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Rame Gowda
Emeritus Scientist, Seed Technology Research Unit, All India Co-ordinated Research Project on Seed (Crops), University of Agricultural Sciences, Bangalore, Karnataka, India

Roopashree B
Research Associates, Seed Technology Research Unit, All India Co-ordinated Research Project on Seed (Crops), University of Agricultural Sciences, Bangalore, Karnataka, India

Uma Rani K
Research Associates, Seed Technology Research Unit, All India Co-ordinated Research Project on Seed (Crops), University of Agricultural Sciences, Bangalore, Karnataka, India

Corresponding Author:
Roopashree B
Research Associates, Seed Technology Research Unit, All India Co-ordinated Research Project on Seed (Crops), University of Agricultural Sciences, Bangalore, Karnataka, India

Application of nanotechnology in groundnut: developments and prognosis: A critical review

Rame Gowda, Roopashree B and Uma Rani K

Abstract
Nanotechnology was key to the agrotechnological revolt, which has the ability to change the robust agricultural system while ensuring food security in the near future. As a result, nanoparticles have risen as a groundbreaking product capable of revolutionizing modern agriculture processes. Diverse formulations based on nanoparticles, such as nano-sized fertilisers, insect deterrents, fungicides, herbicides, and sensors, have been carefully explored for crop management of groundnut in the field and warehousing of seeds to preserve its viability, vigour, and health. This study was carried out to provide a synopsis of the studies undertaken on the use of nanoparticles in groundnut.

Keywords: Groundnut, storage, field conditions, seed quality

Introduction

Groundnut (*Arachis hypogea* L.), which is grown largely for its oil, protein, and carbs, is among the world's top and most lucrative oleaginous crops grown in tropical and subtropical zones (Panhwar, 2005) [29]. It comes from South America and is a member of the Leguminaceae family. One of the most significant cash crops in our nation is groundnut. Oil from groundnut seeds, which is utilized for both industrial and culinary applications, is present in good amounts (between 46 and 52%). Additionally, it has high calcium, thiamine, and niacin contents and is abundant in protein (22-26%), carbohydrates (26%), and fat (3%), which contribute significantly to the protein needed for human and animal nutrition. Groundnut is grown in about a hundred countries but, India is the world's top in terms of both output and area. It is predominantly grown in several states including Karnataka which contribute to (80%) of the total area and output. In addition to being high in energy (567 calories per 100g), groundnuts include vitamins, minerals, antioxidants, and elements essential for preserving good health. They contain enough oleic acid and other mono-unsaturated fatty acids. LDL, or "bad cholesterol," is reduced, while HDL, or "good cholesterol level in the blood," is raised. In terms of vegetable oil production, groundnuts are the second-largest source after palm oil.

The residual oil cake contains N (7%), P_2O_5 (1.5%), and K_2O (1.2%). This is a crucial source of protein for livestock and poultry feed. The plant is fed to animals in its green, dried, or silage form. De-oiled groundnut cake is used as cow feed and organic fertilizer. Groundnut seeds are high in protein and more palatable and digestible than other seeds. Groundnuts are grown on 31.50 million hectares throughout the world and produce 53.6 million tonnes at 1701 kg/ha of productivity (FAOSTAT, 2020) [18]. With a yield of 10.21 MT and productivity of 1676 kg/ha in India, groundnut is produced in an area of roughly 6.09 million hectares. In Karnataka, 0.70 million hectares were covered for 2020–21, with a production of 0.68 MT and productivity of 966 kg/ha (Agricultural Statistics at a Glance, 2021) [5].

The lack of groundnut productivity is primarily attributed to a number of factors, including the growing of crops on marginal and sub-marginal lands, an unpredictable monsoon season that frequently results in drought, poor adaptation of improved agronomic practices, and a lack of improved varieties of high-quality seeds. The viability of seeds during storage is influenced by several intrinsic and extrinsic factors. The importance of these factors is mostly determined by the seed moisture, storage temperature, relative humidity, oxygen availability, and pests and diseases. The physical, physiological, and chemical makeup of the seed plays a major role in the loss of seed viability caused by seed degradation (Delouche *et al*., 1973) [12]. In addition, improper management of plant nutrients, particularly micronutrients, has a significant impact on the development and production of groundnut seeds. Groundnut seed is traditionally stored for a duration of around 8 to 9 months before sown.

Yet, seed quality rapidly deteriorates due to reactive oxygen species generation by lipid peroxidation (Konanki *et al*., 2019) [24].

When it comes to controlling the deterioration of groundnut seeds, the most contemporary tools accessible to extend the shelf life of groundnut seeds on a broad basis are not proficiently minimizing the tangible issues of storage. Numerous efforts have been made over the last ten years to use nanomaterials and nanodevices in biological systems to solve a variety of field challenges. Unfortunately, because there aren't any better post-harvest storage techniques, a lot of seed is lost. But this loss may be somewhat managed by using the latest third-generation therapies. A new tool, nanotechnology, promises to boost agriculture greatly, sparking a new revolution (Konanki *et al*., 2019) [24]. Nanoparticles are different from standard bulk materials because they have distinctive features such as a big surface-to-volume ratio owing to their extremely tiny particles size varying from one to 100nm and their exclusive physiochemical and morphological characteristics and as such ‘Nano sized’ materials currently have been important in studies of basic and applied sciences.

Modern agriculture places a high value on technology and accuracy, necessitating that all seeds germinate quickly and produce a healthy seedling to ensure a higher yield

High-quality seed is a fundamental and crucial element that plays a big influence on agricultural success. Modern agriculture lays a great emphasis on technology advancement and accuracy, necessitating that all seeds germinate fast and produce a normal seedling, to ensure a higher yield. Nanomembranes around the seed help to increase seed storability by incorporating nanopesticides, nanosensors to better manage seed infestation during storage, and insertion of novel genes for a particular trait into seeds are examples of applications of nanotechnology tools in seed science research. Further, the incorporation of bioactive chemicals in their nano form to improve seed quality regard to germination and seed vigour could also e explored for better crop productivity. The kind of crop, its age, and how long a particular nanoparticle is exposed to a crop have important roles, but adding a dose beyond the dangerous threshold can harm plants and the environment.

Nanoparticles aid in seed germination by triggering hydrolytic enzymes engaged in the mobilization of food reserves and promoting water intake via the formation of pores on the seed coat. Further, it activates certain enzymes responsible for controlling an array of metabolic processes (Korishettar *et al*., 2016) [25]. It is well known that nanoparticles can provide free radicals an electron to couple with, squelching their effects. Together, these steps help to reduce the harm done to seeds during storage while increasing their vigor and viability (Sandeep *et al*., 2019) [37].

Approximately 50% of the nitrogen and 90% of the phosphorus used in crop production dissipate into the surrounding environment causing greenhouse gas emissions, eutrophication in waters, and salt buildup in the soil (de Costa *et al*., 2013) [8]. Nanoparticles act as an alternative to traditional smart fertilizers for ensuring excellent crop output and soil rejuvenation (Zulfiqar *et al*., 2019; Achari and Kowshik, 2018) [51, 3]. Compared to conventional micronutrients, NPs are being examined more and more as fertilizers for crop improvement on both a quantitative and qualitative level (Dimkpa *et al*., 2017) [15]. Compared to their traditional counterparts, NPs are more reactive and have the ability to have an impact on plants that is both positive and inhibiting. Plants require trace amounts of micronutrients for their growth; delivering these elements in "*nano form*" could be both affordable and ecologically sound while also substantially lowering the use of pesticides (Dimkpa *et al*., 2019) [14]. When applied as a foliar spray or as soil additions, NPs' ability to permeate plants is one of their key qualities (Pollard *et al*., 2008) [30]. A thorough literature search is started to envision the significance of treating seeds with nanoparticles and its consequences on the quality and productivity of groundnut by taking into account the crucial function that these few nanoparticles have on seed quality and plant growth.

Applications of Nanotechnology in Groundnut

Nanoparticles Mode of Action

Nanoscale materials, which are typically less than 100 nm in size, exhibit novel chemical, physical, and biological properties when compared to bulk equivalents. Nanoscale calcium oxide particles (69.9 nm in size) may penetrate through groundnut phloem tissue and it’s confirmed on visual ratings of calcium deficiency repair and calcium concentration in plant sections. Because bulk calcium cannot be used as foliar nutrition due to its instability in the phloem (Deepa *et al*., 2015) [11].

Nanoparticles through foliar spray

Foliar applications of nanoparticles have been used meticulously in agriculture like fertilizers, insecticides, growth stimulants, and so on, to boost crop production in recent years. However, research on the absorption of nano fertilizers through foliage and their interactions with plants is sparse. El-Metwally *et al*. (2018) [16] assessed the response of peanut plants to various foliar applications of nano-Iron, Zinc, and Manganese under sandy soils and figured that applications of 10, 20, 30, and 40 ppm nano fertilizers drove higher numbers of pods weight and 100 seed weight of peanut over control.

The influence of nanoparticles on growth is typically determined by the nanoparticle concentration and the crop/cultivar. Hussein *et al*. (2019) [21] evaluated three different cultivars of groundnuts NC, Giza 6, and Gregory, to observe how selenium nanoparticles (SeNPs) influenced growth promotion. The cultivars studied differed biochemically and physiologically. Foliar application of SeNPs at the vegetative stage boosted the development of Gerogory cv. and Giza 6 cv., however, SeNPs treatments had a substantial negative impact on NC cv. growth characteristics. SeNPs' influence on groundnut cultivar development was connected to changes in photosynthetic pigments, antioxidant enzymes, total flavonoids, phenols and soluble sugars. In examined groundnut cultivars, nano selenium acts as a stimulant strengthening antioxidant defense mechanisms and boosting plant tolerance to sandy soil conditions.

The effects of foliar spraying on groundnut plants with different levels of bulk tetraethyl orthosilicate (TEOS @ 2000 ppm), and nanoscale silica (N-SiO_2) have been examined in the study by Prasad *et al*. (2023) [33]. Plant height, total dry weight, water use efficiency, photosynthetic rate, nodule count, and ascorbic acid content were all significantly increased over control by the 400 ppm N-SiO_2 foliar spray.

When N-SiO_2 at 400 ppm was used instead of TEOS and the control, the pod yields per plant increased by 25.52 and 31.7%, respectively. Fluorescein isothiocyanate (FITC)-N-SiO_2 penetrate via stomata and moves apoplastically to different parts of the plant by vascular bundles.

The interaction of nanoparticles and plants is a key part of risk assessment since plants are one of the fundamental components of all ecosystems. In order to comprehend this idea, Santos-Espinoza *et al*. (2021) [38] explored the biochemical and physiological repercussions of *Arachis hypogaea* L. plant exposure to Ag, Cu, and Cu/Ag phyto-nanoparticles. For 48 days, NPs solutions were delivered through foliar spray at concentrations of 250, 500, 750, and 1000 ppm. Indicators such as chlorophyll and phytohormone content revealed that nanoparticles might substantially impair plant growth and development. To combat the stress caused by moisture, plants exposed to nanoparticles increased total PAL activity, proline, phenols, and antioxidant enzymes. The fatty acid content in peanut kernels changed, suggesting that these NPs may have an impact on crop productivity and quality. Therefore, it is important to look into any potential effects on peanut food quality.

A key objective is to produce more oil crops in reclaimed soils while also increasing seed and oil yields. Therefore, a field experiment was carried out by Abdel-Hamid Ali Abdel-Mawla *et al*. (2020) [2] using the three groundnut cultivars NC-9, Gregory, and Ismailia with zinc oxide nanoparticles at different concentrations. For the majority of the examined features, significant variations between zinc oxide nanoparticle (ZnO NP) concentrations were found. The spraying of zinc nanoparticles resulted in remarkably good reactions from all peanut varieties. Increasing the concentration from 200 to 600 ppm resulted in an improvement in the majority of the evaluated features. Additionally, the NC9 cultivar produced the highest seed yield, with non-significant variations across peanut cultivars for oil output. As a result, the study reveals that the impact caused by nanoparticles is dependent on cultivars and dose.

Impact of nano-chemicals on plant growth and yield

Conducting field studies is necessary to examine the impacts and varied responses of nanoparticles on crop productivity. For the first time, Prasad *et al*. (2012) [32] picked the peanut plant as the model system because it is widely cultivated in India and other areas of the world and because nanoparticles may have an impact on its growth. Different quantities of chelated bulk zinc sulfate ($ZnSO_4$) suspensions and nanoscale zinc oxide (ZnO)-25nm suspensions were applied to independent treatments on peanut seeds. Treatment with 1000 ppm nanoscale ZnO enhanced seed germination and seedling vigor, leading to early establishment in the field correlating to early flowering and higher chlorophyll content and compared to chelated bulk $ZnSO_4$, pod output per plant increased by 34%. As a consequence, a field-testing utilizing nanoscale ZnO particle at a 15-fold lower dosage than the recommended chelated $ZnSO_4$ produced 29.5% and 26.3% higher pod yields, respectively.

Sandy soil, which quickly diffuses nutrients, is frequently used to cultivate peanuts. The practicality of iron oxide nanoparticles as a fertilizer substitute for conventional Fe fertilizer was examined by Rui *et al*. (2016) [35]. Fe_2O_3 NPs and a chelated-Fe fertilizer were tested in sandy soil on the growth and development of a peanut crop that is highly susceptible to Fe deficiency. Fe_2O_3 NPs boosted the plant height, biomass, and chlorophyll values in peanut plants by directing phytohormone and antioxidant enzyme activity. Adsorption of Fe_2O_3 NPs on sandy soil increases Fe accessibility to plants. These findings showed that Fe_2O_3 NPs might be used instead of standard Fe fertilizers in the peanut field.

Nano-fertilizers are ranked as the most effective inputs to agriculture for improving crop growth metrics, yield and its components, and crop quality by improving nutrient usage efficiency. Field experiments were carried out to study the effect of potassium nano-fertilizer with various concentrations (100, 200, 300 and 400 ppm) at the vegetative stage of the crop and split applications (50+50, 100+100, 150+150 and 200+200 ppm), the one at vegetative state and other at pod development period on groundnut growth parameters, seed yield and quality under sandy soil. The treatment of potassium nano foliar application (@150+150 ppm) surpassed other treatments in shoot fresh weight, dry weight, root circumference, seed, pod, oil yield and nutrient content in shoots while, the foliar treatment (100 ppm) showed total chlorophyll in leaves than other treatments (Afify *et al*., 2019) [4].

In order to learn more about the effects of zinc and calcium nano-chelates on the quantitative and qualitative traits of groundnut, Nobahar *et al*. (2019) [28] conducted the a for mentioned study on the crop. The production of peanuts was boosted by Zn and Ca nano-chelates when applied to the leaves and the soil. Foliar Zn nano-chelate application along with topping the main stem 20 cm above the soil produced the highest seed yield per unit area, harvest index, biomass, oil, protein yield, seed Zn and Ca content. In general, enhancing the nutritional state of groundnut plants using Ca and Zn supplements is advised to increase groundnut production quantitatively and qualitatively.

Nanoscale nutrients are now regarded as newcomers to contemporary agriculture. Prasad *et al*. (2023) [33] released the first research on the impact of combined application of nanoscale nutrients of zinc (N-ZnO), calcium (N-CaO), and silica (N-SiO_2) on groundnut growth and production. With the simultaneous application of nanoscale nutrients at 350 ppm, significant pod output was obtained, representing an 18% increase above bulk nutrients. Increased pod production can be attributed to highest chlorophyll content (8.5%), leaf area, total dry matter other than peg-to-pod ratio (4.7%), and test weight (27%) higher than bulk nutrients.

Abdelghany *et al*. (2022) [1] showed that boron (B) @ 200 ppm + calcium (Ca) @ 200 ppm combination (Ca+B) improved plant height, shelling percentage, 100-seed weight, oil content, seed protein and seed yield to the greatest extent possible. B @ 200 ppm showed the highest amounts of seed nitrogen, pods per plant, and biomass. This implies that nanotechnology and bio-fertilization are the outset towards sustainable progressive farming. The framework established by this study allowed for further investigation of the molecular processes that these nanoparticles and biofertilizers use to benefit plants.

Bio-assay studies

Around the world, and especially in India, diseases of oilseed crops are a big problem. In the work of Bharani *et al*. (2014) [6], increased pesticidal effectiveness against the main groundnut defoliator *Spodoptera litura* was assessed using chitosan nanoparticles incorporating insecticidal protein beauvericin (CSNp-BV). Entrapment and loading efficiency were discovered to be 82 and 85%, respectively. After 24 hours, the *in vitro* drug release profile had virtually reached 91%. All life stages were vulnerable to the CSNp-BV formulation, according to pesticidal activity, and the largest death rate was seen in the first larval instars. Treatment with CSNp-BV showed decreased pupal and adult emergence.

Concern has been raised about the production of functionalized nanoscale particles for use in agriculture. Sekhar *et al*. (2016) [39] synthesized mycogenic silver nanoparticles from the *Trichoderma viride* fungus isolated from the groundnut rhizosphere. The antifungal efficacy of silver nanoparticles contrary to *Sclerotium rolfsii*, which causes stem rot disease in groundnuts, was maximum at 150 ppm dosage (79.44%).

The first investigation on the control of *Caryedon serratus* in groundnut with Azadirachtin compound-based nanoscale zinc oxide and nanoscale chitosan was published by Jenne *et al*. (2018) [22]. Using the developed nanoscale materials, neem seed kernel extract (NSKE) @ 5% and neem oil @ 3000 and 1000 ppm were encapsulated. In comparison to other formulations evaluated, NSKE encapsulated CNPs were able to hold groundnut bruchid for up to 180 days while losing 54.61% of their weight. As a result, biomaterial encased nanoscale formulations have shown to be extremely effective in reducing enormous economic losses by controlling stored grain pests of groundnut.

Farmers are burdened by the post-harvest losses brought on by the groundnut bruchid *Caryedon serratus*, and the economy as a whole suffers as a result. The effectiveness of silica nanoparticles over *C. serratus* was tested by Diagne *et al*. (2019) [13]. Reverse microemulsion was used to create silica nanoparticles, and different concentrations (0.17, 0.33, 0.67, and 1.7 mg kg^{-1}) were examined for their effects on *C. serratus* lethality and fecundity. The results demonstrated that silica nanoparticles were very harmful to *C. serratus* adults. The death rate of adults rose with concentration and period of exposure to each concentration. After 6 and 7-days post-exposure, high doses (0.67 and 1.7 mg kg^{-1}) resulted in up to 100% mortality. Furthermore, silica nanoparticles substantially lowered the fecundity potential of *C. serratus*.

Root rot complex fungal pathogens such as *Aspergillus niger*, *Sclerotium rolfsii*, and *Macrophomina phaseolina* mostly harm groundnut crops. Raja *et al*. (2021) [34] showed that *T. harzianum* cell-free culture filtrates may be employed for the green production of silver nanoparticles (AgNPs) with sizes ranging from 10 to 25 nm. Using biosynthesized silver nanoparticles, *T. harzianum* exhibits effectual mycelial growth inhibition of up to 60–65% towards the root rot pathogens of groundnut.

Green synthesized nanoparticles (GSNPs) derived from plant extracts are an efficient treatment for infections that do not harm host plants or the environment. Vijayalakshmi *et al*. (2022) [48] produced silver nanoparticles from *Foeniculum vulgare* confirming the characteristics of GSNPs. The phytopathogen *Nigrospora oryzae*, which causes serious disease in groundnuts, was successfully combated by the nanoparticles. Consequently, *F. vulgare* seed nanoparticles can be employed as a viable replacement for chemical fungicides without endangering the environment or soil microbes.

Influence of Nanoparticles on seed quality attributes

Although there are many aspects that affect plant development, the absorption and use of certain nutrients is one of the most important ones since it is necessary for plants to operate properly. Due to their tiny size, nanoparticles can penetrate cells via cell walls and affect a number of plant systems. The use of nanoparticles facilitates their internalization into the cells by increasing the pore size of the cell wall. Due to their effectiveness in breaking seed dormancy and their capacity to act as a fertilizer, insecticide, and nutrition for seed development, they are considered promising seed growth enhancers (Singh *et al*., 2021) [42].

The impact of zinc oxide, silver, and titanium dioxide nanoparticles in groundnut was investigated by Shyla and Natarajan (2014) [40]. At several dosages, including 500, 750, 1000, and 1250 mg/kg, the seeds were dry-dressed. The research revealed that all treatments significantly outperformed the control with respect to seedling vigour and germination. ZnO nanoparticles (67%), which were two and three percent higher than Ag (65%) and TiO_2 NPs (63%), respectively, among the treatments, promoted the highest germination percentage. The seedling vigour was considerably increased by seeds treated with a concentration of 1000 mg/kg.

Dastjerdi *et al*. (2015) [9] investigated the effects of zinc oxide nanoparticles (NPs) on groundnut, using nine different concentrations of ZnO-NPs (0, 10, 30, 50, 100, 200, 400, 1000, and 2000 ppm) in MS medium. Root length was reduced by 23.24 and 55.65 percent, respectively, at 50 ppm and 2000 ppm concentrations. The shoot length dropped by 61.14 and 93.71 percent, respectively, above control at 50 ppm and 2000 ppm concentrations, indicating that ZnO NPs had a negative influence on groundnut seedling development, particularly on MS media.

Due to its great ability to break down pollutants, nanoscale zerovalent iron (NZVI) has been added to soils and groundwater for disinfection, while its impacts on plants are yet comprehended. However, research exploring the impact of low-concentration NZVI particles (10–320 mol/L) on peanut plant growth and seed germination revealed that exposure to NZVI at all considered concentrations changed seed germination percentage and the growth of seedlings (Li *et al*., 2015) [26]. The average durations of each NZVI treatment were significantly greater than those of the deionized water-treated controls. Despite being phytotoxic to peanut plants at extremely high concentrations (320 mol/L), NZVI particles at lower quantities promoted root growth and plant growth. The favorable impact was most likely attributable to plant absorption of NZVI particles boosting plant development and growth.

In an experiment conducted by Shyla and Natarajan (2016) [41], inorganic nanoparticles such as zinc oxide, silver, and titanium dioxide, were used to measure seed quality characteristics during storage. NPs of ZnO, Ag, and TiO_2 each at 750, 1000, and 1250 mg/kg of seed were applied to groundnut kernels before they were kept for a year at room temperature. At the end of storage, seeds treated with ZnO NPs @ 1000mg/kg maintained enhanced germination, seedling vigour index, electrical conductivity, catalase activity, and reduced lipid peroxidase activity against the control.

There hasn't been much research done on how metal oxide nanoparticles affect plants. In order to compare with its bulk equivalent, Suresh *et al*. (2016) [44] made an effort to study the possible variation in peanut plant leaves caused by the application of Fe_2O_3 nanoparticles via the pre-soaking method. This approach was used to apply the Fe_2O_3 nanoparticle and its bulk equivalent to the peanut seeds at two distinct concentrations: 500 and 4000 ppm. All leaf samples revealed a sizable increase in glycoprotein, with the greatest increases occurring in samples containing 500 ppm bulk and 4000 ppm nano-Fe_2O_3. Comparing it to other leaf samples, the leaf sample soaked in 500 ppm bulk Fe_2O_3 solution had a larger drop in the total amide I and II protein concentration.

Jhansi *et al*. (2017) synthesized the green NPs of MgO of different sizes (20, 18.5, 18, 16.5, and 15 nm) via white button mushroom aqueous extract which are environmentally friendly and checked their effects on seed germination. Compared to other sizes of MgO NPs and control, it has been discovered that the smaller size (15 nm) MgO NPs improves seed germination and growth metrics. MgO NPs can penetrate the seed coat and increase water absorption. The study is clearly advantageous for growing peanuts in large-scale agricultural production because the smaller size (15 nm) of MgO NPs particles enhances seedling advancement and peanut growth enhancement.

Gnanesh (2018) [18] studied the influence of nano Zinc on the growth and productivity of groundnut and noticed that the seeds primed with nano Zinc @ 300 ppm for about 15 and 60 minutes recorded higher germination and seedling vigour parameters. Thirunavukkarasu *et al*. (2018) [47] studied the response of nano-sulphur and conventional sulphur in groundnut. The findings of the study indicated that nano-sulphur @ 30 kg/ha performed better than conventional sulphur @ 40 kg/ha. The higher pod yield, oil, crude protein, methionine, cysteine and total free amino acid content were recorded under nano-sulphur application, than the rest of the sulphur sources.

Harish *et al*. (2019) [20] standardized the nanoparticles for improving seed quality in groundnuts with various nano micronutrients, such as iron, zinc, aluminum, and calcium carbonate, as well as the same nutrients in bulk at various concentrations (100, 250, 500, 750, and 1000 ppm). The results of the investigation showed that varied nano seed concentrations promoted the germination of old groundnut seeds in different ways. With regard to the treatments, ZnO nanoparticles at 1000 ppm and TiO_2 nanoparticles at 500 ppm promoted the greatest germination percentage and seedling vigor.

The effectiveness of ZnO, FeO, SiO_2, CNT, and TiO_2 nanoparticles with polymer in enhancing the physiological characteristics of the groundnut seed was investigated by Konanki *et al*. (2019) [24]. The findings showed that ZnO substantially improved seed quality characteristics such as germination, root length, shoot length, SVI-I and SVI-II, and amylase activity as compared to control, among the other treatments. These findings showed that the nano ZnO @ 500 ppm significantly impacted the growth and development of groundnuts as well as increased the zinc content in seeds, which is a crucial aspect from the standpoint of human health.

Tejaswini *et al*. (2019) [46] conducted research to determine if nanoparticles are effective in enhancing groundnut seed physiological parameters and seed quality. Different nanoparticle concentrations were applied to groundnut seedlings individually. When compared to the control, alpha-amylase activity and other seed quality criteria changed considerably. These findings showed that the micro ZnO at 500 ppm has a considerable yet advantageous impact on the development and growth of agricultural crops, notably groundnut.

On the quality characteristics of groundnut seed, the effectiveness of biosynthesized silver nanoparticles (Ag NPs) produced using *A. aspera* roots and conventional Ag NPs was investigated (Smitha *et al*., 2019) [43]. Standard Ag NP had an average particle size of 50.37 nm, whereas biosynthesized Ag NPs had a particle size of 23.21 nm. For standard and biosynthesized Ag NPs, the typical absorbance peak was seen at 407.40 and 420.80 nm, respectively. SEM checks indicated that both the conventional and biosynthesized Ag NPs were spherical in form. The seed quality metrics of germination percentage, speed of germination, and seedling vigour were found to be most improved by Ag NPs at 150 ppm.

The efficacy of biosynthesized silver nanoparticles (Ag NPs) obtained using *A. aspera* roots and standard Ag NPs was studied on quality parameters of groundnut seed (Smitha *et al*., 2019) [43]. Standard Ag NP had an average particle size of 50.37 nm, whereas biosynthesized Ag NP had a particle size of 23.21 nm. For standard and biosynthesized Ag NPs, the typical absorbance peak was seen at 407.40 and 420.80 nm, respectively. SEM scans indicated that the conventional and biosynthesized Ag NPs were both spherical in form. The criteria of seed quality, such as germination (%), speed of germination, root length, shoot length, etc., were found to be most improved by Ag NPs at 150 ppm. Besides, the study also revealed that the impact of biosynthesized Ag NPs was equivalent to that of conventional Ag NPs in terms of enhancing the quality of groundnut seeds. For this reason, biosynthesized AgNPs could be used as a new potent alternative for breaking groundnut seed dormancy.

The controlled release of bioactive substances, such as the hormone gibberellic acid (GA_3) as an effective way to deliver, may be achieved using groundnut seeds coated using novel nanotechnology. The best outcomes were obtained by implementing a seed coating formulation that used nano formulation techniques to control the release of hormones without causing any degradation from the infusion of active compounds like hormones (GA_3). The nanoformulation coating in groundnut seeds produced an effective outcome in all growth indices and enzyme activity that varied considerably from untreated seeds. Groundnut seed quality can be improved by applying a seed coating with a nanoformulation enriched with GA_3 (Tamilarasan and Raja, 2022) [45].

Zaheda Banu (2022) [50] conducted an experiment to study the influence of seed treatment with nanoparticles on seed quality and storability in groundnut with SiO_2, TiO_2, ZnO, FeO and Sulphur at different concentrations (0, 250, 500, 750 and 1000ppm). Research findings revealed that dry dressing treatment with SiO_2 NPs @250 ppm recorded higher germination, total dehydrogenase activity and lowest electrical conductivity followed by SiO_2 NPs@500 ppm over control. At the end of six months of storage, dry dressing treatment with SiO_2 NPs@250 ppm recorded higher germination (72%), field emergence (63%) and lower electrical conductivity (249.82µS/cm) followed by SiO_2 NPs@500 ppm.

Nanoparticles showcasing a negative effect

Although, the positive influence of NPs has been reported by several workers, still few workers have also observed ill effects or no effects of NPs on plant growth. For example, metal oxide nanoparticles (NPs), iron oxide (Fe_2O_3), copper oxide (CuO), and titanium oxide (TiO_2) NPs at 50 and 500 mg kg^{-1} treatment considerably reduced plant development in terms of biomass, shoot height, plant yield by 44% and 1000-grain weight was considerably reduced by 10–31%. The total amino acid concentration decreased by 36.2% and 21.1%, respectively, after exposure to 50 and 500 mg kg^{-1} CuO NPs. The level of resveratrol in the grains treated with 50 and 500 mg kg^{-1} CuO NP rose to 1.8 and 2.3 mg kg^{-1}, respectively, in contrast to the control, indicating plant stress response. Overall, nevertheless, these findings revealed that metal-based NPs could affect the nutritional quality and productivity of peanut crops. These results raise questions about how NPs with agrichemicals may be used safely and responsibly to safeguard food quality and safety (Rui *et al*., 2018) [36].

Along with the sharp increase in the use of nanoparticles across a wide range of industries, worries about the unidentified effects caused by their presence in the environment and agricultural systems are being emphasised. More research has been done on the negative impacts of nanoparticles on living species, especially soil health, as a result of the rising trend of Nano Zinc Oxide Nanoparticle (ZnO-NP), one of the most often utilized nanoparticles, being released into the environment. On peanut seedlings grown in Murashige and Skoog medium (MS media), Dastjerdi *et al*. (2016) [10] looked into the phytotoxicity of ZnO-NP. Nine concentrations of ZnO-NP were added to MS media as part of the experimental treatments for this study: 0, 10, 30, 50, 100, 200, 400, 1000, and 2000 ppm. ZnO-NP exposure had an impact on the root and shoot length of peanut seedlings in such a way that the root length at 50 ppm and higher concentrations was considerably lower than that of the control treatment, and the shortest shoot length was seen at 2000 ppm ZnONPs concentration. Furthermore, when the nanoparticle concentration grew, both the root and shoot wet weight dropped. Despite the fact that root and shoot dry weight decreased as concentration increased, there was no significant change. The root dry weight of peanut seedlings treated with 10 ppm ZnO-NP, on the other hand, was substantially greater than that of peanut seedlings treated with more than 200 ppm ZnO-NP.

Conclusion

Nanotechnology is widely regarded as a novel and rapidly evolving technique that entails the fabrication, processing, and application of structures, electronics, and systems by regulating form and size at the nanoscale scale. The relevant research clearly indicated that seed treatment with nanoparticles had both good and negative impacts on seed germination and quality attributes, as well as during storage. Because most nano compounds are crop-specific, the treatment effects vary greatly depending on the type of chemicals, their concentrations, period of exposure, and so on. However, the negative effects of nanoscale chemical application on both pre-sowing and pre-storage might be mitigated by proper treatment procedures. Furthermore, research of this type is few in oilseeds, particularly in tropical countries like ours, therefore a complete study is planned to pique the interest of candidates and enhance the application of nanotechnology in agriculture.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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