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Nanoparticles in Agriculture and Medicine: A Dual-Action Approach for Sustainable Farming and Health

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ABSTRACT

Nanoparticles have emerged as powerful tools with multifaceted applications across various domains, including agriculture, biotechnology, and veterinary medicine. This comprehensive review aims to elucidate the profound impact of nanoparticles in these fields, shedding light on their diverse roles and potential implications. In agriculture, nanoparticles exhibit remarkable capabilities in improving crop yield, enhancing nutrient uptake, and mitigating environmental stressors. Through targeted delivery systems and controlled release mechanisms, nanoparticles offer precise solutions for addressing challenges such as soil degradation, water scarcity, and pest management. Furthermore, their influence extends to biotechnology, where nanoparticles play pivotal roles in drug delivery, gene editing, and biomolecular sensing. By leveraging their unique physio-chemical properties, nanoparticles enable precise manipulation at the molecular level, opening new avenues for biomedical research and therapeutic interventions. Nanoparticles hold promise for advancing disease diagnostics, drug formulation, and animal health management. Their ability to traverse biological barriers and selectively target diseased tissues offers novel strategies for combating infectious diseases, enhancing vaccination efficacy, and promoting animal welfare. However, the widespread adoption of nanoparticles also raises important considerations regarding safety, environmental impact, and regulatory frameworks. Addressing these challenges requires interdisciplinary collaboration, robust risk assessment methodologies, and transparent communication channels. Overall, this review provides a comprehensive overview of the diverse applications of nanoparticles in agriculture, biotechnology, and veterinary medicine, while also highlighting the opportunities and challenges associated with their harnessing in these critical sectors. This review delves into the diverse applications of nanoparticles in the realms of agriculture, biotechnology, and veterinary medicine. Specifically, it elucidates their pivotal role in enhancing plant tissue culture, eliciting secondary metabolites, and driving pharmaceutical innovations. The potential of nanoparticles to revolutionize these fields through targeted delivery, enhanced efficacy, and environmentally sustainable practices is thoroughly examined. The dual-action approach of utilizing nanoparticles in both agriculture and medicine holds immense potential for creating a more sustainable and healthier future. By continuing to advance this field, we can address critical global challenges and pave the way for innovative solutions that benefit both farming and healthcare.

Keywords: *Nanotechnology, Pharmacology, nanoparticles, plant tissue culture, elicitation, Biotechnology, Agriculture*

Introduction

Nanoparticles are extremely small particles, typically measuring between 1 and 100 nanometers, and they possess distinct physical and chemical characteristics when compared to larger versions of the same material. These minute structures can be synthesized from a variety of substances including metals, polymers, and ceramics, and they are utilized in numerous industries and disciplines due to their exceptional properties. Nanoparticles can be classified based on their composition, size, shape, and method of synthesis. Common classifications include organic nanoparticles, such as liposomes and polymer-based nanoparticles; inorganic nanoparticles, like metal and metal oxide nanoparticles; and hybrid nanoparticles, which combine organic and inorganic components. Additionally, nanoparticles can be categorized as colloidal nanoparticles, nanocrystals, dendrimers, quantum dots, and carbon-based nanoparticles, each with distinct properties and applications (**Fig.1.**) Nanoparticles have become groundbreaking assets in the realm of medicine and pharmaceuticals, providing unparalleled prospects for precise drug delivery and diagnostic endeavors. They present distinctive attributes such as thermodynamic, electrical, structural, and optical capabilities, rendering them suitable for a myriad of applications in drug delivery, diagnostics, prognosis, and therapy [1]. Nanotechnology, with its emphasis on materials at molecular and sub-molecular scales, holds the promise of transforming medical and biotechnology tools and procedures, enhancing their portability, cost-effectiveness, safety, and ease of use**.** Nanomaterials, including nanoparticles, have flexible chemical, biological, and physical characteristics that enhance their efficacy compared to bulk counterparts [2] Pharmaceutical nanotechnology, particularly nano-drug delivery systems, has the capability to regulate drug delivery, enhance in vivo distribution, and improve treatment effectiveness . Nanoparticles provide several benefits including elevated stability, precise targeting, targeted release, controlled delivery, and the capacity to transport both hydrophilic and hydrophobic drug molecules [3]. Nanotechnology has emerged as a promising field in animal health and production, offering

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various applications such as therapy, diagnostics, vaccine development, and nutrition [4] . Due to their unique characteristics small size, high surface-to-volume ratio, and ease of surface functionalization—antiparticle have drawn interest in light of their potential to improve the nutrition and health of cattle. The integration of nano biotechnology, leveraging biotechnological approaches to enhance biocompatibility and reduce the cytotoxicity of nanomaterials, has broadened the scope of nanotechnology applications in veterinary science. Nanomaterials, including metal and metal oxide nanoparticles, carbon-based nanoparticles, and liposomal nanoparticles, have shown benefits in animal production and health by improving the shelf life of animal products, monitoring food-borne diseases, and enhancing nutrient delivery [5]. However, it is crucial to examine the potentially harmful effects and dangers connected with nanoparticles, and further research is needed to explore their usage in veterinary medicine and cattle reproduction [6].

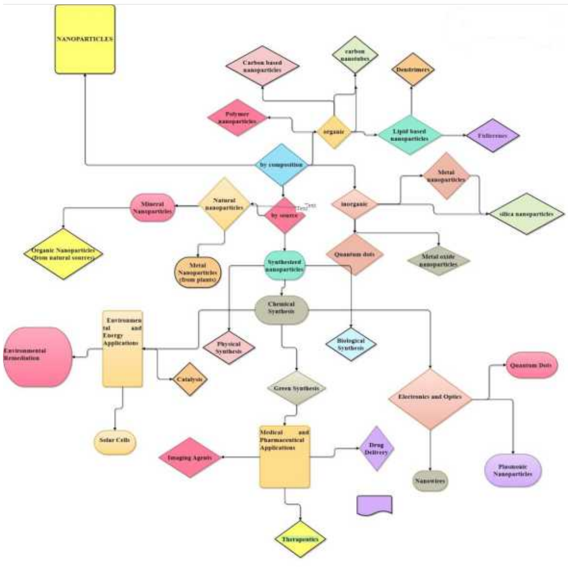

Fig.1.Nanoparticle classification

2. Methodology

2.1. Search Strategy and Selection Criteria

All currently available suitable studies were found by searching electronic databases: Wiley Online Library, Science Direct, Nature Journals, Elsevier's Scopus, PubMed, and SpringerLink. To guarantee complete coverage of the literature on the use of nanomaterials and nanotechnologies in veterinary care, the search was conducted without regard to a time limit. The terms " Nanotechnology', veterinary medicine', Nanoparticles', plant tissue culture', Elicitation' Biotechnology,' Agriculture were found through the search. There were several combinations of the keywords used. The titles and abstracts of every reference were verified by other separate writers. Only research that fit the criteria for the article were was included.

2.2. Data Extraction and Analysis

The author performed data extraction independently. The following information was obtained for each publication: publication year, publication type (original article, review article, book chapter, patent, etc.), journal title, type of article, publication region, first author, veterinary medicine, and animal species. The extracted data will be analyzed using qualitative methods to identify trends, patterns, and gaps in the current research. The analysis will also focus on evaluating the potential of nanoparticles to address key challenges in agriculture, plant tissue culture, biotechnology, and veterinary medicine, and to drive innovation in these fields. An article could be classified into several groups at the same time.

3. Nanotechnology and plant tissue culture

Plant biotechnology is a great tool in several fields of human life such as medicine, pharmacology, agriculture, biomass, and bio fuels. The use of nanotechnology represents and improvement in plant tissue culture that is a technique mostly used to produce clones of a plant in a method known as micropropagation with different stages. In vitro plant regeneration systems using cell and tissue culture are essential for biotechnological crop improvement programs. In vitro plant regeneration involves culturing, cell division, multiplication, de-differentiation, and differentiation of cells, protoplasts, tissues, and organs on defined liquid or solid media under aseptic and controlled conditions. Recent progress in plant tissue culture has made it a dynamic and promising area in experimental biology. Several studies have been published on in vitro plant regeneration in broccoli, including direct organogenesis, indirect organogenesis, and somatic embryogenesis [7] These studies provide valuable information to researchers and scientists working towards producing healthy, stress-resistant plant materials and conducting genetic transformation studies to produce transgenic plants.

The realm of nanotechnology has experienced rapid expansion and has found application across a spectrum of scientific disciplines. Nano-biotechnology, in particular, has been widely employed in drug and gene delivery, pathogen detection, disease management, and biological labeling. In the context of plant tissue culture, nanotechnology has been harnessed to enhance seed germination, increase yield, improve bioactive compound production, and provide plant protection [8] . Nanomaterials possess distinctive characteristics including low molecular weight, large surface-area-to-volume ratio, capacity for electron exchange engineering, specialized electronic and optical properties, and reactive surface capabilities. The passage of nanoparticles (NPs) into plant cells can occur through various aboveground and underground openings, and their effects on plants depend on several factors such as plant species, development stage, exposure time, and application method. NPs can be transported within the plant through the phloem via pressure differences between the leaves and roots or through the endodermis and cell wall pores. The route through which NPs enter the plant can alter various plant processes, such as germination, antioxidant activity, chlorophyll content, and photosynthesis [9] NPs can pass through the cell membrane and cell wall, binding to carrier proteins, ion channels, and aquaporins. The passage of NPs through the cell wall depends on their pore size. Small-sized NPs can pass through the cell wall, while larger NPs can pass through the stomata, hydathodes, and stigma. NPs are widely used in agriculture to enhance crop tolerance to abiotic stress, and they can have beneficial effects on plant growth, such as improving nutrient uptake, increasing yield, and enhancing resistance to pests and diseases. Metallic and metal oxide nanoparticles, including nano-Ag, -Au, -Fe, -ZnO_2, -TiO_2, and -CuO_2, have been documented to exert beneficial effects on plant tissue culture. These nanoparticles have been observed to bolster morphological potential and propagation while augmenting plant resistance to stress factors [10].

Nanoparticles possess unique properties that enhance their biochemical reactivity, and plants are exposed to them in the environment as abiotic stress agents.

At sub-toxic concentrations, nanoparticles act as abiotic stress agents, while at higher concentrations, they act as Phyto toxic agents . In the field of plant tissue culture, nanotechnology has progressively gained importance by offering new techniques to increase the efficacy and efficiency of genetic alteration and plant propagation. Through manipulation at the nanoscale, scientists can customize nanoparticles to deliver nutrients, growth regulators, and genetic materials directly to plant cells and tissues.

Plant explants have been grown and developed in vitro with the help of nanoparticles such as carbon nanotubes, gold nanoparticles (AuNPs), and silver nanoparticles (AgNPs). These nanoparticles have the ability to can transport plant growth regulators in a regulated manner facilitating precise regulation of plant growth and organogenesis [11].

Furthermore, nanomaterials can enhance the absorption of water and nutrients by plant cells, leading to improved nutrient uptake and overall growth. New techniques for genetic modification and gene transfer into plant cells are made possible by nanotechnology, which makes it easier to create transgenic plants with desired characteristics. The use of nanotechnology in plant tissue culture holds great promise for increasing crop yields, accelerating breeding programs, and developing plants with improved resistance to biotic and abiotic stresses, ultimately contributing to sustainable agriculture and food security [12]

Plant in vitro culture is a biotechnological process involving the cultivation of plant cells, tissues, or organs in a controlled environment under aseptic conditions with an artificial nutrition medium. The utilization of plant in vitro culture for purposes such as plant propagation, crop improvement, and pharmacological applications has been extensively discussed [13]. In agriculture, plant in vitro culture finds wide application in the mass production of low-proliferating crops, crop improvement, and as an ex-situ conservation approach for endangered species. This technique has been employed across a diverse array of botanical species using various methods and procedures, which is crucial in light of environmental concerns. Moreover, plant tissue culture serves as an important platform for the production of secondary metabolites, which have extensive applications in pharmacology and industry [14]. Recently, nanoparticles (NPs) have been utilized to eliminate microbial contaminants from explants, leading to successful outcomes in callus induction, organogenesis, somatic embryogenesis, soma clonal variation, genetic transformation, and secondary metabolite production. Plant secondary metabolites are responsible for the traditional medicinal use of many plants worldwide, and many studies have revealed to verified their pharmacological effects through bioassays and phytochemical studies [15]

[16] researched the cloning of secondary metabolite biosynthetic genes and the genetic modification of key genes to enhance metabolic flux towards target compounds. [17] investigated the impact of methyl jasmonate (MeJA) on Scopadulcic Acid-B (SDB) production in cultured tissues of *S. dulcis*. They discovered that MeJA suppressed the accumulation of chlorophylls, carotenoids, phytol, and β-sitosterol in the tissues. Moreover, MeJA has been observed to selectively stimulate the biosynthesis of enzymes such as Geranyl-geranyl-di-phosphate (GGDP) synthase and/or GGDP cyclase, along with other enzymes involved in SDB production in S. dulcis. [18] revealed that silver nanoparticles and their ions induced the biosynthesis of camalexin, hydroxycamalexin O-hexoside, and hydroxycamalexin malonyl-hexoside, essential phytoalexins for the Brassicaceae family, particularly the Camelinae clad, in response to both biotic and abiotic stresses.

Additionally,[19] also explored how nanoparticles affect callus culture, aiming to increase the production of bio-active phytochemicals. Similarly, in C. tuberculata shoot cultures, various ratios of plant growth regulators (PGRs) and silver nanoparticles (AgNPs) were introduced into in vitro cultures to achieve consistent and sustainable biomass production and antioxidant secondary compound synthesis. Their findings revealed that the highest phenolic and flavonoid content, as well as phenylalanine ammonolysis activity, were observed in callus extracts grown in MS medium supplemented with 90 μg/L AgNPs.

[20] found that plants recognize elicitors through plasma membrane-bound receptors, leading to the activation of various signalling pathways, including mitogen-activated protein kinase phosphorylation (MAPK), G-protein activation, NADPH oxidase activation, Ca^{2+} burst, respiratory burst (ROS), cytoplasmic acidification, ion fluxes, and downstream signalling molecules like methyl jasmonate (MeJa), jasmonic acid (JA), and salicylic acid (SA). [21] discovered that breakdown products of glucobrassicin (GBS) and neogluco-brassicin (NGBS), namely indole-3-carbinol and N-methoxy-indole-3-carbinol, have been identified as potential cancer preventive compounds.[22] conducted a study on the influence of ZnO and CuO ENPs on in vitro root formation, non-enzymatic antioxidant activities, and production of steviol glycosides (SGs) in regenerants of Candy leaf, *Stevia rebaudiana*. [23] evaluated the potential effect of ZnO nanoparticles (NPs) on callus proliferation and thymol and carvacrol production in three Thymus species: *T. vulgaris*, *T. daenensis*, *T. kotschyanus* and *Zataria multiflora*. Callus induction was performed on Murashige and Skoog (MS) medium having different plant growth regulators (PGRs).

[24] concluded that silver nanoparticles (AgNPs) have the potential to significantly enhance the production of bioactive antioxidants in callus cultures of C. tuberculata, a plant that is currently endangered but is significant due to its medicinal qualities. However, alongside their potential benefits, the use of nanoparticles (NPs) in agriculture raises certain concerns. These include the potential accumulation of NPs in soil and water, the risk of toxicity to non-target organisms, and the possibility of developing resistance in target organisms. Therefore, it is crucial to carefully assess both the advantages and risks associated with the application of NPs in agriculture, and to establish guidelines and regulations for their safe and responsible usage. Continued research in this field is essential to deepen our understanding of the mechanisms governing interactions between NPs and plants, and to devise effective and sustainable strategies for enhancing crop productivity and resilience in the face of environmental challenges.

4. Elicitation

Elicitation is a technique used to increase a plant's capacity to create secondary metabolites, hence improving the production of those metabolites . Elicitors are substances that trigger biological and physiological changes in plants. When exposed to these stressors/elicitors, plants activate defence responses against pathogens or natural stimuli that affect their bodies, ultimately leading to the formation of phytochemicals. Elicitors are mainly two main types: exogenous and endogenous. Exogenous elicitors originate from external sources, such as pathogens. In contrast, endogenous elicitors are produced by plants to trigger their immune response against specific stress factors.

Elicitors can be biotic, abiotic, chemical, or physical in nature. Abiotic factors can act as elicitors or facilitate the action of other elicitors, leading to increased production of secondary metabolites such as anthocyanins, flavonoids, and glycosides [25]. Utilizing advanced "omics" technologies such as proteomics, metabolomics, and transcriptomics provides important information into the intricate biosynthetic pathways of plants. These technologies help in understanding how plant secondary compounds are produced and how they are related to primary metabolism. By studying changes in gene expression after stimulation and observing the production patterns of specific secondary compounds, researchers can identify metabolic bottlenecks and potential areas for intervention. Furthermore "Omics" technologies, which control the expression of important genes like transcription factors and master regulators, are essential for modifying secondary pathways [26] While increasing the expression of these genes can enhance production levels in specific biosynthetic pathways, the incorporation of elicitors remains essential for achieving optimal yields. Therefore, choosing the most appropriate elicitor for plant cell culture is crucial for achieving successful production. Recent advances in synthetic biology have made it possible to accurately generate secondary proteins in heterologous systems

However, successful decision making in the cost-effective and sustainable marketing of plant secondary metabolites (PSM) is based on an in-depth understanding of the metabolic reactions occurring in plants and their underlying processes. Plant tissue culture has become a popular and sustainable method for producing high-value, economically significant metabolites under regulated conditions. To increase the yield of metabolites, strategies that involve supplementing plant cell culture media with elicitors have been employed to simulate natural conditions. Studies on nanoparticles (NPs) have explored their potential as substitutes for biotic elicitors like phytohormones and microbial extracts, with investigations into the elicitation of specialized metabolism. By designing mono dispersed-stimulus-responsive-, and hormone-carrying-NPs of precise geometries, it is possible to enhance their elicitation capabilities for specific metabolite/plant cell culture types. The progress in NP-mediated elicitation includes stimulation of specialized metabolic pathways, elucidation of the underlying mechanisms, examination of impacts on gene regulation, and evaluation of NP-associated cytotoxicity. This approach is novel in unleashing the potential of designer NPs to improve yield, harness metabolites, and transform nano elicitation from an exploratory investigation to a commercially viable strategy.

Elicitation is a popular method for boosting biosynthesis and can be applied to produce more of the compounds that are normally found in small quantities [27]. The efficacy of elicitation demonstrates variability based on the nanoparticles (NPs) utilized, with certain NPs demonstrating the capability to notably elevate the concentrations of specific compounds crucial in medicine. For instance, apigenin, emodin, and select xanthones, known for their therapeutic attributes including anti-inflammatory, neuroprotective, anticancer, and antimicrobial properties, were observed to be produced in increased quantities [28]

Among the NPs tested, Ag NPs induced the greatest accumulation of bis xanthone, gancaonin O, and fusaroskyrin in *H.perforatum* cells. Other NPs were also found to induce the formation of specific compounds, such as hypoxanthine C (Au), apigenin (Cu), emodin (Pd), emodin anthrone (CeO_2), dihydroxydimethoxyxanthone I (CuO), quercetin (TiO_2), and gallic acid (ZnO). Although these compounds belong to different categories of secondary metabolites, they can all be classified as phenolics, It has been demonstrated that NP types, such as Ag, Au, CuO, TiO2, and ZnO, promote the production of phenolic compounds in cell cultures [29]. On the other hand, the excretion of secondary metabolites from cells into the culture medium in response to other NPs that do not affect cell viability could be a result of stress response , nutrient uptake mechanism.[30].

[31] demonstrated the release of flavonoids such as quercetin, apigenin, naringenin, and rutin from cultured *Dracocephalum polychaetum* borne cells into the medium upon oxidative stress induced by Fe_2O_3 NPs. The detoxification processes observed in *Solanaceae nigrum* plants exposed to CuO NPs have been recognized to the elimination of phenolic compounds [32]. Additionally, the absorption of TiO_2 NPs by *Arabidopsis thaliana* plant cells, followed by their exocytosis as NPs-flavonoid conjugates, has been documented [33]. Plant innate immunity involves the triggering of defense mechanisms upon the recognition of conserved microbe-associated molecular patterns (MAMPs) by plant cells, acting as general external elicitors. Pathogen attacks can also trigger plants to release endogenous elicitors or danger-associated molecular patterns. Pathogen-secreted effectors previously known as particular elicitors represent a secondary level of perception including multiple families, including proteins, glycans, and lipids. {34}

Plant responses to elicitor-induced stress generally initiate at the plasma membrane. While the nucleus and plasma membrane-associated cytoplasm includes a large number of receptors, the focus of this analysis is on plasma membrane-associated elicitors because of their considerable cell culture research. Significant efforts have been made to isolate elicitor signaling molecules and identify their corresponding receptors. Given that elicitors can trigger responses in many ways, it is theoretically possible for plants to have multiple receptors to capture them. There are multiple elicitor binding sites in the cytoplasmic membrane for multiple elicitors with different chemical structures. In the entire process, R and avr products play an important role [35] Detection of elicitor signals by receptors involves activation of second messengers that sign the following effects [36]. The process involves recognition of elicitors, reversible dephosphorylation and phosphorylation of the plasma membrane and cytosolic proteins, increase in cytosolic calcium concentration, Cl and K+ ion flux and H+ ion flux, extracellular alkalinization, and cytoplasmic acidification of mitogens. The creation of reactive oxygen species and nitrogen (ROS and RNS), early immunity, the synthesis of jasmonic acid, late immune expression, and the buildup of secondary metabolites are all caused by the activation of protein kinase (MAPK) and NADPH oxidase. [37] . Plants respond to attack by incorporating antibacterial substances such as phytoalexins and pathogen-related proteins (PR), which play an important role in insect defense , recognition of Elicitor may improve plant resistance in the future [38].

4.1 Nano particle elicitation for secondary metabolism

In vitro cultures of plants supplemented with metal, metal oxide, and metal alloy nanoparticles are increasingly recognized as a technology for producing economically significant secondary metabolites consistently and in large quantities. Nanoparticles play diverse roles in plant biology, serving as triggers for secondary metabolites, sources of micronutrients, and even as antimicrobial agents. They also stimulate callus induction, organogenesis, shoot growth, and root initiation.

They have long been recognized to be poisonous and to induce abiotic stress in plants, but recent studies suggest they might also have applications in molecular pharmaceutics. This rapidly developing topic investigates the use of nanoparticles as agents for extracting these metabolites as conjugates from plant cells and as means of augmenting the production of advantageous secondary metabolites in plants, both in vivo and in vitro. The size, shape, application concentration, and chemical and mineral content of nanoparticles all affect how well they elicit secondary metabolites. Research revealed that nanoparticle concentration may have hormetic effects, further highlighting their complex role in plant biology.

Moreover, the morphology of nanoparticles plays a crucial role in the elicitation of anthocyanins in Arabidopsis seedlings, with spherical nanoparticles exhibiting the highest efficacy. As each nanoparticle-plant interaction is distinct, it is imperative to ascertain the optimal size, shape, concentration, and other parameters for maximizing secondary metabolite production on a case-by-case basis. Additionally, thorough investigations into the physical, chemical properties, and biological activities of the secondary metabolites derived from nanoparticle-treated plants are essential to assess their quality and effectiveness. It is necessary to thoroughly assess the potential toxicological risks of applying nanoparticles for the elicitation of secondary metabolites and to provide safety guidelines for the dosage and delivery methods of certain plants. Monitoring the complete life cycle of these nanoparticles, from fabrication to storage, transportation, application, and eventual disposal, is essential. Furthermore, the feasibility of implementing this technology for scaled-up production in field conditions or industrial settings requires evaluation, including an assessment of the associated costs of commercial production. A general outline of elicitation of secondary metabolites as in **Fig.3**

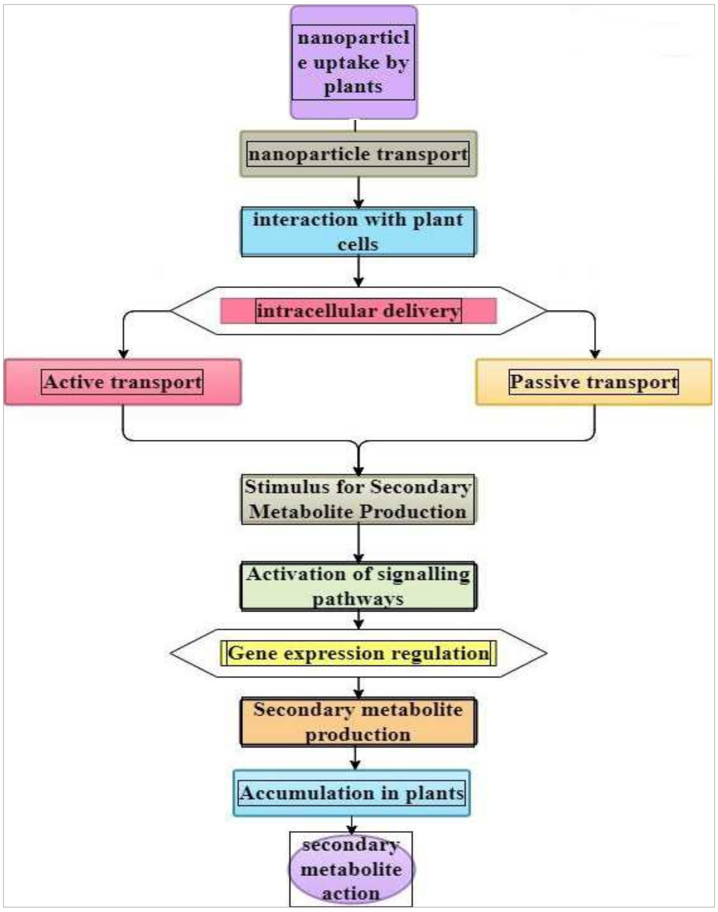

Fig. 3. General overview of the elicitation process

The research investigated the effects of nanoparticles (NPs) on secondary metabolism in various types of plants. For example, in Arthrospira platensis and Haematococcus pluvialis, treatment with TiO_2 NPs increased the release of phenolic compounds into the intercellular space. Following treatment with AgNPs, Artemisia annua's artemisinin content increased, and this rise was linked to oxidative stress. Fenugreek showed increased plant growth and diosgenin concentration after AgNP application. Ferulic acid and isovitexin levels increased in barley plants exposed to airborne CdO NPs. Additionally, Arabidopsis exhibits upregulation of anthocyanin and flavonoid biosynthetic genes in response to AgNPs [39]. Oxygen Species (ROS) itself can initiate metabolism in the central part of the plant, especially during work injury. These signaling molecules can directly or indirectly regulate secondary metabolism [40]..

ROS produced by nanoparticles (NP) may also serve as a signal for secondary metabolism,accordingtoindirectevidence . For example, ZnONP treatment induces salicylic acid (SA) but inhibits jasmonic acid (JA) in Arabidopsis. In addition, SAmediated systemic adaptive immunity against microbial infection is observed in A. After treatment of Arabidopsis thaliana with silver (Ag), titanium dioxide (TiO_2) nanoparticles , and carbon nanotubes (CNT). NP also influences nitric oxide (NO), brassinosteroid (BR), ethylene (ET), and other signaling pathways. The expression of elements involved in ET biosynthesis was shown to be downregulated in Arabidopsis plants treated with silver nanoparticles (AgNPs); this suggests that NPs may interfere with ET sensing and affect ET production, NP also has an impact on BR, a steroidal phytohormone that is crucial for plant development, secondary metabolism, and stress[41].

Plant responses to stress occur at both cellular and organismic levels, with stress signals initially perceived by receptors on the cell membrane. This sets off an intricate intracellular signaling flow that results in the production of additional signal molecules. One such molecule is inositol triphosphate (IP3), formed through the hydrolysis of phosphatidyl-inositol 4,5 bisphosphate (PIP2) by phospholipase C (PLC). IP3 diffuses into the cytosol, eliciting the release of Ca2+ ions from intracellular stores and the apoplastic space. Calcium sensors like calmodulin (CaM), calcium-dependent protein kinases (CDPK), and others interpret calcium signals to initiate a phosphorylation cascade regulating gene expression. Additional signaling molecules in plant stress responses encompass abscisic acid (ABA), salicylic acid (SA), polyamines, jasmonates (JA), and nitric oxide, often engaging in cross-talk [42].

Numerous secondary metabolites in plants are synthesized in reaction to stress, with their biosynthesis modulated by (methyl) jasmonate [(Me)JA], a plant hormone. The regulation of secondary metabolite production is influenced by developmental and tissue-specific factors, as well as external signals [43]. In the quiescent state, a protein family known as JAZ binds and inhibits specific downstream transcription factors (e.g., MYC_2) to suppress JA responses. Upon receiving the JA signal, the F-box protein COI1 interacts with and ubiquitinates JAZs, marking them for degradation via the 26S proteasome. This liberates downstream transcription factors to govern gene expression and initiate JA responses [44].

The size of nanoparticles dictates their cell penetrability, allowing them to enter plant cells through the apoplast and traverse the plasma membrane via endocytosis. Subsequently, symplastic flow facilitates their translocation within the plant.

The electron transport chain in mitochondria and chloroplasts has been shown to be harmed by nanoparticles, leading to an oxidative burst and the build-up of reactive oxygen species (ROS), such as singlet oxygen (1O2), hydroxyl radicals (OH), superoxide anions ($O_2.^-$), and hydrogen peroxide (H_2O_2) [46]. Exposure of duckweed Spirodelapunctata to Ag and ZnO NPs and cultured tobacco BY cells to Al_2O_3 NPs can induce reactive nitrogen species (RNS) (nitric oxide, NO) [47]. NO is recognized as a significant elicitor of plant secondary metabolism . The detrimental effects of metal and metal oxide nanoparticles (NPs) on plants have been the subject of numerous studies; these effects are primarily associated with the ROS burst [48]. ROS can interact with many parts of cells, causing lipid peroxidation, protein changes, and damage to DNA [49]. Furthermore, they activate the plant's enzymatic and non-enzymatic antioxidant systems, including key enzymes such as SOD, APX, catalase, and GST. These enzymes catalyze the conversion of $O_2.^-$ to molecular oxygen (O_2) or H_2O_2, detoxify H_2O_2 using ascorbic acid as a substrate, decompose H_2O_2 into water and O_2, and catalyze the conjugation of the reduced form of glutathione (GSH) to xenobiotic substrates for detoxification [50]. In conclusion, the utilization of nanoparticles for eliciting and extracting plant secondary metabolites holds promise for positively impacting industrial activities reliant on secondary metabolites, provided the technology is standardized and tailored for commercial application.

Types of nanoparticles used in plant tissue culture

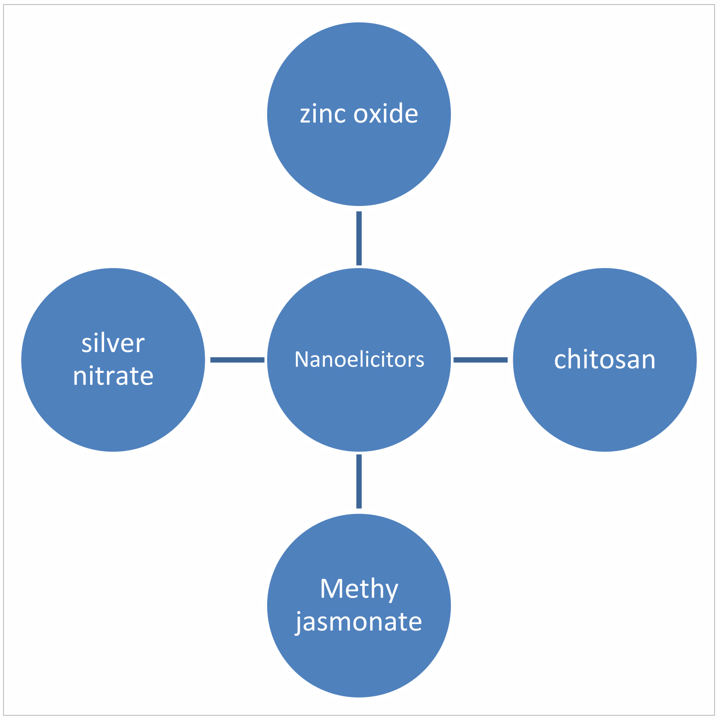

Fig.2. Nanoparticles for elicitation

4.2 Silver nitrate nanoparticles.

Silver nanoparticles (Ag NPs) have demonstrated beneficial effects on plant growth, development, and antioxidant activity. They can enhance photosynthetic rates and plant productivity while serving as antimicrobial agents against plant diseases. However, the impact of Ag NPs on plants varies with concentration; elevated concentrations may impede seed germination and hinder plant growth. Hence, it's crucial to regulate the application of Ag NPs in agriculture to make the most of the benefits while minimizing potential drawbacks.

It's noteworthy that despite their positive effects, the environmental and human health implications of Ag NPs should be taken into consideration. The slow release of Ag NPs into the environment can lead to their accumulation in soil, water, and plants, potentially disrupting the food chain and ecosystem. Furthermore, their potential toxicity to humans, including respiratory and neurological issues upon exposure, necessitates careful monitoring and regulation in agriculture and other sectors to ensure safe and responsible use.

Silver nanoparticles (Ag NPs) have become a popular choice in agriculture for crop enhancement and disease management due to their unique properties when reduced to nano size. It has been discovered that Ag NPs improve the general antioxidant status of plants and increase their growth and productivity. The effectiveness of Ag NPs is concentration-dependent, with a 50-ppm dose being ideal for improving plant growth[51]. However, high concentrations of Ag NPs can inhibit seed germination. Ag NPs are also used as antimicrobial substances to manage diseases in plants. While the utilize of Ag NPs in agriculture shows promise, it is very important to consider their potential toxicity and long-term effects on the environment and human health. Moreover, silver suppresses the expression of proteins linked to ATP synthesis . Ag NPs produced biologically improved tree seed germination and seedling growth. . In a hydroponic solution supplemented with Ag NPs, the germination of zucchini plant seeds and their root growth showed no adverse effects, although a decline in the presence of this NP, plant biomass and transpiration were found to prolong their growth [52]. Additionally, research was done on the application of Ag NPs as a pesticide substitute for the management of phytopathogenic fungi that develop sclerotium [53].

Furthermore, Ag NPs have demonstrated the capacity to improve nutrient uptake and utilization efficiency in plants. For example, In a study on maize plants, Ag NPs at a concentration of 10 mg/L significantly enhanced root length, root surface area, and root volume, improving the plants' ability to absorb and use nutrients [54]. Ag NPs have also exhibited the ability to enhance photosynthetic rate and efficiency in plants by increasing chlorophyll content and photosynthetic rate. A study involving spinach plants treated with Ag NPs reported a 30% increase in photosynthetic rate compared to the control group[55]. Additionally, When it comes to treating plant diseases, Ag NPs have proven to be a successful substitute for chemical pesticides. Their antibacterial qualities have been shown beneficial against a variety of plant diseases, including as bacteria, viruses, and fungi . In conclusion, Ag NPs offer significant prospective for enhancing various aspects of plant growth, including nutrient uptake, utilization efficiency, photosynthetic efficiency, and disease management in the agricultural sector. However, to avoid any unfavorable consequences on the environment or public health, its use must be closely regulated and monitored.

4.3 Zinc nanoparticles

Apart from enhancing growth and development, Zn NPs have demonstrated antimicrobial capabilities. For example, in a study examining the impact of ZnO NPs on Fusarium oxysporum-infected tomato plants, it was found that these nanoparticles effectively decreased the severity of the infection while promoting plant growth [56] However, the use of Zn NPs in agriculture is not without potential risks. Excessive accumulation of Zn in the soil can lead to environmental contamination, and the toxicity of Zn to both plants and animals at high concentrations is well-documented [57].

Thus, in order to reduce any potential harm to the environment and public health, it is crucial to strictly control the usage of Zn NPs in agricultural activities. Additionally, Zn NPs have been reported to improve photosynthesis and growth in various crops. In a study on maize plants, foliar application of Zn NPs significantly increased photosynthetic pigment content, photosynthetic rate, and biomass compared to control plants[58]. Similarly, in tomato plants, the application of Zn NPs resulted in increased growth, chlorophyll content, and antioxidant activity [59]. Moreover, Zn NPs have been shown to alleviate heavy metal toxicity in plants. In a study on soybean plants, Zn NPs reduced the negative effects of cadmium toxicity on growth, photosynthesis, and antioxidant activity [60]. Overall, Zn NPs have great potential for use in agriculture to improve crop growth and productivity, especially in Zn-deficient regions and under environmental stress conditions.

Zinc has an essential function in photosynthesis by controlling the activity of carbonic anhydrase, which is required for the conversion of CO_2 to bicarbonate, in addition to its responsibilities in plant growth and stress tolerance[61]. Zinc deficiency can result in decreased photosynthesis rates, inhibited growth, and diminished crop yield [62]. Therefore, the utilization of Zn NPs can act as an effective method to enhance plant growth, yield, and stress tolerance, particularly in Zn-deficient soils. Additionally, Zn NPs have been found to enhance photosynthetic rates and chlorophyll content in plants. For instance, a study involving rice plants revealed that Zn NPs augmented chlorophyll content and photosynthetic rates, consequently leading to elevated grain yield [63]. Furthermore, Zn NPs exhibit potential as plant growth promoters, enhancing the growth and yield of various crops such as wheat, maize, and soybeans. Additionally, zinc nanoparticles (Zn NPs) have antibacterial qualities against plant pathogens, which reduce the frequency and severity of plant diseases[64]. However, like other NPs, the effects of Zn NPs on plants can vary depending on their concentration, exposure time, and application method. Therefore, proper regulation and safe application of Zn NPs are crucial to ensure their beneficial effects on plants and avoid any negative impacts on the environment.

4.4 Methyl jasmonate and jasmonic acid.

Plant phytohormones known as jasmonates, such as methyl jasmonate (MJ) and jasmonic acid (JA), are crucial for controlling a plant's growth, development, and reaction to stress. JA and MJ are derived from linolenic acid and are involved in various physiological processes in plants, including the modulation of gene expression, defence responses, and stress tolerance, in particular, has been shown to trigger the reprogramming of gene expression in plants, allowing them to respond to environmental stresses such as insect attacks, pathogen infections, and abiotic stress. It has been demonstrated that MJ administration increases the expression of genes such as OPDA-reductase, lipoxygenase, and allene oxide synthase that are involved in JA production and related metabolic pathways. Overall, the regulation of gene expression by JA and its derivatives is complex and involves multiple signalling pathways and transcription factors. Further research is needed to fully understand the molecular mechanisms underlying JA signalling and its role in plant development and stress responses.

Pathogen invasion and bodily damage trigger the manufacture of these hormones, which in turn trigger local defense and response mechanisms.

Methyl jasmonate (MeJa), in particular, is one of the key JAs that regulates how plant defense genes signal [65]. MeJa (100200 μM), when applied externally to plant cell cultures of various species, positively affects the secondary biosynthetic pathway, resulting in increased production of plant secondary metabolites (PSM), such as terpene compounds, flavonoids, alkaloids, and phenylpropanoids [66]. MeJa added to the growth media increases the synthesis of aryl tetrahydropodo phytotoxin a PSM of medicinal interest. The family Trichodermaceae, which comprises six species of annual plants in Southeast Asia (five species) and eastern North America (one species, Podophyllum), is the source of podophyllotoxin. veil). Other plant species include Jeffersonia, Diphylleia, Dysosma, Catharanthus, Polygala, Anthriscus, and Linum also synthesize podophyllotoxin. Studies on pharmacology have shown that podophyllotoxin and its analogs have cytotoxic, antibacterial, and antifungal effects [67] Balkan-native flax species have long been employed as cancer treatments, which makes the flax genus one of the most researched for podophyllotoxin production. In cell suspension culture of the Linum album cell line 25aH, Hazra, *et al*. (2016) demonstrated a rise in podophyllotoxin and 6methoxypodophyllotoxin following MeJa induction. Furthermore, there was a 1.2-fold increase in the formation of 6 and 4'-dimethyl-6-methoxypodophyllotoxin in bull hair root culture upon the addition of exogenous MeJa.

Ginsenosides are a group of plant secondary metabolites (PSMs) that have demonstrated success in biotechnological processes. Ginsenosides are triterpenoid saponins known as the main pharmacologically active components in ginseng. Ginseng is a perennial plant belonging to the Araliaceae family that is widely used in health foods and traditional medicine. Many medical benefits of ginseng are thought to exist, such as enhancing immunity, boosting energy, enhancing general health, and lowering stress. There has been much research done on increasing growth and yield, yet there is still a shortage of this crucial chemical. On the other hand, there has been improvement in raising the ginsenoside content MeJa induction of ginseng hair culture [68]

Similarly, Methyl jasmonate (MeJA) from Anchusa italica research has been shown to be beneficial for the growth of perennial salt plants. Under salt stress, plant growth and several physiological traits such as new leaf weight, leaf area, chlorophyll concentration and protein content were reduced. However, the exogenous application of MeJA ameliorated these effects, leading to increased levels of chlorophyll a, total chlorophyll, proline, soluble sugars, protein, K+, and Ca_2+, while decreasing Na+ content in salt-stressed plants [69] Additionally, When exposed to salt stress conditions, pre-treatment with methyl jasmonate (MeJA) improved the development parameters of A. *italica*, including increased leaf and root fresh weights, leaf and plant dry weights, leaf area, and relative water content (RWC). These results revealed that MeJA shows promise for improving salt tolerance in A. italica and may be valuable in mitigating salt stress effects in other plant species.

Methyl jasmonate treatment of barley leaves decreased their nitrogen concentration. Additionally, certain HvTIP genes that are in charge of moving nitrogen molecules from the vacuole into the cytosol were upregulated as a result of this treatment. This process facilitates the remobilization of ammonia and urea. Furthermore, the MeJA pathway affected the expression of certain aquaporin genes involved in water transport during drought. [70] In three cultivars of Brassica oleracea L., the effects of a pre-sowing soaking treatment with varying concentrations of jasmonic acid (JA) and methyl jasmonate

(Me-JA) on the photosynthetic efficiency and expression of PSII-related genes. They discovered that both JA and Me-JA treatments increased the maximum quantum efficiency of PSII (Fv/Fm) in comparison to control seedlings. The improvement was more pronounced in the Me-JA-treated seedlings. The expression of PSII genes was differentially regulated among the three varieties of *B. oleracea*. The gene PsbI was upregulated in var. botrytis after treatment of JA and Me-JA, whereas PsbL was upregulated in capitata and botrytis after supplementation of JA. The gene PsbM showed enhanced expression in italica and botrytis after treatment with JA, and by both JA and Me-JA treatments. PsbTc(p) and PsbTc(n) were also found to be differentially expressed, revealing specificity with the variety chosen as well as JA or Me-JA treatments[71]. However, the RuBP carboxylase activity remained unaffected by either JA or Me-JA supplementation in all three varieties of *B. oleracea* L. The study concludes that exogenous application of JA and Me-JA to seeds before germination could improve the assembly, stability, and repair of PSII in the three varieties of *B. oleracea* examined. This improvement in the PSII machinery enhanced the photosynthetic efficiency of the system and improved the photosynthetic productivity in terms of saccharides accumulation.

4.5 Salicylic acid

Plant defenses are regulated by salicylic acid (SA), which triggers the resistance response (SAR) against a range of pathogens . A defense response is triggered by the fast accumulation of SA at the infection site, which results in an allergic reaction that spreads to other areas of the plant [72]. A common metabolic intermediary, SA encourages the synthesis of certain secondary metabolites (PSMs) in plants.

The use of salicylic acid (SA) induction to create diterpene alkaloids in the Taxus genus has been the subject of several investigations. For instance, According to [73] treating annatto cell suspension culture with the recommended dosage of 20 mg/L SA resulted increased paclitaxel synthesis. Furthermore, in paclitaxel cell culture, SA with magnetic stimulation improves paclitaxel. Additionally, SA has been shown to boost the synthesis of paclitaxel in hazelnut cell culture.

Salicylic acid (SA) has been shown to have a positive effect on Brassicaceae plants. In one study, it was observed that SA application alleviated the stress caused by NaCl in Indian mustard seedlings, leading to enhanced antioxidant enzyme activity and proline content [74]. Another study identified GH3 proteins in *Arabidopsis thaliana*, a model Brassicaceae plant, that can conjugate SA to regulate hormone concentration and downstream responses[75]. Additionally, the review article highlighted that plants produce signalling molecules like SA in response to stress factors, which can affect the production of phytochemicals in Brassicaceae plants . Furthermore, BABA, a non-protein amino acid, has been found to enhance defenses in Brassicaceae plants against pathogens and inhibit insect feeding, including aphids and Lepidoptera larvae [76].

SA derivatives and analogues, such as 2,6dichloroisonicotinic acid (INA) and benzothiadiazole (BTH) derivatives, have been used as drug inducers of systemic acquired resistance (SAR) in plants, protecting against fungi, diseases or diseases. In particular, BTH derivatives can activate the SA signaling pathway, thus strengthening the immune system. Antibiotics do not cause disease resistance in many crops, such as beans, cabbage, cucumbers, tobacco, apples, and pears, but one of these compounds, benzobenzolSmethyl (ASM), has been demonstrated to do so. [77] stated that the administration of 50 µM benzothiadiazole resulted in an increase in βsitosterol, campesterol, stigmasterol, sterols, and vitamin D levels in a Solanum malacoxylon cell culture. Preincubation of cultures with this drug promotes the induction of coumarin derivatives by fungal elicitors, especially in low responsive cell groups, because of variability in low elicitor concentrations and ambiguous development circumstances. Cell sensitivity to the elicitor appears to be correlated with the number of genes encoding enzymes involved in coumarin production.

Various studies have reported the impact of SA on broccoli harvesting parameters. In one study, SA treatment notably increased broccoli head weight, head diameter, and head volume[78]. Similarly, another study found that SA treatment enhanced broccoli yield and quality by improving head size, color, and marketable yield. In summary, SA has demonstrated positive effects on proline accumulation and broccoli harvesting parameters. SA treatment can elevate proline content in broccoli under stress conditions and enhance yield and quality by improving head size, color, and marketability. However, additional research is necessary to ascertain the optimal SA concentration and application method for maximizing these benefits.

4.6 Chitosan nanoparticle

Chitosan is a biopolymer derived from chitin, a substance present in the exoskeletons of crustaceans such as shrimp and crabs. Chitin, a polysaccharide with a long chain consisting of β-(1-4)-N-acetyl-D-glucosamine units, is widely distributed in several species, including yeast and fungi. Chitin deacetylase can be used for enzymatic hydrolysis of solid chitin or partially deacetylate it in an alkaline environment to produce chitosan, an important chitin derivative The construction and functionality of the cell wall depend on this process. These ingredients have been used in a variety of sectors after being refined from the crude extracts of yeast and fungus. It has a wide range of potential applications in the field of agriculture, such as acting as an elicitor and bio-stimulant to control physiological processes in plants and enhance their growth and development. Carbohydrate electors, like chitosan and chitin, have been applied in several ways. One of the benefits of using chitosan in agriculture is that it is non-toxic, biodegradable, and abundant in nature.

Chitosan nanoparticles (CsNPs) represent an innovative area of study, demonstrating potential in safeguarding plant photosynthetic machinery amid abiotic stress like drought or salinity. Furthermore, through inducing the antioxidant defense system in plants, CsNPs demonstrate the ability to mitigate the symptoms of poisoning. By upregulating genes linked to defense and raising the production of secondary metabolites, they can also strengthen a plant's innate immunity, helping it defend itself against pests and diseases. Because of this potential to lessen dependency on chemical pesticides, chitosan NPs are a viable tool for sustainable agriculture [79]. In a study investigating the impact of two different concentrations (0.05% and 0.1%) of chitosan nanoparticles as priming solutions for Vicia faba seeds cv. Sakha 1, followed by germination and subsequent growth of seedlings for seven days, it was found that chitosan nanoparticles prepared using methacrylic acid, with a mean size of 20 ± 2 nm, exerted both positive and negative effects. While both concentrations of chitosan nanoparticles negatively impacted germination and seedling growth criteria compared to the control (distilled water), the higher concentration (0.1%) had a more pronounced detrimental effect on germination.

On the other hand, when compared to the control seedlings, the lower quantity of CsNPs (0.05%) increased the amount of total phenols and the activity of antioxidant enzymes (catalase, ascorbate peroxidase, peroxidase, and polyphenol oxidase) [80] [81] conducted a study to determine the effects of chitosan-salicylic acid nanocomposite (CS-SA NCs) on grape plants under salt stress. They used two factors in a completely randomized factorial design: salt stress at three levels (0, 50, and 100 mM NaCl) and CS-SA NCs at three levels (0, 0.1, and 0.5 mM). The study found that salinity stress lowered the levels of chlorophylls (a,b, and total), carotenoids, and nutrient elements (except sodium) but increased levels of proline, hydrogen peroxide, malondialdehyde, total soluble protein, soluble carbohydrate, total antioxidant, and antioxidant enzymes activity. However, applying CS-SA NCs under different levels of NaCl mitigated these negative effects. Salinity stress also caused damage to the photosynthetic system, resulting in reduced values of Fm', Fm, and Fv/Fm. Nevertheless, the application of CS-SA NCs improved these indices during salinity stress. Moreover, in stress-free conditions, using CS-SA NCs enhanced the grape plant's physiological, biochemical, and nutrient elemental balance traits. The results revealed that CS-SA NCs at 0.5 mM had the most positive effect on the studied grape plant traits under salinity stress.

Chitin and chitosan induction causes strong podophyllotoxin production in L. album cell culture, along with a corresponding upregulation in the expression of genes involved in podophyllotoxin biosynthesis [82]. Similarly, they also found that paclitaxel synthesis was enhanced when chitin and chitosan were added to individual S. sinensis cell suspensions. According to study, T. sinensis cells treated with chitosan respond more favorably to several induction methods[83]. Phenylethanol glycosides accumulate in Cistanche Deserticola cell suspension culture when conditions are favorable for chitosan addition . In V, chitosan increased trans-resveratrol by a factor of 2.5[84].

Grape cell suspension culture promotes the accumulation of anthraquinones, phenolics, and flavonoids in adventitious roots of Morinda officinale . In vivo, chitosan induction in Hypericum perforatum roots causes a strong activation of secondary metabolism [85]. Triterpenoids with antibacterial, antifungal, antiviral, and antiAIDS activities increased in white birch cell culture treated with chitosan [86] . Moreover, adding chitosan to the mixture increased artemisinin production. Increased concentration of flavonoids in suspension cultures of Artemisia annua root hairs and Andrographis paniculata cells[87] . Therefore Chitosan nanoparticles have emerged as a promising tool in plant tissue culture and agriculture, particularly in elicitation processes. Their unique properties, including biocompatibility, biodegradability, and antimicrobial activity, make them suitable for various applications. In elicitation, chitosan nanoparticles are used to induce plant defense mechanisms, enhancing resistance to pathogens and environmental stresses. Furthermore, these nanoparticles have shown promise in plant tissue culture, where they can be used as carriers for the delivery of various compounds, such as growth regulators and nutrients, improving plant growth and development. As research in this area progresses, chitosan nanoparticles hold great promise for sustainable agriculture, offering novel solutions for crop protection and enhancement.

4.7 Copper oxide nanoparticles (CuO NPs)

CuO nanoparticles (NPs) have found widespread application across diverse fields such as superconductors, batteries, gas sensors, and agriculture, where they serve roles ranging from pesticides, herbicides, and fertilizers to additives for soil remediation and growth regulators [88].. Copper stands as a crucial element for plant growth and metabolism, exerting substantial influence on numerous physiological processes including photosynthesis, mitochondrial respiration, responses to oxidative stress, and hormonal signaling. These are some of the most extensively used metal oxide nanoparticles (NPs) in a range of industries, such as skin care goods, electronics, textiles, and wood preservation. Copper, a transition metal and a component of CuO NPs plays an essential role in redox processes in both animal and plant cells. In plants, copper is involved in regulating proteins, phenol oxidases, ascorbate oxidase, superoxide dismutase (SOD), and in electron transport during respiratory and photosynthetic processes.

Numerous enzymes, including superoxidase dismutase, amino acid oxidase, and cytochrome c oxidase, require copper as a cofactor [89]. Researchers are investigating the use of metal nanoparticles to boost growth and production in agriculture. Although a great deal of research has been done, it is still unclear how important mycorrhizal are to plants overall. Some studies indicate positive effects, whereas others reveal negative outcomes, Depending on the kind, size, and concentration of the nanoparticles, there are different effects on plants. CuO nanoparticles (NPs) have been shown to have both beneficial and detrimental impacts on plant growth. Biogenic CuO NPs were found to have a favorable impact on pigeon pea growth by [90]. On the other hand, rice plants treated with 1000 mg/L with CuO NPs showed lower photosynthetic pigment content, transpiration rates, and photosynthetic rates.

Moreover, CuO NPs have been found by [91] to cause oxidative stress and cytotoxicity in HEp-2 airway epithelial cells. Remarkably, the study discovered that oxidative damage and cytotoxicity in cells were not substantially induced by Cu_2+ ions released by CuO NPs. However, these ions were crucial in starting the Escherichia coli bacteria's generation of reactive oxygen species (ROS) and DNA damage. This suggests that the particle shape of CuO NPs may not be the direct mediator of these stress reactions [92]

[93] reported the special effects of copper oxide nanoparticles (CuO NPs) on the phytochemicals (GSLs and PCs) and gene expression levels as well as their biological activities (antioxidant, antimicrobial, and antiproliferative) in the hairy roots of Chinese cabbage. The CuO NPs elicited hairy roots showed a significant increase in copper content, glucosinolates (gluconasturtiin, glucobrassicin, 4-methoxyglucobrassicin, neoglucobrassicin, 4-hydroxyglucobrassicin, glucoallysin, glucobrassicanapin, sinigrin, progoitrin, and gluconapin) and transcript (MYB34, MYB122, MYB28, and MYB29) levels. Moreover, CuO NPs-elicited hairy roots showed enrichment of phenolic compounds (hydroxybenzoic and hydroxycinnamic acids), total phenolic and flavonoid contents, and gene expression (PAL, CHI, and FLS) levels.

[94] noticed that exposure to diverse concentrations of CuO NPs led to changes in chlorophyll, sugar content, and antioxidant enzyme activity in plants, which were dose-dependent. While lower concentrations of CuO NPs modestly boosted the pigment and sugar content of tomato plants, higher concentrations significantly reduced the chlorophyll and sugar content of the two test plants. The study also revealed that CuO NPs affected lipid peroxidation and electrolyte leakage in plants. CuO NPs glucobrassicin, neoglucobrassicin, 4-hydroxyglucobrassicin, and 4-methoxyglucobrassicin in hairy roots of watercress and broccoli.

Additionally, the aromatic glucosinolates of glucotropaeolin were found to be higher in hairy roots of *Tropaeolum majus* compared to callus, cell suspension culture, and two-month-old plant leaves [95].

It has been found that tomato seedlings germinate and grow more quickly when exposed to carbon nanotubes (CNTs). According to a study by [96]seeds that germinated on a medium containing carbon nanotubes produced a significant amount more biomass and showed far greater germination rates than seeds that were left as controls. On the other hand, studies have observed that copper oxide nanoparticles (CuO NPs) have dose-dependently inhibited growth in mustard and Hordeum vulgare [97]. However, copper is known to function as a micronutrient in plants, leading to the hypothesis that nanoparticles could be used as micronutrients to enhance plant growth and yields.

To investigate this hypothesis, a study was conducted by [98] to explore the effects of CuO NPs on mustard plants. In this study, mustard plants were subjected to foliar sprays of CuO NPs at concentrations of 0, 2, 4, 8, or 16 mg/L, and the nanoparticles were characterized using a scanning electron microscope. In contrast to the control group, the outcomes demonstrated that B. juncea benefited from lower concentrations of CuO NPs. Nevertheless, there is a scantiness of information in the literature on the beneficial effects of CuO NPs in plants, and more study is required to comprehend their impacts at the physiological and biochemical levels. Additionally, another study demonstrated that soaking wheat seeds in a nanoparticle suspension for two hours increased germination percentage and shoot growth, while copper nanoparticles (CuNPs) decreased germination percentage and severely reduced seedling vigor.

Numerous research on CuO nanoparticles has shown a range of effects on the growth and development of plants. According to [99], these nanoparticles can damage DNA and severely impede the growth of radish seedlings. At 10 mg/L, CuO nanoparticles were found to stimulate growth in Brassica napus, while higher doses had harmful effects. Furthermore, exposure of germinated canola seeds to CuO nanoparticles caused changes in the transcript levels of genes related to root and shoot tissues. CuO nanoparticles also inhibited the growth of duckweed more effectively than bulk CuO, with the negative effects on frond number changes in Lemna minor being partly attributed to Cu2+ released by CuO nanoparticles in the media[100]. Therefore Copper oxide nanoparticles have emerged as promising tools in elicitation and plant tissue culture, revolutionizing agriculture practices. Their unique properties, including small size, high surface area to volume ratio, and reactivity, make them effective elicitors, enhancing plant growth, development, and stress tolerance. Additionally, in tissue culture, they have been instrumental in improving plant regeneration and transformation efficiency. Despite their potential, further research is needed to fully understand their mechanisms of action, potential environmental impacts, and optimal application methods. Overall, copper oxide nanoparticles hold great promise for sustainable agriculture and plant biotechnology, offering novel solutions for enhancing crop productivity and resilience.

All things considered, the use of nanoparticles in a variety of industries, such as biotechnology, veterinary care, and agriculture, has sparked important breakthroughs recently. This thorough analysis explores the various ways that nanoparticles are used in different fields. Nanoparticles are transforming conventional agricultural methods by strengthening soil health, reducing environmental stress, and increasing nutrient uptake. Furthermore, using them in plant tissue culture methods has hitherto unseen possibilities for quick multiplication, genetic modification, and breeding resistance to disease. Furthermore, nanoparticles serve as potent elicitors, stimulating the biosynthesis of secondary metabolites in plants, thereby augmenting their medicinal and therapeutic properties. In the realm of veterinary science, nanoparticles play a pivotal role in drug delivery systems, diagnostic tools, and disease management strategies, ushering in a new era of precision medicine for animal health. Additionally, the intersection of nanoparticles with pharmaceutical sciences holds immense promise, facilitating targeted drug delivery, sustained release formulations, and personalized therapies. This manuscript provides a comprehensive synthesis of current research, shedding light on the multifaceted applications of nanoparticles and their transformative impact across diverse disciplines.

5. Conclusion

In conclusion, The fascinating and frequently surprising impacts of nanoparticles' small size are what make their *studies* so fascinating. The systematic study of nanoscience is still in its infancy, although some of these phenomena have been used for decades in materials technology. There is still much to learn. Innovations in nanotechnology lead to new effects being discovered, new nanomaterials being created, and models and conceptions being developed to explain experimental results. The considerable potential of nanoparticles for various applications has shifted the focus from pure scientific inquiry to technological innovation. Notably, one of the most fascinating aspects of nanoparticle research lies in the fact that conventional materials such as titania, carbon, or gold exhibit entirely different properties at the nanoscale. Consequently, these size-dependent properties enable the exploration of entirely new realms of application without necessitating the development of entirely novel material compositions. Simply varying the size, shape, and assembly of nanoparticles opens up avenues for diverse applications. Therefore the exploration of nanoparticles in agriculture, biotechnology, and veterinary medicine presents a compelling narrative of innovation and potential. Through this comprehensive review, it becomes evident that nanoparticles offer a multifaceted toolkit for addressing various challenges across these disciplines. In agriculture, nanoparticles hold promise for sustainable farming practices, improving crop yield, resilience, and nutritional value. Their integration into plant tissue culture techniques revolutionizes plant breeding and propagation methods, paving the way for enhanced crop productivity and disease resistance. Moreover, the elicitation of secondary metabolites through nanoparticle-mediated approaches opens new avenues for harnessing the therapeutic potential of plants in pharmaceutical and nutraceutical industries. In veterinary medicine, nanoparticles offer novel solutions for drug delivery, diagnostics, and disease management, thereby advancing animal health and welfare. Additionally, the synergy between nanoparticles and pharmaceutical innovations promises to reshape the landscape of personalized medicine, enabling targeted therapies and improved patient outcomes. As we continue to unravel the intricacies of nanoparticle applications, it is imperative to prioritize further research, collaboration, and ethical considerations to realize their full potential while ensuring environmental sustainability and safety. By harnessing the transformative power of nanoparticles, we can unlock new possibilities for addressing global challenges in agriculture, biotechnology, and veterinary medicine, ultimately benefiting human health, animal welfare, and ecological resilience.

Recommendations

Given the challenges and contributions highlighted in the study of nanoparticles in agriculture and medicine, we recommend a multifaceted approach to address these issues effectively. First, we advocate key difficulties include ensuring the safety and environmental impact of nanoparticles, optimizing their effectiveness in diverse agricultural settings, and understanding their long-term effects on human health. Additionally, there is a need for rigorous regulatory frameworks and interdisciplinary collaboration to navigate the scientific, ethical, and logistical aspects of nanoparticle applications. Despite these challenges, the study makes notable contributions by advancing our understanding of how nanoparticles can enhance crop yields and medical treatments simultaneously. It highlights innovative strategies for sustainable farming practices and offers insights into how nanoparticles can be harnessed for targeted health interventions, paving the way for future research and practical applications in both fields.

Conflict of interest

The authors declare that there is no conflict of interest regarding this Review article.

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