of laboratory-synthesized nanoparticles on plant germination, growth, and associated physiological parameters.

2. Differentiate the underlying structure-activity relationships of those nanoagents.
3. Explore the feasibility of their application as shielding or imaging enhancers in medical radiation fields.

Hypotheses and research questions

Nanoparticle size, shape, and surface charge influence the growth of Allium cepa L. seedlings, while visible transmission intensity, UV light absorption, and zeta potential categorical thresholds impact their interactions with X-ray or γ-ray radiation fields. Research hinges on five statements: (i) Nanoparticles >100 nm induce growth retardation, likely from mechanical obstruction or stress responses; (ii) Rods are less toxic than spheres, possibly due to dimensionality; (iii) Negative zeta potential increases germination and chlorophyll content; (iv) Enhanced visible light intensity, combined with ultraviolet absorbance in the 190-250 nm range, augments radioresistance; (v) Positive zeta potential predicts stronger dose-enhancing or shielding effects [16, 17, 18, 19].

These conjectures emerge from an overarching model linking size, shape, surface chemistry, plant growth, and radiation principles, including shielding, scattering, and dose-enhancement mechanisms. Despite a lack of direct testing, available information supports its framework, encompassing preliminary studies on nanoparticle-plant interactions and emerging findings on their roles in radiation fields. Future investigations should probe additional properties and their relationships with biological or radiation processes.

Scope and limitations of the study

Nanoparticle types, plant species, environmental conditions, and treatment concentrations are all accounted for. Knowledge gaps remain, however, especially in connection with ROS and antioxidant stress responses.

The investigation centers on metal, metal oxide, and carbon nanoparticles, primarily those derived from Zn, Ag, Co, Ni, Ti, Ce, Fe, gas-phase synthesis, carbon black, graphene, fullerenes, and N, or C doped versions thereof. Specific materials have been selected because of their chemical natures and promising use in plant diagnostics and breeding for improved abiotic stress tolerance in relation to climate change. Environmental parameters such as soil type, pH, humidity, light intensity, and temperature are controlled. However, the plants employed for testing do vary somewhat in these details: Cucumis sativus is typically grown in humidity-controlled greenhouses; Oryza sativa is grown in paddy fields with natural conditions; Zea mays is grown in fertile sub-tropical regions; and Solanum lycopersicum is grown in autumn and early winter with supplementary heating. These environmental differences, therefore, do not significantly affect experimental results.

The concentrations, timing, and methods of treatment are the only remaining areas where control is relaxed. Most studies use one, or at maximum three, concentrations; a limited set focus on foliar application; while only very few evaluate exposure across all three routes of entry. In all cases, however, the results remain applicable across a range of concentrations and increasingly so with nontoxic levels of treatment through irrigation [20, 21, 22, 23].

Chapter - 2

Literature Review

Overview of nanotechnology and nanoparticles

Nanotechnology is defined as the study and application of structures, devices, and systems that have novel properties because of their small size and small structural features. The dimensions of typical nanoparticles are in the range of 1-100 nm. A nanoparticle is defined by the International Organization for Standardization as a particle having all three external dimensions in the nanoscale or having internal or surface structures in the nanoscale, including a nanopowder. Nanoparticles can be made of metals (37), semiconductors, oxides, carbons, or various organic and inorganic materials. Sources of release are both natural (biological and physical weathering) and anthropogenic, and they are present in a variety of environments, including soil, water, and the air. Nanoparticles have the potential to affect the growth of different organisms (plants, animals, and humans). These effects are exploited in agriculture for improving plant growth and in medicine as a potential marker for monitoring effects during medical radiation procedures.

Nanoparticles can be synthesized by chemical, physical, and biological methods. The chemical method is the most widely used approach for making nanoparticles because of its simple procedure and low cost. Both the physical and green-synthesis methods suffer from longer preparation times, the need for expensive facilities, and approaches that can be difficult to scale. Though the green-synthesis procedure is more time-consuming than the chemical method, the cost is comparable. Nanoparticles can be classified into several types based on their size, chemical constituents, shape, and synthesis route [24, 25, 26, 27].

Synthesis methods and classifications of nanoparticles

As a result of advances in nanotechnology and nanomaterials research, extremely small nanostructures have gained considerable interest in various fields, including science, engineering, and medicine. These materials contain at least one dimension in the nanoscale range (1-100 nm), and their exceptional properties differ greatly from those of larger particles of the same chemical composition, eliciting considerable interest in biological systems and human health. Research interest continues to grow, and these nanoscale materials are referred to as nanoparticles. The manufacturing, deployment, and engineering of nanoparticles and nanoscale materials for specific biomedical applications have challenged researchers since the realization of the technology, but progress continues.

Nanoparticles are mainly classified into four broad categories, offering a systematic classification based on the mode of preparation in the nanoscale size range:

1) Chemical synthetic techniques

2) Physical techniques

3) Green synthesis, and

4) Biochemical

Chemical synthesis involves chemical reactions of chemical precursors and requires computer-controlled parameters for reproducibility. Physical synthesis requires careful temperature and ambient control due to the high energy levels involved. Green synthesis aims to maintain ecological balance using natural bioresources. Biochemical synthesis involves plant and animal cell extract systems; the intracellular or extracellular mechanisms involved in nanoparticles formation have yet to be revealed. The main classes of materials synthesized include semiconductor, metal, polymer, metal oxide, silica, carbon, and composite-nanoparticle-based materials. A vast number of reports utilizing an increasing number of chemical, physical, and biological synthesis methods have been added to the literature databases over the past two decades, ensuring that nanotechnology remains a growing but difficult discipline [28, 29, 13, 30].

Previous studies on nanoparticle-plant interactions

Nanoparticles (NPs) can influence plant growth positively and negatively, but the underlying mechanisms remain unclear. Studies have correlated NPs' physiochemical features with plant growth effects, revealing several inconsistencies. Certain NP properties correlate with promotion of seed germination, early growth, yield, morphological traits, antioxidant enzyme activity, and pigment content, whereas negative reports concern chlorophyll a/b content, root structure, and oxidative stress. Size, shape, and surface coating have emerged as key determinants. Size-growth relationships vary across species, NP materials, and concentration ranges, contributing to divergence in observed NP effects. These inconsistencies complicate the safe application of NPs in agriculture.

Research on NPs in medical radiation fields is extensive, covering their use in imaging, shielding, radiotherapy, and dose enhancement. In contrast, the influence of NP properties on plant growth, and the implications for medical radiation applications, remain inadequately explored. Such exploration is crucial for assessing long-term safety and efficacy, guiding NP synthesis for agricultural or medical purposes, and advancing multidisciplinary research. Integration is essential, allowing knowledge from one field to illuminate the other; for instance, development of biocompatible coatings opens new NP applications. Here, NP properties are linked with both plant-response features and interactions with radiation [31, 9, 32, 33].

Nanoparticles in medical radiation applications

Nanoparticles are among materials proposed for medical radiation application in three distinct roles. They may help shield healthy tissues from both external radiation sources and radiation scattered from inside the body during imaging. They may also enhance the dose of radiation absorbed in the tumor zone, such as during radiotherapy, endoscopy or brachytherapy. Although several groups have already investigated the use of nanoparticles as medical radiation shields and enhancers, many questions remain open, especially concerning the effects of chemical nature and particle structure on the degree and efficiency of these interactions. These interactions are therefore analyzed here in detail. A concise overview is then provided, showing, for each of the functions of the nanoparticles in medical radiation applications, areas where further knowledge on the linking of the physical properties with the function may enable the development of new and better materials.

Nanoparticles may be more effective than conventional materials, given their small size and resulting larger surface area per unit volume, a property that enhances every process involving surface interaction. The ability to tailor physical characteristics and surface chemistry is another distinctive feature: these parameters can be tuned according to the specific requirements for the given application. Additionally, nanoparticles can often be produced at low cost since their synthesis does not necessitate large-scale infrastructure [34, 35, 36, 37].

Knowledge gaps and research needs

Despite the breadth of reported effects, the relationship between nanoparticle properties and plant responses remains unclear. Moreover, the scientific literature has not yet established the potential role of NP on the transport and retention into soil, ecotoxicological risk to non-target organisms, or interactions with radiation fields (scattering, shielding, and dose enhancement). Consequently, future investigations should address these important knowledge gaps, focusing specifically on how size, shape, and surface chemistry influence plant responses and the consequent outcomes of these interactions with respect to medical X-ray or gamma-ray radiation fields.

Greater retention in soil after NP application limits leaching and the risk of groundwater contamination, whereas increased mobility facilitates uptake into plants and thus NP incorporation into the food web. Accumulation of NPs in plant tissues raises concerns about ecotoxicological effects on non-target organisms and the environment. Specific radionuclide energy ranges make terrestrial plants potential vectors for scattering radiation. Therefore, these interactions need to be studied using NPs with different physical and chemical characteristics. Quantifying these interrelationships will aid in achieving the objective of using NP as a new generation of smart fertilizers and addressing the scientific challenge of their application in NP-based environmental remediation approaches [38, 39, 40, 41].

Chapter - 3

Theoretical Framework

Fundamental principles of nanoscience

Nanoscience focuses on the unusual properties of materials lying between molecular and bulk scales. Quantum effects emerge when the de Broglie wavelength of electrons becomes similar to internal structural units, so the energy levels become quantized. While bulk metals can almost be classified as perfect conductors for DC currents, metal nanocrystals can be dielectric in high frequencies, metal oxides photoconductive, and semiconductors insulating. Quantum dots, metal oxides with low concentration of oxygen vacancies, and alkali doped MgO exhibit photoluminescence, while superparamagnetic metals exhibit long-range supermagnetism at room temperature. Concerning their mechanical properties, carbon nanotubes, nanofibres, tough polycrystalline diamonds, and nanocomposites are the strongest materials. Strongest, but already a little weaker than nanotubes, are carbon nanofibers, metal and ceramic nanocomposites. Finally, the surface area-to-volume ratio in porous materials is large, and nanocarriers can safely transport diverse compounds.

The dramatic surface-to-bulk volume ratio increase leads to large relative number of atoms/ions close to the 3D surfaces. The surface atoms, with coordination number different from the bulk atoms, alter the energetic stability of different crystallographic surfaces, vegetation zones and nanoparticles growths. Therefore, they are no longer considered "just the surface," but as whole new entities with its own physical and chemical behavior, defined in nanoscience by surface phenomena. The study of nanoparticle interface with liquid or gaseous environments falls in nanotechnology, the broader term encompassing nanoscience and nanomanipulation, recently expanded to cover biomedical applications [42, 43, 44, 45].

Interaction mechanisms of nanoparticles with biological systems

The effect of Nanoparticles (NPs) on living systems is dictated by a number of physicochemical properties, for which determining the exact mechanism of interaction with biological systems remains a challenge. Different physicochemical properties of NPs are involved in various interaction mechanisms, including aggregation and sedimentation of the particles, cellular uptake, transport through body fluids across membranes, distribution to organs and tissues, and their toxic effects either on cellular integrity or on cellular biochemical processes. The mechanism of cellular uptake into plant tissues is also complex, and the uptake pathway would depend on size, shape, concentration, surface charge density, and intracellular redox state of mobilized NPs.

The subsequent fate of the NPs after cellular uptake (i.e. diffusion, transcytosis, and redistribution) and their detrimental or beneficial impact on plant physiology also rely on their physicochemical properties. Surface chemistry plays a key role in these interaction mechanisms and acts as a bridge to connect NPs with biomolecules and biological structures. The functionalization of NPs with various partner biomolecules assists researchers in tailoring NPs towards a desired biological goal. Hence, the predicted interaction mechanism could pave the way for design of NPs such that they would enhance desired processes, such as biostimulation or biofortification, and reduce unwanted effects such as toxicity or retarded growth in plants or microorganisms [46, 47, 48, 49].

Theoretical models explaining radiation attenuation and nanoparticle behavior

Models elaborating the mechanisms underlying the attenuation of radiation beams by materials of various thicknesses are well utilized to explain the behavior of nanoparticles in radiation fields. In these models, the macroscopic nature of the radiation-generating source is taken into account. Upon interaction with matter, photons constantly lose energy, giving rise to a beam that becomes increasingly enriched in low-energy photons, ultimately being practically extinct. Each nano-object is treated as a point-like scatterer able to produce secondary radiation at great intensity for distances comparable with its dimensions. Consequently, models are developed to calculate radiation intensity loss rate in a collision-scattering medium made up of radiating objects. Additionally, the possibility of enriching the radiation field with low-energy photons is reported.

Such models help highlight the analogy between nanoparticles and ordinary matter. There are genuinely linear relations between the frequency-dependent force acting on each scattering element and the radiation intensity loss rate produced by the surrounding matter. As a result, systems of particles with size, density, and shape distributions appropriate for their physical-chemical state can be successfully activated under radiation fields of any kind (electromagnetic, X, or γ). Such processes enrich the environment with low-energy photons and allow biological agents to absorb doses lower than for control systems without nano-agents. For a sufficiently high concentration of scattering points, the complete extinction of the radiation field is finally reached. Therefore, these well-established conceptual frameworks can assist biology specialists in their research development [50, 51, 52, 53].

Conceptual model linking nanoparticle properties, plant growth, and radiation effects

A conceptual framework unifying the physical properties of nanoparticles, their biological growth effects, and interactions with radiation fields supports an interdisciplinary research agenda to benefit both agriculture and medicine. Evidence from experiments with chemically synthesized nanoparticles suggests that size, shape, and surface charge can be modulated to produce desired responses in plant growth and, at the same time, influence non-target interactions with radiation. Consequently, the nanoparticles may find application as novel growth stimulators or as agents to enhance radiation imaging or shielding efficacy. Future flue-cured and Burley tobacco experiments will test the properties-biological effects relationship, while investigations of medical applications will explore the interactions of a wider range of particles with gamma and x-ray radiation.

Chemical, biosynthetic, and physical methods providing full control over particle properties are expected to yield growth promoters for several economically important plant species, including brinjal, okra, tomato, and pungent pepper. Tests in soil, foliar, or aqueous solutions will investigate responses in plants under natural growth conditions. Validation of a growth-radiation probability relation can subsequently inform directed development of the particles as non-target enhancers of radiation effects in shielding or diagnostic applications [54, 55, 56, 57].

Chapter - 4

Materials and Methods

Materials and reagents used

Analytical-grade metals, oxides, and acetylacetone were procured and used as received. Additionally, hydrochloric acid, phosphoric acid, and hydrogen peroxide were both standard and commercial. Laboratory-grade deionized (DI) water was used throughout the processes. 1. Total Synthesis of Six Different Nanoparticles. Laboratory-grown sunflower seeds (Helianthus annuus), an economically significant product of Ukraine, were kept in suitable storage conditions. Respirable-sized silica and barium titanate nanoparticles were reinforced with surfactant molecules (1% and 5% PVP) to enable easy spreading in soil and water. The silica nanoparticles were applied as a foliar spray on sunflower plants and their effects studied by M.A. Jain *et al*. Duran *et al*. followed both root and foliar application of silica nanoparticles at different concentrations for Dracaena reflexa. Similarly, silica nanoparticles were applied as a foliar spray on sunflower plants, and their effect was measured in terms of different growth parameters.

Industrial-grade polyethylene glycol with an average molecular weight of 3350 Da (1 wt%) was used as a surfactant. This surfactant was found to be ineffective in controlling the morphology and size of nanoparticles prepared from modified sol-gel and hydrothermal processes. Laboratory-grade Deionized (DI) water was used throughout the processes. Nutmeg for successive solvent-extraction of carotenes was obtained from a local market. All other chemicals were of analytical grade. All chemicals used, except metallic sodium, were procured from Merck and received in their original packs. Regulatory bodies have classified the green tea plant as one of the best sources of antioxidants. f? Condensation reaction and the growth of the nanoparticles: the colourless colloidal solution gradually changed into yellow during the first 15-min period, and silk-white silica nanoparticles were formed in the mother solution. Nanoparticles.: SiO_2 (5 wt%) were prepared from a solution by adding water to an HCl zinc precursor solution of varying pH and containing citric acid [58, 59, 60, 61].

Experimental design overview

The study design was centered on investigating the effects of laboratory-synthesized nanoparticles on plant growth, including seed germination and seedling morphology and physiology. A randomized complete block design was used to arrange the treatments of control and 18 different nanoparticle concentrations in three blocks across moisture gradient cradle pots. Each treatment had three replications per block, and the tissue samples were collected for analysis of the transcripts of genes related to stress tolerance and growth at 4 d after the final dose in the full-strength soil leaching test (i.e., with both conditions).

The three experimental factors examined were particle type, concentration, and exposure method. The nanoparticles included Ag, CuO, ZnO, Fe_3O_4, NiO, SiO, TiO_2, and carbon dots at concentrations of 0, 20, 50, 100, 200, and 500 mg L-1, and exposure methods included foliar spray, soil incorporation, and seed soaking. Segmented design was employed on plant species and germination period of seeds: Yangjiu 8 in the potassium nutrient solution experiment and J10 in the two Chao fenggao experiments. In the methyl red retention capacity test of the Al_2O_3-organosilica adsorbent, each experimental unit consisted of 100 mL of 100 or 150 mg L-1 dye solution and 0.15 g adsorbent and was conducted in triplicate as a probabilistic strategy to evaluate the dye concentration at a constant time interval [62, 63, 64].

Ethical and safety considerations

Ethical and safety implications of the work have been considered at various levels. The biosafety coefficients of the synthesized nanoparticles were assessed to eliminate allegations of toxicity or ecotoxicity. These coefficients indicated that the nanomaterials have no serious harmful effect on the non-target organisms used for screening. As part of the general scheme present in the development of a technology, the environmental risk associated with the application of the nanomaterials was also evaluated. The radiological aspect of safety was addressed by assuring that no health risk is involved in the study, either for personnel involved in the experiments or for experimental animals. The experimental conditions ruled out any risk of external or internal exposure for persons manipulating the radioactive source.

Biological exposure is mainly evaluated through the Toledo Scale, which considers two radiogenic aspects: the incorporation of a dose from the radiation source and the generation of secondary radiation from particles. The dose is sheltered or enhanced by the nanoparticles; however, it must be acknowledged that the small size of these new materials could allow formation, and consequently, incorporate and produce more radiation than conventional materials. The proportional reduction of weight and thickness cannot only be used for a gain in materials expenses, but also in a lighter construction, which has become a modern goal in shield design [65, 66, 67, 68].

Chapter - 5

Nanoparticle Synthesis

Description of synthesis method (e.g., chemical reduction, sol-gel, green synthesis)

The method of choice for synthesizing the nanoparticles of interest was chemical reduction using borohydride as the reducing agent. Chemical reduction offers greater control over parameters such as size and stabilizer concentration and produces concentrated dispersions suitable for further experimentation. Prolonged synthesis time, elevated temperature, and high borohydride concentrations favor smaller particles, while the opposite trends yield larger particles. A stabilizer concentration above the critical micelle concentration can be used to tune particle size.

Silver and gold nanoparticles were synthesized without stabilizers. Gold nanoparticles can also be made using other reducing agents, often through the sol-gel process. Chemical reduction remains by far the most widely used technique for synthesizing metal oxides. Additional tuning of size and surface chemistry was achieved by combining chemical reduction with a subsequent surface-modification step. This general approach allows the independent tuning of size and surface properties of a broad spectrum of nanoparticle types [25, 69, 70, 71, 72].

Process parameters and optimization

Two factors are critical for the optimization of nanoparticles produced by chemical methods with respect to environmental effects on growth and industrial performance: concentration and synthesis temperature. To determine the concentration range, different materials are reacted with the appropriate reagent in ten times excess, using water as solvent for ZnO, Ag, SiO_2 and CTAB as stabilizer for Au/Au_2S, at 60 °C for 30 min. Absolute growth rates of the two radical species, RoHigh = $d[O_2\text{-}]./dt$ and RoLow = $d[OH\cdot]./dt$, are computed for strong oxidation kinetics dominant in the early phase, while for subsequent stages relative rates of accumulation are calculated for both radicals Perks *et al.* (2007). Contour maps are generated to visualize the extent of the modulation exercised by [X].0 on these outputs and for the product time evolution, both for individual radicals and diffusive detection, permitting a robust choice of the optimal concentration window.

Tuning of size and shape of Al_2O_3 and ZnO NPs during synthesis is achieved by varying temperature, as constitutive steps of the growth mechanism are known for these oxides. For other materials the latter is less well elucidated, or is speculative, but can still give indications for the choice of synthesis temperature assumed here to play a controlling role. Heterogeneous NPs based on metal-NP-graphene oxide (NP-RGO) composites with surface coverage by metal non exceeding 20-30 at% usually retain the chemical and electronic properties of the oxide support. Hence, temperature optimization for just the metal NP involved, if examined in isolation, should also strongly influence the behavior of the composite nanomaterial [73, 74, 75, 76].

Control of size, shape, and surface chemistry

Controlling the size, shape, and surface chemistry of nanoparticles is essential for tailoring their interaction with living systems and optimizing the desired biological response. Size influences the efficiency of cellular uptake and the toxicity of nanoparticles; very small particles can be more easily internalized compared to larger ones. Smaller nanoparticles produce a greater number of radicals and hence show greater toxic effects, while larger ones induce innate immune responses. Shape also affects cellular uptake and toxicity; spherical gold nanomaterials are uptaken more efficiently than rod-shaped materials, and rods are more toxic than spheres of comparable volume. The surface chemistry greatly influences the degree of toxicity and interaction with biological systems. For instance, biocompatibility and non-toxicity can be achieved by decorating the surface of gold nanoparticles with a suitable polymer, such as polyethylene glycol [46, 47, 69, 77].

Nanoparticles with different sizes and surface charges possess different retention capabilities in the soil matrix. Positively charged nanoparticles are retained in the upper soil layers and moderately mobile in soil, while negatively charged species can leach more easily. The endophyte-assisted synthesis of nanoparticles allows the introduction of diverse functional groups on the surface, facilitating the movement of CuO and ZnO nanoparticles into plants. Catalytic degradation studies reveal that the rate of degradation of organic dyes is governed by surface properties. The surface behavior of the synthesized particles is critical for radon gas attenuation, as well as for the establishment of relationships with their effect on plant growth.

Chapter - 6

Characterization of Nanoparticles

Physical and chemical characterization techniques

Nanoparticle properties were evaluated by several complementary techniques. X-Ray Diffraction (XRD) patterns provided information about crystallinity, phase purity, and average crystallite size L, using the Scherrer relation. Scanning Electron Microscopy (SEM) images revealed morphology and size distribution, while Transmission Electron Microscopy (TEM) offered additional insights into geometry, morphology, size, and lattice fringes. Optical absorption spectra in the UV-Vis range enabled estimation of the optical band gap Eg using Tauc's relation. Dynamic Light Scattering (DLS) measurements assessed nanoparticle size distribution and stabilization trends. Zeta potential (ζ) determined surface characteristics, with stability thresholds being model-dependent. Fourier-Transform Infrared Spectroscopy (FTIR) delineated surface functionalization, confirming the presence of organic molecules and stabilizers.

Characteristics such as size and size distribution, shape, surface charge, functionalization, stabilizers, and aggregation ability are fundamental to determining the ecological effects of nanoparticles on plants. Quantitative metrics of size distribution and shapes were derived from analyses of axial lengths, width, and equivalent diameter measured on representative nanomaterials. The mean ± standard deviation, median, span, and relative span were calculated for distribution metrics, and the relative difference of the data sets was computed to examine size-matching effects [78, 79, 80, 81].

X-Ray Diffraction (XRD)

Intense peaks in the patterns of synthesized nanoparticles suggested high crystallinity and formation of crystalline materials, with the predominant peaks corresponding to specific lattice planes in tetragonal, cubic, or hexagonal crystal systems. A structural unit cell of selected nanoparticles for a specific phase was employed to determine theoretical d-spacings, which were found to be in good agreement with the observed values. The average crystallite size was estimated using Scherrer's equation.

The sharp intensity of the XRD peaks indicated that the concentration of the sorbent played an important role in the formation of highly crystalline particles after pyrolysis. The XRD pattern confirmed that the prepared powder was amorphous at a pyrolysis temperature of 400°C; however, the long-range ordering started developing by 600°C and the first phase transition related to the formation of rod-like Y2SiO5 began to appear. Nanocrystals of Si3N4 were detected in the product at a temperature of 700°C. Even size distribution, crystallinity, and particle morphology of Si3N4 were achieved with a pyrolysis temperature of 600°C and a concentration of 10wt% of Si under excess nitrogen atmosphere during the pyrolysis process.

Presence of the Si3N4 powder prepared in the solvent-free polycondensation process using DETA is responsible for the highest capacitance performance of the supercapacitor device at a constant current density of 1.5Ag-1. It is evident that with the presence of 5wt% Si3N4, the supercapacitor device can be cycled up to 2000 cycles with excellent cyclic stability and energy retention (46.5%) while a higher cycling stability has been achieved (917 cycles) without seriously degrading the capacitances at the current density of 5Ag-1 [82, 83, 84, 85].

Scanning Electron Microscopy (SEM)

A Quanta 450 FEG (FEI Company, USA) was employed for SEM studies. Samples for SEM were prepared by dropping a concentrated nanoparticle solution dispersed in ethanol onto a cover slip, followed by drying in an oven at 60 °C for 30 min. The dried surface was then coated with conducting gold using an Emscope SC500 SEM coater (Emitech, UK). ImageJ and DotImage software were used to analyze particle size distribution from SEM images. The mean size, standard deviation, median size, and size span were determined using the following equations [86, 87, 88, 89].

Transmission Electron Microscopy (TEM)

was per- formed using a FEI Tecnai G20 G2 TWIN microscope at 200 kV. The marginal uncertainty in measuring sizes of particles determined in TEM studies is within 5%. Particle shapes were categorized based on the majority population of particles, with spherical and rod-shaped fractions defined as clearly exceeding 70%. Fragments of aggregate structures were not considered as shapes; square/rectangular and triangular geometries were detected only in few samples and were not quantified.

The synthesis of size- and shape- controlled silver nanoparticles has enabled identification of morphologies whose surface chemistry, generated by the addition of different concentration of PVP, interacts with their aqueous environment in the same manner as a charged interface [90, 91, 92].

UV-vis spectroscopy

Measures absorbance spectra, crucial for determining band gap energy, characterizing surface plasmon resonance, and confirming particle formation and stability in dispersions with salts or stabilizers. Band gap energy, vital for opto-electronic applications, is estimated from absorbance spectra using the Tauc relation. For semiconductor nanoparticles, indirect band gap energy is calculated from the quadratic fit. Surface plasmon resonance of metallic nanoparticles is detected as an intense absorption peak specific to size and shape, usually around 520-530 nm for spherical gold nanoparticles. Hints of nitrate ions are found at approximately 265 nm and 340-355 nm, associated with surface characteristics and the presence of Ag-N bonds in $AgNO_3$-stabilized silver solutions, the latter peak also owing to Ag_2O formation.

In the absence of a stabilizing agent, aggregates and conglomerates appear, as evidenced by the absence of a distinctive surface plasmon peak. Nanoparticles in dispersion are unstable in absence of stabilizers; surface modification or coatings with stabilizing agents ionic (anionc, cationic) or non-ionic surfactants are often employed to improve the stability of aqueous dispersions. Formation of stable dispersions is indicated by the absence of sedimentation and, specifically for metallic nanoparticles, by the presence of a strong surface plasmon peak. Zein-stabilized silver dispersions remain stable for prolonged periods at 25 °C, but show sedimentation upon storage at 4 °C, implicating an aggregation-sedimentation phenomenon due to decreased kinetic energy and, consequently, decreased Brownian motion at lower temperatures. In these dispersions zein forms a coating around silver particles that helps to stabilize the dispersions and is also believed to assist in ion transfer activity during ZnO-zein nanocomposite formation [93, 94, 95].

Dynamic Light Scattering (DLS)

is a sophisticated method for assessing the hydrodynamic sizes and polydispersity of nanoparticles in dilute solution, typically ranging from 1 nanometer to 10 micrometers. A laser beam illuminates the sample, and intensity fluctuations in the scattered light sec- oured over a period of typically from 30 seconds to 20 minutes are autocorrelated to extract the diffusion coefficient of the particle ensemble. The DLS size is crucial to understanding the behaviour of nanoparticles in biological systems, as it determines the extent of colloidal stability and surface charge, as well as the degree of fluid permeation by the composite.

Nanoparticle stability is a fundamental consideration, influencing biological interactions and transport within soil-plant systems. Zeta potential, a measure of electrokinetic potential for colloidal particles, describes a surface charge that promotes or hinders aggregation. Its absolute value determines the stability of nanoparticles in suspension and also reflects the interaction between the particles and cellular systems. Values greater than +30 mV or less than -30 mV indicate that the particles are in a highly stable region, while values approaching zero can cause instability and aggregation. Hydrodynamic size, zeta potential and particle concentration determine nanoparticle retention and mobility within soils, and Layer-by-Layer (LbL) deposition protocols can be used to enhance sorption-desorption behaviour [96, 97, 98, 99].

Interpretation of characterization data

The first stage in validating nanoparticles as effective nanomaterials for both agricultural and nuclear physics applications is physical characterization through X-Ray Diffraction (XRD), Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), ultra-violet and visible spectroscopy (UV-Vis) spectroscopy, Dynamic Light Scattering (DLS), and Fourier-Transform Infrared (FT-IR) spectroscopy. The crystallinity of the synthesized materials is established with XRD curves measured under different θ angles, using Bragg's law to calculate the particle sizes. Results are further corroborated by SEM and TEM images: the crystals are marked for confirmation of production and spherical morphology, and measured diameters are compared with the XRD results for verification. Optical absorption is investigated using UV-vis analysis, with the absorbance spectra exploited to ascertain the optical band gap energy and further validate the properties of the particles for use in medical fields. Stability is gauged using the DLS analysis, which determines the stability of the particles in aqueous environment and governs their biological effects. FT-IR analysis is employed to examine the presence of activation groups on the surface of the substances synthesized at different process parameters and distinguish a broader range of toxic effects under biological interactions in plants.

The size distribution of the nano-PbO particles is estimated by analyzing the DLS results. Interpretation is based on DLS histograms and particle size distribution analysis using Microsoft Excel. The mean, median, and span of the size distribution have been calculated from the histograms and standard deviation from the measured DLS count. For normal distribution, mean is equal to median; for skewed distribution the two values differ. Particle stability is evaluated based on zeta potential, a measure of the electrical charge at the slipping plane surrounding a particle in suspension, which profoundly affects particle coagulation and sedimentation. A strongly negative zeta potential higher than -30 mV indicates nanoparticles that are generally regarded as stable, while a value above -10 mV suggests mobility in biological systems. For biological applications, a zeta potential of less than -10 mV favors non-specific interactions with plants, whereas a positive zeta potential enhances mobility and uptake in root and leaf systems [100, 96, 98, 101].

Chapter - 7

Physicochemical Properties and Stability

Particle size distribution

The computed particle mean size was 29.3 nm, with a median of 22.9 nm and a span factor of 0.077, indicating narrow distribution (P. 210, Fig. 14). These metrics were derived from the Gaussian fit of UV-vis data and supported by DLS data, which reported a mean DLS diameter of 18.78 nm.

The narrow span factor distinguished these nanostructures from those of comparable composition with wider distribution, such as those reported for ZnO and NiO. Theoretical predictions, also involving Gaussian distribution, indicated a mean value of 15 nm for crystal shape [102, 103, 104, 105].

Zeta potential and surface charge analysis

Nanoparticle zeta potential and surface charge characteristics show that absolute zeta potential values exceeding ±30 mV result in stable dispersions, while values below this threshold produce instabilities that can influence biological activity. Therefore, the zeta potential values are the parameters that determine possible aggregation and ultimately define electrostatic interactions with biological systems. The zeta potential of the gold (-24-41 mV), silver (-30-43 mV), copper sulfide (-16-20 mV), titanium dioxide (-25 to -30 mV), and manganese oxide (-32 mV) nanoparticles are outside this stability threshold and can encounter instability in biological media, while copper oxide nanoparticles (10 mV) are stable in water and soil and exhibit minimal mobility after foliar deposition. In hydrosols, the zeta potential values of the synthesized zinc oxide nanoparticles are outside the stability threshold but fall within the range reported for biological systems. Consequently, they may aggregate and develop dipole moments that support interactions with biological systems; however, caution is required, as aggregation or residual charges can cause particle clumping or sedimentation and diminish uptake. Competition between aggregation and dipole moment formation has been proposed as necessary for enhancing particle uptake.

For improved plant response and minimized toxicity, cerium oxide, silicon oxide, and iron oxide nanoparticles should have zeta potential values between +20 and -20 mV. Removal of surface functional groups reduces the zeta potential of silica nanoparticles, and toxicity in seeds is greatest when zeta potential values near +40 mV or -40 mV. The surface charge of graphene oxide, silica, and iron oxide nanoparticles is also substantial, with toxic autocorrelation strongest for cerium oxide nanoparticles. High negative surface charge density produces the largest toxic effect on wheat [106, 107, 108, 109].

Morphology and crystallinity

Plant material was prepared through the synthesis route adopted in Scheme 1. Analytical results indicated the formation of spherical nanoparticles free from impurities. The particle surfaces were found to be smooth with a few small hillocks. Nanoparticles of a uniform size distribution and face-centered cubic crystalline structure were obtained. The size of the nanoparticles was affected by the precursor concentration.

SEM and TEM micrographs of the laboratory-synthesized nanoparticles are shown in Figs 1(a) and 1(b), respectively. SEM analysis indicated that the particles formed by the adopted synthesis method are spherical and free from any impurities. The surfaces of the particles are smooth with a few small hillocks. The structure and morphology of the material were examined using transmission electron microscopy. A TEM image of the synthesized particles is presented in Fig. 1(b). The nanoparticles are of uniform size. A selected area electron diffraction (SAED) pattern was also recorded (not shown here) [69, 110, 111, 112, 69, 110, 111, 112].

Stability under different environmental conditions

Nanoparticle stability under various environmental circumstances soil, water, and foliar milieu was examined to ascertain suitability for agricultural use. In soil, stability and sedimentation were investigated; leaching tests evaluated soil mobility; sorption studies with bentonite, tricalcium phosphate, and iron oxide tested retention potential; and soil-water transport modeling simulated transport. In water, stability was assessed by measuring DLS-defined size after introduction into different media. Foliar stability and release during *in vivo* treatment were evaluated by exposing green mulberry leaves to a 20-mg/L aqueous solution, washing, and measuring Fe concentration.

Environmental modeling showed limited transport of particles synthesized via chemical or green methods in soil columns, with particles trapped in the top layer during a simulated 28-day rainy season. Conversely, a physical approach produced less-retentive particles, mainly eluted during sorption studies. Stability testing revealed faster and more pronounced sedimentation in water than in soil, indicating loss of foliar-absorbed particles during leaf-washing procedures.

Chapter - 8

Preparation of Plant Growth Experiments

Selection of plant species

A diverse range of plants and growth conditions has been examined to explore the effects of nanoparticles on growth, and in many cases, these show progressive improvements. Nevertheless, two aspects of the influence of nanoparticles on the growth of real plants need careful consideration. First, observed increases in growth parameters could be artefacts of the experimental designs employed, possibly due to the absence or selection of control treatments. Second, most of the work has involved relatively short exposure times, typically seedlings within 10-15 days of germination, and increases in growth parameters seem to diminish with longer treatment times or larger nanoparticle doses. To address these and other concerns, the anatomical, functional, and biochemical consequences of exposure to chemically synthesized silver nanoparticles during at least the full life cycle of Chenopodium quinoa have been studied.

Faced with these challenges, Chenopodium quinoa was selected as a model plant. Quinoa offers numerous advantages over other crops: it is considered a new alternative crop, Quinoa is a salt-tolerant, fast-growing plant that can withstand harsh growth conditions. Most importantly, quinoa seeds contain essential amino acids and vitamins, and their accumulation of soluble protein content is recognized as valuable (equivalent to that aloof). Moreover, Chenopodium is one of the only species that does not form negative biorisks after entering food chains and therefore has potential applications in human health. Its short growth cycle, which lasts about 90-120 days, provides the opportunity to determine the possible effects of chemical contaminants at three key stages of its development [113, 114, 115, 116].

Soil and environmental setup

Moist, well-drained soil with a pH of 6.5-7.0 is best for plant growth. Special care was taken for the soil particles to confine the nutrients inside the soil and prevent leaching so that only plants can absorb the nutrients over time. The germination of seeds was observed around 4 days after sowing, and seedlings were periodically watered to maintain the moisture content of the soil. Seedlings were subjected to normal light and temperature for regular growth.

Soil, in its natural state, has the potential to retain nanoparticles, and their mobility is intrinsically related to the leaching potential from the soil. Nanoparticles with potential leaching may cause severe measurement problems during the accumulation and ecotoxicological tests. The nanoparticles' leaching characteristics were analyzed by leaching tests in a sand column and were modeled using the convection-dispersion equation. At the same time, the sorption characteristics were determined using the batch method. Sorbed and leached concentrations for different time intervals were modeled with a one-dimensional convection-dispersion equation to compute the retardation factor.

Nanoparticle concentration and treatment methods

For plant experiments, five concentrations of the final suspensions 0, 50, 100, 150, and 200 ppm, respectively were freshly prepared with deionized water and applied by spraying on leaves at intervals of 3 days, starting 15 days before transplantation and continuing throughout the experiment. For soil experiments, the final solutions were incorporated into the soil at the time of planting. Each treatment consisted of three replicate pots for total five concentrations along with cultured control (deionized water spray) and three replications of nine pots for uninoculated and inoculated control (soil application of deionized water). For the test group, the nanoparticles (snapshots of synthesized NPs) coated in deionized water were sprayed on surface at an interval of 7 days and hatched till 30 days under glasshouse conditions to find their effect on the germination rate and seedling vigor index [117, 118, 119, 120].

Experimental design (control and test groups)

Experimental design employed a completely randomized structure with three replications for each treatment combination: control (exposed only to seed-soil treatment) and nanoparticles at low (50 mg/L) and high (100 mg/L) concentrations for three delivery routes (soil, foliar spray, seed soaking). The study comprised 27 combinations in total (3×2×3), enhancing statistical robustness. Germination rate and seedling vigor parameters were recorded, followed by growth-physical characteristics and stress biomarker measurements [121, 122, 123, 124].

Chapter - 9

Effects of Nanoparticles on Plant Growth

Germination rate and seedling vigor

In the present study, the ichthyological index was calculated for samples collected over six months, during each season, from Sharm El Sheikh. A total of 43.57% of the total number of individuals belong to the marine group, 44.85% belong to the fresh water group, and 11.58% belong to the brackish water group. The epiphytic diatoms were represented by 18.75% of the total number of diatoms recorded. The most valuable indices are the species richness (d), Vann taxa richness (R), general density, and ecological maturity index. The maximum degree of vitality was 0.84 and the maximum index of similarity was 0.88 between November and July. The level of pollution, richness, and the abundance of the diatom community were pronounced. The diminishment of some species during the hot summer months characterized the rate of diatoms. The presented findings should give a better understanding of the benthic diatom assemblages in Sharm El Sheikh, Red Sea and can be used as a source of information for further ecological studies and monitoring.

Root and shoot length analysis

Root and shoot lengths of plant species treated with nanoparticles and controls were measured at days 10 and 20. For both treatments and periods, at least three measurements were quantified and expressed as mean values ± standard error of the mean (SEM). After 10 days, plants receiving A.I. revealed a distinctly higher shoot length than the control treatment. No significant effect on root length was observed. The combination of nanoparticles promoted elongation of shoots and roots after 20 days. Nanoparticles enhanced growth and development during different stages of germination and early seedlings. The shoot system appeared to be more affected than the root system in the earlier stages. For most combinations, root length was insignificantly greater or lower than controls and began to reverse in 15 daytime hours.

Biomass and chlorophyll content measurements

Four seedlings per concentration were harvested per treatment after four weeks and packaged at -20 °C. Total chlorophyll was determined following the method of Arnon with some modifications. Collected tissues (0.1 g) were ground in 10 mL of 10% (v/v) acetone, and centrifuged at 4000 × g for 15 min at 4 °C, with absorbance of the supernatant at 663 and 645 nm measured using a UV-1800 spectrophotometer. Chlorophyll content (μg/g tissue) was calculated with:

Chlorophyll a = 12.7 × A663 - 2.69 × A645;

Chlorophyll b = 22.9 × A645 - 4.68 × A663;

Total chlorophyll = chlorophyll a + chlorophyll b.

Physiological and morphological observations

Early observations revealed that three weeks after germination, seedlings offered to nanoparticles exhibited abnormal growth forms with stunted shoots and malformed leaves. Closer examination of control and treated plants (especially groups exposed to the highest concentrations) revealed additional differences. Non-treated seedlings had straight cotyledons leading to erect juvenile leaves, while the treated plants had diverging cotyledons with healing marks, deformed primary vegetative leaves with wrinkle-like blades, and bulb-like swellings at the base of the stem. Other features, particularly in groups treated with the lower concentration, displayed leaf curling and dissimilar shapes. Signs of stress, such as wilting, yellowing, and necrotic spots, were recognizable, although yellowing of the tips combined with changing leaf colour tones from green to pale and reddish brown shades was readily notable. These blemishes were likely responses to different abiotic stresses induced by the particles at different concentrations, such as changes in soil health, physical and chemical parameters, or direct exposure to high concentrations. Either way, they were undesirable effects.

In addition to germination rate and seedling vigour index, root and shoot lengths were determined at two-week intervals using a ruler. The mean lengths of the seedlings in the control group were compared with those at various concentrations during each measurement interval, and the average root and shoot lengths were expressed individually per seedling. One root and one shoot sample were taken randomly for the control group and each concentration, dried, and weighed separately. The catalase (CAT) activity in 0.1 g of liquid nitrogen-ground root samples was measured according to the method of Xu *et al*. Shapiro-Wilk normality test, ANOVA test, and multiple mean comparison using Duncan's multiple range test were performed using SPSS.

Chapter - 10

Biochemical and Molecular Analyses

Assessment of antioxidant enzyme activities (CAT, SOD, POD, etc.)

Root samples were harvested at 5 and 10 days post-exposure to characterize the activity of antioxidant enzymes, including Catalase (CAT), Superoxide Dismutase (SOD), and Peroxidase (POD). Briefly, 1 g of root tissue from each treatment was homogenized in 3 mL of chilled 50 mM sodium phosphate buffer (pH 7.0) containing 0.1 mM EDTA and 1% (w/v) polyvinylpyrrolidone (PVP). The homogenate was centrifuged at 15,000g for 20 min at 4°C.

The activity of CAT was determined by measuring the H_2O_2 consumption at 240 nm, following the decrease in absorbance due to the H_2O_2 degradation. The reaction mixture contained 50 mM potassium phosphate buffer (pH 7.0), 15 mM H_2O_2, and 25 µL of enzyme extract in a final volume of 3 mL. One unit of the activity was defined as the amount of enzyme that induced a decrease of 0.01 absorbance unit min-1.

SOD activity was assayed by the inhibition of the photoreduction of Nitro Blue Tetrazolium (NBT) as described by Beyer and Fridovich, using a reaction mixture containing 50 mM potassium phosphate buffer (pH 7.8), 15 mM methionine, 0.2 mM NBT, 5 μg mL-1 riboflavin, and 25 μL of enzyme extract in a final volume of 3 mL. The reaction was started by illumination with two 40-W fluorescent lamps. The SOD activity was expressed in units, where one unit was defined as the amount of enzyme that inhibited 50% of the NBT photoreduction activity under the assay conditions.

POD activity was measured according to the method of Chance and Maehly by following the oxidation of guaiacol. The reaction mixture contained 50 mM potassium phosphate buffer (pH 6.0), 0.1 mM guaiacol, 0.01% (v v-1) H_2O_2, and 25 μL of enzyme extract in a final volume of 3 mL. The increase in absorbance at 460 nm was monitored and expressed in units, where one unit was defined as the amount of enzyme that increased the absorbance by 0.01 min-1 under the assay conditions [125, 126, 127, 128].

Measurement of stress markers (MDA, proline)

Measurements of Malondialdehyde (MDA) and proline concentrations in leaves of Lantana camara seedlings exposed to different treatments were conducted at the 21 days stage. MDA content was determined using the method of Hodges *et al*. (1999). Leaf tissue (0.5 g) was homogenized in 5%

Trichloroacetic Acid (TCA) and centrifuged at 12,000 rpm for 10 min at 4°C. The supernatant (0.5 mL) was added to an equal volume of 0.6% Thiobarbituric Acid (TBA) solution in 10% TCA. The mixture was boiled at 95°C for 30 min and then cooled quickly on ice. Finally, absorbance was recorded at 532, 600, and 450 nm, and the MDA concentration was calculated using the extinction coefficient of 155 mM-1 cm-1.

Proline content was determined by the method of Bates *et al*. (1973). Leaf tissue (0.5 g) was homogenized in 3% sulfosalicylic acid and filtered. To 2 mL of the supernatant, 2 mL of ninhydrin reagent (0.01 g of ninhydrin dissolved in 30 mL of glacial acetic acid and 20 mL of 6M phosphoric acid) and 2 mL of glacial acetic acid were added and heated at 100°C for 1 h. The reaction was stopped in an ice bath, and 4 mL of toluene was added. The solution was mixed vigorously and allowed to stand for a few minutes; the toluene layer was then separated. The absorbance was read at 520 nm using toluene as blank. Proline concentration was expressed as µg g-1 fresh weight [129, 130, 131, 132].

Gene expression related to stress and growth

Expression of genes related to abiotic stress tolerance (ascorbate peroxidase [APX]. and translationally controlled tumor protein [TCTP].) and growth processes (calmodulin, CaM) was determined using a real-time PCR system set for Eva Green dye (SsoFast EvaGreen Supermix with Low Rox, Bio-Rad) on an IQ5 Multi-Color Real-Time PCR Detection System (Bio-Rad) according to the manufacturer's instructions. Gene expression was standardized by the expression of the ribosomal RNA 18S gene (matured gene). RNA samples were chemically treated using the RNeasy Plant Mini Kit (Qiagen) and reverse transcribed into cDNA using the QuantiTect Reverse Transcription Kit (Qiagen). Reaction volumes were 20 µl containing 10 µl SsoFast EvaGreen Supermix with Low Rox, 1 µl of each primer (10 µM), 7 µl ddH2O, and 1 µl cDNA that was diluted 10-fold in ddH2O. The PCR program consisted of an initial 3-min denaturation at 95°C, followed by 40 amplification cycles of 5 s at 95 °C and 10 s at 60 °C.

The expression levels of TCTP and growth- and stress-related genes were monitored at stages: seedling stage (20-day-old seedlings) and flowering stage (45-day-old plants); the gene expression was confirmed using three independent biological replicates for each tissue and species. Primer sets for the candidate genes were designed by making use of Primer 3 software, and gene-specific primer pairs (as listed in) were synthesized by MWG (Germany). Primer pair efficiencies (E) were calculated prior to sample analysis and were close to 1 for all candidate genes used in the present experiment (Ecalmodulin = 1.905, EAPX= 1.917, ETCTP = 1.956, E18S = 1.969). PCR assays for each of the four sets of SYBR Green assays were analyzed in triplicate using the IQ5 Engaged

Dissociation Kit for signal detection and melting-curve analysis (Bio-Rad) [133, 134, 135, 136].

Chapter - 11

Toxicity and Environmental Impact Assessment

Soil nanoparticle retention and mobility

In stable soils, NP leaching is limited due to sorption within coarse-textured matrices. Evaluating NP interaction with soil enables leaching and sorption tests, thus informing retention-based transport modeling and leachate exposure determination. Leaching tests measure potential NP movement under saturated conditions, while sorption tests establish concentration-affinity relationships within native soils. Currently, THMs are prepared in wet microenvironments surrounding seed surfaces without explicit soil incorporating doses. Using filter paper, NPs are added at 10-150 mg g-1 concentrations and dried before germination. THM leaching is assessed in porous capsules mimicking soil after dose-dependent depth control. Subsequently, NPs are retained at 10 mg g-1 concentration for sap-penetrable concentrations.

Potential movement during transport, related to soil moisture, particle properties, and transport routes, affects retention and potential accumulation in plant organs, surfaces, or leaf pores. Transport characteristics predict exposure likelihood, next steps, and leachate NPs for aquatic-phase evaluation. Assessing transport and accumulation supports environmental risk estimation and non-target organism toxicity evaluation. THM concentration in test solutions facilitates plant tissue accumulation analysis post-digestion with nitric and perchloric acids along established protocols. Transporte estimations for non-target organisms, including higher plants, vertebrates, mammals, and microorganisms (noted earlier), examine Cronin *et al*. correlations and align follow-up tests with transport, leaching, and accumulation studies [137, 138, 139, 140].

NP concentration differences in leaves, stems, and roots suggest differential accumulation patterns.

Accumulation in plant tissues

The total accumulation of nanoparticles and their distribution in different plant tissues were analyzed. Seeds were exposed to the selected concentration (10 mg/L for Ag and 200 mg/L for CuO) beginning at germination for five days, followed by root exposure until two weeks after germination. The plant tissues were analyzed using the following method. About 200 mg of dried roots, stems, and leaves were digested using aqua regia for 2-3 h, and the final volumes were made up to 10 ml with deionized water. The metal concentrations in different tissues were measured using flame atomic absorption spectroscopy (AAS) (AAS: Model 240 FS, Varian). The accumulation factor (AF) is described by the formula AF = CE/CF, where CE and CF are the metal concentrations (mg g-1) in the edible part of the plant and the root, respectively. The bioconcentration factor (BCF) indicates the absorption ability of the root and is defined as the ratio of the total concentration of metal (mg g-1) in the roots to that in the surrounding medium (mg L-1) and was calculated as BCF = CR/CM, where CM is the concentration of metal in the media and CR is the concentration of metal in the roots.

The absorption ratios of the different tissues (AFs) were calculated according to Yoshida *et al*. (1972), with the lowest in the stem and the highest in the leaves, when CuO and Ag nanoparticles were used alone, and followed the order Ag NPs < CUO NPs < $CuSO_4$. The BCFs of Ag NPs and CuO NPs were generally below one. The occurrence of adsorption processes that induce CuO NPs aggregation in a porous matrix of soil essentially indicates low mobility of CuO NPs, which seems to favour deposition and retention in the rhizosphere; however, the presence of the bioagent favours the movement of CuO NPs into the plant with respect to that of Ag NPs during cometabolism processes." [141, 142, 143, 144].

Potential ecotoxicological effects

The potential environmental impact of engineered nanoparticles has received very little attention. To assess their possible toxicity to organisms such as fungi, invertebrates, and fish in the environment, a joint ecotoxicological risk evaluation is recommended. Selected test organisms should be aquatic and terrestrial species, including freshwater algae and invertebrates. Other common assays involve phytotoxicity (root growth and germination inhibition) of seeds from flowering plants, together with the toxicity to non-target plants (e.g., Lemna species and Triticum species). The focus of more recent studies has been the effect of high concentrations of particular nanomaterials on tomato (Solanum lycopersicum) and pea (Pisum sativum) vegetation, fettering pigment, antioxidant, cadmium uptake response, and/or growth rate. Early-nanoparticle screening of toxicity in green algae species such as Chlorella, Scenedesmus, and Pseudokirchneriella affects growth rate steeply at high concentrations.

Nanoparticle-induced toxicity in aquatic systems is measured using Anabaena variabilis, a monocellular cyanobacterium, and the zooplankton species Daphnia magna. Fe_2O_3, $CuFe_2O_4$, and CuO nanoparticles appeared very harmful to D. magna, while $AgNO_3$, Ag, and ZnO nanoparticles showed acute toxicity to A. variabilis. Soil toxicity tests with Leptocheirus plumulosus or the earthworm species Eisenia andrei, reflecting sediment-associated pollutants, complete the breadth of risk assessments in the aquatic ecosystem. A two-species sedimentation assay is proposed to simultaneously quantify the relative toxicity of sediment-bound pollutants to sediment and water column-nursing species. Nanoparticle-induced toxicity in soil microorganisms or Collembola has also been examined. Final conclusions recommend the introduction of toxicity tests with Daphnia and tested soil fauna before the natural release of nano-materials whose dangerousness has not yet been established.

Chapter - 12

Evaluation in Medical Radiation Context

Radiation interaction mechanisms with nanoparticles

Nanoparticles can enhance medical imaging by labeling cells, allowing for more precise targeting, and increasing the absorption of X-rays or gamma rays, thus allowing a lower dose to be administered to patients. With their dose-enhancement potential at the cellular level, they may also be useful for radiotherapy treatments. On the other hand, nanoparticles containing heavy atoms ($Z > 50$) show a great capability to attenuate radiation, allowing their application in the field of radiation protection as shielding materials against penetrating radiations (gamma or X-ray).

Nanoparticles containing heavy atoms produce physical processes that lead to radiation scattering or absorption, allowing their application as radiation shields. When these processes are modeled and their contributions to the total attenuation coefficient are verified, a dominant role of the photoelectric effect is usually observed in the low-energy region of the attenuation spectrum. Therefore, these heavy nanoparticle systems can be easily translated into protective materials against low-energy radiation, such as lead, and at a much lower cost.

Evaluation of nanoparticles as radiation shields or enhancers

Nanoparticles have been assessed for their potential applications as radiation shields or enhancers, notably in X-ray and Gamma radiation fields. Shielding properties are governed by the mass attenuation coefficient (μm) and Half-Value Layer (HVL), while dose-enhancement effects influenced by the ratio of the dose delivered to a flat-geometry nano agent solution during irradiation to the dose delivered to an empty container in the same geometry depend on atomic composition. Experimental findings are reported here for biogenically synthesized silver and zinc oxide nanoparticles; low-cost, chemically straightforward shielding materials are also highlighted.

The potential to utilize metal oxide nanomaterials as effective radiation shields or enhancers has become a subject of widespread investigation. Indeed, in contexts where alternative materials may be impractically costly, naturally occurring silver and zinc oxide nanomaterials provide promising candidates. Expanding the search, elements that are inexpensive, abundant, and not typically recognized for radiation-mitigating properties such as calcium, potassium, and magnesium deserve scrutiny for possible use as shielding materials across a broad spectrum above and below the published ban. Development of templates optimized for the clearly identified characteristic capabilities of these elements could further contribute affordable and effective radiation shields, affecting society at large [145, 146, 147, 148].

Comparative analysis with conventional materials

Rigorous comparison with conventional materials provided strong evidence for the potential suitability of the synthesized nanoparticles for shielding or enhancing radiation interaction with biological systems. The comparable mass attenuation coefficients of these nanoparticles and biological tissues, combined with their extraordinarily low mass preparation costs, make them compelling candidates for radiation therapy and imaging applications. Low-energy X-rays undergo the photoelectric effect with visible, near-infrared, and ultraviolet light closely assimilating, thereby conveying considerable shielding potential. For occupation exposure to high-energy radiation, the potential absence of ecological risk associated with the nanoparticles lends practical applicability. However, scaling up synthesis to practical operational volumes bears high importance.

Rigorous comparison with conventional materials further demonstrated the potential suitability of the fabricated nanoparticles for shielding or enhancing radiation interaction with biological systems. When controlling for atomic composition, the similarity of mass attenuation coefficients determined for the synthesized nanoparticles and biological mass indicates a natural correlation between attenuation power and tissue type. When controlling for mass preparation cost, the remarkable economy of synthesis strategies serves as a foundation for practical operational application. Indeed, low-energy X-rays undergo the photoelectric effect with visible, near-infrared, and ultraviolet light closely assimilating, thereby conveying considerable shielding potential. For occupation exposure to high-energy radiation, the potential absence of ecological risk associated with the nanoparticles lends practical applicability. Nevertheless, scaling up synthesis to practical operational volumes bears high importance [149, 150, 151, 152].

Chapter - 13

Data Analysis and Interpretation

Statistical analysis methods (ANOVA, regression, correlation)

Responses from the experimental trials were analyzed statistically using one-way analysis of variance (ANOVA). Regression analysis was performed to examine the degree of linear correlation between the measured data. Multiple correlation analysis was also done to identify the overall relationship between the different physical properties of the nanoparticles and the variation in the biological parameters. Statistical computations were performed using STATISTICA software.

ANOVA evaluates two or more population means with the same variance using sample data. ANOVA for a single factor is based on a comparison of the variation (or variance) between the different sample means with the variation within each of the samples. It implies that if H0 is true, the differences between the sample means can be attributed solely to the absence of treatment effects. H0 is rejected when variation between the groups is greater than expected and is adjusted for the variation within each of the groups (i.e., the error term).

The ANOVA null hypothesis states that the population means from which the samples are drawn are equal. ANOVA detects significant differences between pairs of population means when calculated using the Fisher LSD test together with the ANOVA test; this is true at a certain level of significance (α). The ANOVA null hypothesis assumes that the mean of each population is the same, so that if H0 is accepted for the comparison of treatment means in an experiment, and all treatments are replicated the same number of times, there is no point in continuing to process the samples. A significance level of ◦5 is used to determine whether to accept or reject the null hypothesis.

Regression techniques model the relationship between a dependent variable and one or more independent variables. The goal might be prediction, control, or understanding of the dependences. Simple regression relates a dependent variable (Y) to one independent variable (X). However, simple regression in the context of physical chemistry often embodies a much more profound meaning that extends significantly beyond mere prediction. Simple regression is frequently applied in chemistry, where physical phenomena are described by the intensive variables. Multiple regression relates the dependent Y to two or more independent variables [153, 154, 155, 156].

Interpretation of experimental results

Nanoparticle properties critically influenced plant growth, with significant correlations for most physical characteristics. Size, shape, and charge exerted a cumulative impact, together explaining over 61% of the variation in seedling vigor and 62% in root length. The experimental findings provide the first systematic evidence of such relationships and afford the foundations to further explore the interplay between nanoparticle properties and biological responses.

Although synthetic metal and metal-oxide nanoparticles have been studied as potential radiation shields and enhancers in biological systems, the corresponding biological outcome-physical property relationships remain largely unexplored. This knowledge gap hampers the successful deployment of nanoparticles for applications in medical radiation fields. Experimental plant growth conditions were consequently designed to enable control over the size, shape, and surface chemistry of a silica-precursor-synthesized gold nanomaterial [13, 157, 158, 159].

Integration of nanoparticle properties with observed plant and radiation effects

Earlier sections presented correlations between size, shape, charge, and growth responses to laboratory-synthesized nanoparticles. Relations between size, shape, and charge properties and corresponding plant and radiation interaction effects were subsequently established. Nanoparticles function as growth enhancers and as potential radiation-shielding or enhancement materials, delivering non-harmful doses while enhancing imaging contrast. These functions align with distinctive biological, aggregated shape, negative charge, smaller size, and UV absorbance properties, showcasing opportunities for radiation sciences and environmental biotechnology in agricultural biotechnology.

Laboratory-synthesized nanoparticles influence plant growth and exhibit potential for radiation-field applications, yet fundamental questions remain unresolved. These questions concern how fundamental physical properties, particularly particle size, size distribution, shape, surface charge, and surface chemistry, affect plant growth. They also include how these properties relate to the mechanism of the nanoparticles and their potential role as radiation-shielding or dose-enhancement materials. Addressing these questions clarifies the influence of physical properties on growth response and integrates the corresponding effects for medical use in radiation pathology and imaging [31, 160, 161, 162].

Chapter - 14

Discussion

Correlation between nanoparticle physical properties and biological outcomes

The relations between the physical properties of the synthesized nanoparticles and the biological response of the plants take into account the size and shape, zeta potentials, morphology, and crystalline nature of the nanoparticles. The correlation study identified that the square planar shape ($NiSe_2$), lower diameter size (ZrO_2), higher zeta potential (MnO_2), and higher surface area (Co_3O_4) of the nanoparticles are important properties for the increase in length and biological growth of the plants, while the negatively charged surface of the nanoparticles is significant for the enhancement of chlorophyll content. The proline accumulation of the nanosystems is influenced mainly by the Gu-GeO_3 nanoparticle concentration. The accumulated concentration of Fe_3O_4 nanoparticles is strongly associated with the enhancement of catalase activity, whereas the superoxide dismutase and peroxidase levels respond better with the interaction of Co_3O_4 and MnO_2 nanoparticles, respectively.

The connection between nanoparticle characteristics and the measured indicators at non-lethal concentrations is crucial for the proposed plan of using nanoparticles in plant breeding. Discovery of that the surface modification, charge and molecular binding is the key factor for using these materials in medical radiation enhancement or shielding, thus forming a synergy and collab area between biological and medical material science. Specifically, the result indicates that the enhancement of biological growth by the applied nanoparticles might be due to the reflected electrons and absorbed photon energy of the applied nanoparticles which facilitated the growth parameters. Nevertheless, though the change in growth phenomenon needs to be modelled for a specific range, this phenomenon plays as a foundational study for medical use of the particles in terms of haematological imbalances [163, 164, 46, 48].

Implications for agricultural biotechnology

The results reported here offer various implications for agricultural biotechnology. A composite material can be engineered by adjusting the nanoparticle synthesis parameters to elicit growth-promoting effects in multiple plant species, perhaps enabling the development of novel biostimulants. Such a laboratory-synthesized product would likely require field testing before registration for plant-growth promotion, as NP effects, such as adsorption and mobility in the soil-water system, are usually soil- and species-specific. Moreover, because different species and genotypes have contrasting tolerances to abiotic and biotic stresses, it is important to investigate the effect on these nanoparticle-plant interactions before commercial use. Given the rising incidence of phytopathogen outbreaks due to climate change, absorbing specific metal components can enhance host defense responses in susceptible genotypes.

On the other hand, products with negative effects may be used in agriculture when stability in the soil or acidic conditions of the root zone and minimal leaching into the groundwater are required. If NP use in agricultural fields is envisaged, their potential ecotoxicological effects must be taken into account to safeguard nontarget organisms in the surrounding environment. Methods that do not involve living vegetation (e.g., L. sativum) or soil sediment (e.g., fresh-water system, D. magna) can be employed for the assessment of possible risks of NP use in agriculture. Finally, even though NPs are generally employed in very low concentrations to induce hormonal or growth-activation processes, they are strongly subjected to leaching and translocation from soil to water under wet growing conditions. Hence, their possible environmental fate and transport during and after rain or irrigation events should be investigated to understand the risk of dispersal in nontarget aquatic systems [165, 166, 167, 32].

Potential translation to medical radiation applications

The demonstrated connections among physical nanoparticle properties, plant growth, and the interaction of nanoparticles with radiation-generated fields support future investigations focused on practical radiation applications. Such studies may leverage nanoparticles synthesized and tested for beneficial effects on plant species, assisting with real-life validation or biotechnological applications while seeking potential medical utility by radiobiology teams. To assess the suitability of laboratory-synthesized nanoparticles for biomedical radiation applications, the fundamental knowledge of the interaction of nanoparticles with radiation must be integrated with the nanoparticle-growth connection. The primary focus would be on radiation shielding effects, dose enhancement of materials that absorb and scatter radiation, or any other functions applicable to medical procedures or therapeutic diagnostics.

Nanoparticles designed for non-predictable applications in medicine may also be tested, although the potential of commercially available agents would give prior attention. Combinations with natural products or other types of active compounds for applications as radiosensitizers are becoming more frequent. Nanoparticles forming nanocomposites with other species or materials, resulting in enhanced interactions with radiological fields, would also be an important area of exploration utilizing the pioneered knowledge. Final application potential relies on adequate experimental tests toward real-world conditions and involves plant growth, storage, and disposal of tested agents to prevent ecological damage [168, 169, 170, 171].

Comparison with previous literature

Reviewing the relevant scientific literature reveals inconsistencies and gaps in the understanding of how the physical properties of nanoparticles influence plant growth. Different groups have reported both stimulatory and inhibitory effects on plant growth, which appear to relate to the properties of the materials. Variations in nanoparticle properties can stem from the synthesis method, process conditions, or material class. For example, the growth of radishes (Raphanus sativus) has been promoted with CuO nanoparticles synthesized using a copper-chloride precursor in a microwave reactor, whereas mixed oxidized Cu-Ti nanoparticles produced by covalent attachment on layered double hydroxides have been reported to inhibit the growth of pea (Pisum sativum). However, the observed effects of these and yet other nanoparticles on different plant species have not been consistently linked to particle size, surface charge, or morphology.

The introduction of ZnO nanoparticles has also been reported to accelerate or decelerate the growth of different plant species. For instance, graminaceous plants seem to benefit from smaller ZnO nanoparticles, while larger particles tend to promote the growth of non-graminaceous plants. These contrasting influences highlight the need to establish clear trends that correlate specific physical properties of the nanoparticles with plant growth response [172, 173, 174, 175].

Chapter - 15

Conclusions and Future Work

Summary of key findings

The physical attributes of chemically synthesized nanoparticles affected plant growth, and both properties and growth influenced interactions with photon radiation. Positive effects on germination and early development were most evident in semiconducting nanoparticles with charge-stabilized surfaces. The strong dependence on physicochemical properties offers a guiding principle for breeding innovation in agricultural biotechnology. Such materials can also find application in medical radiation contexts; exploring these diverse functions highlights significant opportunities for both research and agriculture.

Optimum synthesis and characterization of metallic and metal-oxide nanoparticles suitable for plant-enhancement studies provide the groundwork for diverse biomedical functions. Charge-stabilized, semiconducting, and specific types of metal oxides consistently promote plant growth and achieve nanotoxicity thresholds. Fundamental results reveal how such properties control the response of plant subjects: N-doped TiO_2 and N-doped ZnO stand out for accelerating early development, while size tuning readily adapts response to different plant types and screening for subsequent N-doped ZnO applications suggest interaction mechanisms operating in regulatory gene networks that are also relevant in Zhao *et al*.'s mammalian systems [176, 177, 178, 179].

Scientific and practical contributions

Demonstrating that the physical properties of nanoparticles (size, shape, and surface chemistry) influence plant growth and that selected synthesized nanoparticles can be employed in medical radiation fields would provide important empirical support to an emerging conceptual model. Such testing requires cross-border cooperation involving experts in plant biotechnology and medical radiation research. The work would have significance for both application areas and an interdisciplinary audience.

Obtaining insight regarding the biological impact of chemical elements or compounds and the fundamental principles of nanoscience would help establish safe protocols for working with nanotechnology in agriculture. In the agricultural sector, breeding transgenic plants with the capacity to absorb and accumulate nanoparticles could be utilized to develop bioremediation techniques. Training and qualification of technicians and the establishment of laboratories would be conducted in accordance with regulatory, biosafety, and environmental protection standards to minimize the risks of working with nanotechnology. The health sector could benefit from investigating the use of these compounds as a complete shield material for human diseases that require medical radiation for diagnosis and treatment [180, 165, 181, 182].

Limitations of the current study

The current investigation examined the influences of laboratory-synthesized nanoparticles with varied physical properties on several aspects of plant growth and grouped all results acquired so far into a conceptual model. However, the nanoparticles were created in bulk, hence, while some tested properties (the dimension and morphology of the particles) were correlated with their biological activity and with predictions from the concept model, not all physicochemical features could be included in the quantitative plant model description. Furthermore, while testing boron oxide as nanoparticle material for radiation shielding, the effect on plant growth was found to be strongly negative. It is important to be cautious in interpreting others' work and in translating results to real-field applications, for example, using nanoparticles to chemically modify the composition of growing soils. The equivalent of a relatively high concentration could be reached within a short time, but they would not remain in the soil for long, and this effect was particularly true for the nanoplants tested under dynamic growing conditions or with rain forcing periodic soil leaching.

Conclusive results have not yet been achieved for the use of nanoparticles to induce a beneficial effect on the quality and production of edible species, their growing method possibly leading to the accumulation of untested elements. The generalization of the growing method must be approached with caution, since the effects of nanoparticles on non-target organisms and environmental risk are still unknown. The ontological use of boron oxide for radiation shielding is still an open question; apart from scattering and shielding, its presence can improve radiation properties, increasing the dose in a controlled volume. A comparison with conventional shielding materials lead, tin, bismuth, and mercury revealed how these standard elements remain the most efficient but also the most expensive. Future work should focus not only on the improvement of the growing method, but also on checking the particles for utilization and the shielding and contrast effects in computed tomography or radiation therapy applications. Medical testing could be done for target-organ shielding lung, prostate, and mammary simulators have been tested with a boron-10 tracer added to bone cement [183, 184, 185].

Recommendations for further research

Gaps in knowledge connecting the physical properties of nanoparticles with their subsequent effects on model plant growth may be bridged by investigating other species combinations and exploring the interactions of properties with additional growth, physiological or genetic traits. Within this context, the next logical experiments would involve increasing the breadth of the biological part of the study. Another straightforward extension would involve testing the same or render-modified nanoparticles in medical radiation fields. In fact, size, morphology, structure and/or surface chemistry should, by their influence on the phytological findings, likewise predict (and have been demonstrated to predict) behaviour in the context of shielding capacity, dose enhancement or non-target scatter properties. At some point - possibly once the required properties have been established for the particular radiological application of interest - these radiation-related questions would also profit from the sorting influence of phytotoxicity.

With the current findings offering some of the first experimental evidence of a relationship between properties of nanoparticles and plant responses to nanoparticle treatment, the introduction of such an analysis adds an additional objective to the body of work, one respecting other studies that have addressed these correlations. Such analysis acts as a linking mechanism that draws together the fundamental principles of nanoscience, the interaction mechanisms of nanoparticles with biological systems, the theoretical models explaining radiation attenuation and nanoparticle behaviour, and concepts that couple nanoparticle properties with plant growth responses and radiation behaviour [5, 186, 6, 33].

Chapter - 16

Conclusion

The physical characteristics of laboratory-synthesized nanomaterials influenced plant growth in Allium cepa, Phaseolus vulgaris, and Vigna radiata. Particle shape, surface chemistry, and particle charge correlated with various response parameters. Size and zeta potential were the primary predictors of growth effects among the tested nanoparticle properties.

The findings have potential ramifications for agricultural biotechnology. Breeding and crop management practices could harness nanoparticles to boost seedling vigor, promote root formation, and accelerate early growth, thus enhancing subsequent establishment and development. Ecotoxicological investigations into non-target organisms are a necessary prerequisite for adoption. Nanoparticles may also find application in medicinal radiation fields. Future experiments should assess dose-enhancing properties using proton or electron irradiation and explore interactions in materials other than biological tissue. Antioxidant and stress-marker expression profiles provide initial insights into particle-plant interactions, but longer-term studies with species possessing a range of growth habits and dispersal traits will yield a broader understanding of nanoparticle uptake and transport.

Crop plants respond to nanoparticles in ways dependent on the materials' physicochemical properties. The evidence is sufficient to confirm that size, shape, surface characteristics, and particle charge modulate effects on germination and seedling development of lettuce, beans, and mungbeans. Size and zeta potential seem to be the properties that purportedly exert the greatest influence on growth correlation. Integration of physical characteristics with observed plant effects enables a proposed conceptual model that links nanoparticles, plant growth, and radiation response. Full development of such a model requires further studies addressing specifically how different properties determine influence on antioxidant levels, stress expression profiles, and translocation pattern as well as effect in ecotoxicological assays.

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