Nanotechnology's enhancing bioavailability of fertilizers in agricultural crops

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Abstract

Research reveals that these Nano fertilizers can significantly enhance nutrient use efficiency, reducing environmental consequences, and advancing the cause of cleaner production. Nano fertilizers release nutrients in the soil in a regulated, sustained manner and are highly effective and target oriented. It increases plant surface area for metabolic activities, speeding photosynthesis and agricultural yield, it also enhances direct nutrient uptake into the plant system and releasing fixed nutrients to restore soil fertility. It protects crops against biotic and abiotic stress, lowers cultivation costs, reduces fertilizer waste, and enhances nutrient usage efficiency. Studies suggest that Nano fertilizers boost fertilizer efficiency, reduce soil toxicity, reduce over dosage risks, and release nutrients precisely. Foliar application is possible in poor soil and weather conditions. Nanostructured formulations can release active ingredients more precisely in response to environmental stimuli and biological demands through targeted delivery. Nano biosensors diagnose crop input demands in controlled environments and supply them on time and in the proper area. Nanotechnology enables new paths for agricultural research and has higher promise for sustainable agricultural practices find the solution against the issues arising in modern agriculture due to conventional fertilizer application.

Keywords: Nano fertilizers; Plant Nutrition; Sustainable Agriculture; Yield; Plants; Efficiency; Stress Resistance

1. Introduction

Nanotechnology is modernizing the whole food chain from production to processing, storage, and consumption. Scientific reports suggest that nanotechnology can improve the thermal stability, water solubility, and oral bioavailability of nutrients (Ndlovu et al., 2020). Nanoparticles (NPs) for the delivery of edibles are biologically consistent tiny materials that vary in size from 1 to 100 nm and are produced through different methods. They have significant chemical and physical characteristics such as solubility, colour, strength, infusibility, and high-surface-to-volume ratio (Priyanka, 2018). These properties of NPs provide various valuable applications in different fields such as tissue engineering, cell therapy, drug delivery, diagnostic tools, biomaterials, and signalling molecules (Jain, 2020; Sajid et al., 2020).

Nano biotechnology may assist in passing the barriers in the human body for targeted drug delivery to directed organs, for example, crossing the blood-brain barrier to reach the brain. Nanomaterials found their applications not only in human wellbeing but also in food safety and quality (Jain, 2020). Recently, many organizations, researchers, and industries are adopting unique methods that have important applications of NPs in food technology (Dasgupta et al., 2015). Nanotechnology is being considered as a ray of hope for the treatment of the ongoing COVID-19 outbreak. It is considered that chloroquine, an approved malaria drug may help in Nano-medicine investigation for the potential treatment of the COVID-19 (Tony et al., 2020).

Functional food components such as vitamins, phytochemicals, minerals, and antioxidants are necessary for optimal human health and disease prevention. Nutraceuticals' terms are a fusion of pharmaceutical and nutrition, which are derived from or any part of food that provides physiological, preventive, or therapeutic significance beyond the basic nutritional requirements (Yao et al., 2015). Worldwide, nutrition awareness and escalation in the rate of morbidity due to chronic diseases have developed a huge demand for dietary supplements. According to Prasad (2016), the global demand for nutraceuticals is dramatically expected to reach $302.307 million by 2022 which is foreseen based on a growth rate of 7.04% annually from 2016 to 2020. Moreover, it has been challenging to incorporate these nutraceuticals into food because they have chemical instability, undesirable flavor, and poor solubility characteristics (Mc Clements et al., 2015). Various formulation tactics have been proposed to overcome the poor solubility but their benefits are limited by the possible interaction of excipients employed in preparation.

On the other hand, nanoparticle technology has received extensive acceptance as it includes the use of a minimum quantity of excipients to enhance the solubility of micronutrients (Charoo et al., 2019). The solution to these problems can also be delivered by encapsulating the bioactive ingredients in nanoparticle-based delivery systems (Jafari & Mc Clements, 2017). However, encapsulation of different micronutrients requires precise and appropriate nanoscale delivery systems depending on the properties as well as nature of the micronutrient (Joye et al., 2014). The objective of this review is to highlight the role of nanotechnology in improving the bioavailability of micronutrients through targeted delivery systems.

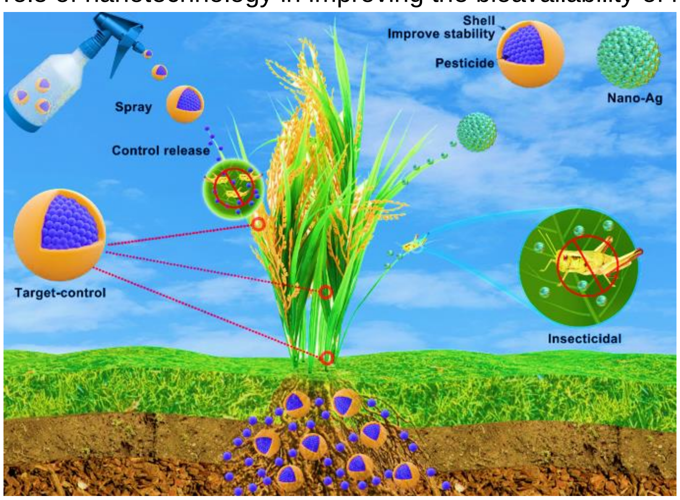


Fig 1: Nanomaterials loaded with pesticides. NMs loaded with pesticides can reduce the degradation of AIs caused by environmental influences, achieve target-controlled release of AIs by the properties of nanomaterials, thus prolonging the shelf life of pesticides; Some NMs have their own insecticidal and fungicidal activities; When applied to soil, NMs help pesticides to be fixed in the soil for plant root absorption in order to reduce the loss of pesticides by leaching

2. What is Nano-fertilizers?

Nano-Fertilizers are substances that are produced and modified using nanotechnology to boost soil fertility, increase crop quality, and increase agricultural production. A product is referred to as a Nano-fertilizer if it increases nutrient efficiency by utilizing nanotechnology or nanoparticles. Nano-fertilizers are designed to regulate the release of nutrients based on crop requirements. They are considered to be more efficient than conventional fertilizers. Nano-fertilizers can be used to reduce nitrogen loss due to leaching, emissions, and long-term uptake by soil microorganisms. Fertilizers with a slow, regulated release help enhance soil by minimizing the negative consequences of excessive fertiliser use. Three categories of Nano-fertilizers are proposed:

1. Nanoscale fertilizer: Nanoparticles which contain nutrients in it.
2. Nanoscale additives: Traditional fertilizers containing nanoscale additives.
3. Nanoscale coating: Traditional fertilizers coated or loaded with nanoparticles.

Conventional fertilizers are mostly employed in the current agricultural system to fulfil the nutritional needs of the crop plants. The two main methods used to apply conventional fertilizers in agricultural fields are spraying and broadcasting.

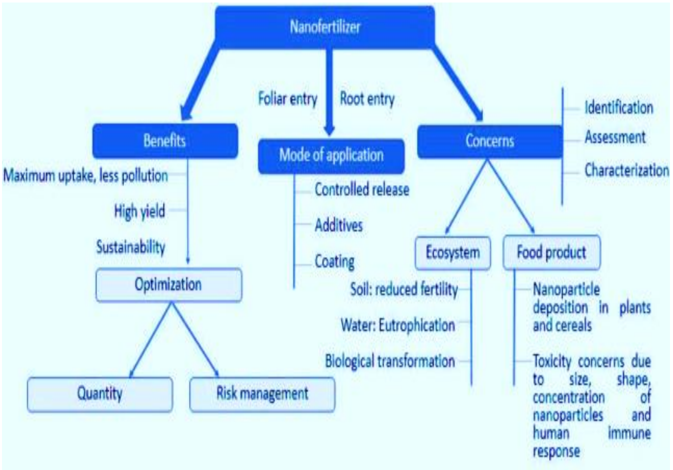
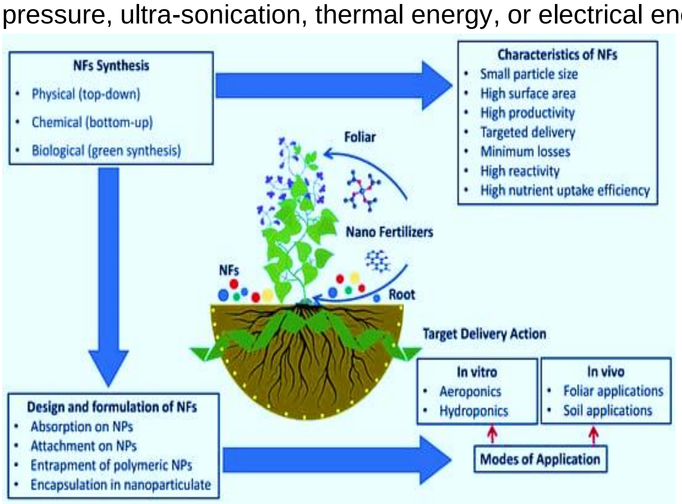


Fig 2: Classification of Nano Technology

Out of the overall concentration or volume applied, the concentration of conventional fertilizers that actually reaches the targeted site in the plants is much lower than the desired concentration. The primary causes of conventional fertilizer losses include runoff, leaching, evaporation, and drift, hydrolysis by soil water, microbiological breakdown, and photolytic destruction. The natural flora of the soil is declining due to increased fertilizer use, and the soil's capacity to fix nitrogen is also decreasing. Nanotechnology has made it possible to study Nano structured materials as fertilizer or controlled vectors for the construction of smart fertilizers as new facilities to improve NUE and reduce the costs. Improved nutrient uptake efficiency, site-directed agrochemical distribution, and decreased environmental toxicity, particularly in water bodies, are the main advantages of Nano fertilizer over conventional fertilizers. When compared to traditional fertilizers, the mineral nutrients have a better bioavailability. Compared to conventional fertilizers, the chemicals would be available to plants for a longer period of time. The remaining conventional fertilizers are transformed into insoluble salts in the soil and are only available at the time of delivery.

3. Synthesis of Nano-fertilizers

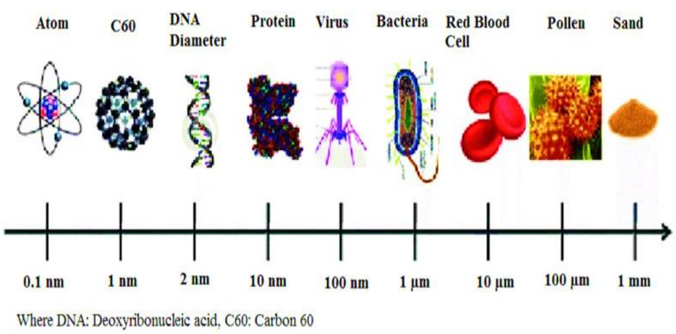
According to Arole and Munde's (2014) report, there are two established approaches for synthesizing nanomaterials: the Top-down approach, which involves breaking down bulk materials into small pieces by applying an external force, and the Bottom-up approach, which involves combining and gathering gas and/or liquid atoms or molecules. In terms of how NPs are made, Satyanarayana and Reddy (2018) highlighted out that physical techniques such as irradiation, mechanical pressure, ultra-sonication, thermal energy, or electrical energy are used to melt, abrade, condense, or evaporate materials.



Sources: Zahra Zahra et al, 2022

Fig 3. Overview of design and formulation of Nano fertilizers based on the respective synthesis method and their characteristics.

The top-down strategy used in these physical procedures has the advantages of being time- and energy-consuming, solvent-free, and producing homogenous monodisperse nanoparticles; nevertheless, physical processes are less cost-effective due to the large amount of waste generated during this synthesis. Conversely, some of the most often used techniques in the synthesis of nanoparticles are chemical ones, such as the sol-gel method, hydrothermal synthesis, micro-emulsion technique, polymer synthesis, chemical vapour synthesis, or plasma accelerated chemical vapour deposition technique. Green synthesis and biosynthesis, two bioassisted techniques that are efficient, low-toxic, and safe for the environment, are offered as alternatives to chemical and physical approaches in the synthesis and fabrication of nanoparticles.

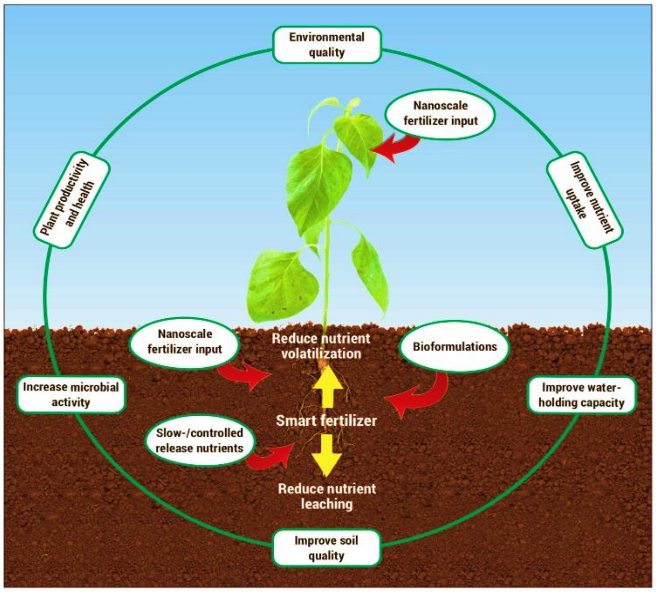


Sources: Heliyon. 2021 Dec 4; 7(12)

Fig 4: pictorial exhibition of things in the "Nano" (<100 nm) and "micro" (>100 nm) size ranges. Where DNA: Deoxyribonucleic acid, C60: Carbon 60

4. Types of Nano-fertilizers

I. Macronutrient Nano Fertilizers: Macronutrient Nano-fertilizers are made up of one or more macronutrient elements, such as nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and sulphur (S). But eventually, significant amounts of these fertilizers (N, P, and K) find their way into surface and groundwater, seriously harming aquatic ecosystems. Therefore, in order to achieve sustainable food production based on the preservation of the ecological environment, it is imperative to produce highly effective and environmentally safe macronutrient Nano-fertilizers.



Schematic diagram of potential smart fertilizer effects in the soil-plant system. Adapted from Calabi-Floody et al. 2017.

Fig 5: Effect of Fertilizers on Soil Plant Systems

1. Nitrogen Nano fertilizer: Different approaches, such as polyolefin resin-coated urea, neem coated urea, and sulphur coated urea, were taken to regulate the N release in order to address the issues related with nitrogen leaching during fertilisation. However, slow-releasing fertilisers are frequently expensive, and when N levels grow high, N is released slowly. Cation exchangers can be used as fertiliser additives to limit NH4 + release and decrease N loss. Zeolite increases crop productivity by retaining necessary nutrients and releasing them when they are needed. The porous material clinoptilolite zeolite (CZ), which has a high cation exchange capacity (CEC, up to 300 c mol (p+) kg-1) and a strong affinity for NH4+(Ming and Mumpton, 1989), has been utilised to reduce NH3 emission from farm manure (Amon et al., 1997) and to eliminate NH3 toxicity to plants (Gupta et al., 1997). According to Perrin et al. (1998), clinoptilolite not only increases the effectiveness of nitrogen fertilisation, but also lowers nitrate leaching by preventing the nitrification of ammonium to nitrate. Lefcourt and Meisinger (2001) stated that Zeolite has the capacity to decrease ammonia volatilization by sequestering ammonium-N on exchange sites. Latifahet al. (2011), reported that the combination of urea with zeolite and sago waste water provided a significant advantage over urea alone,as the mixture promoted the synthesis of ammonium and readily available nitrate ions over ammonia. Additionally, the mixture increased the soil's ability to retain available nitrate and exchangeable ammonium.

2. Phosphorus Nano Fertilizer: As the zeolite absorbs Ca2+ from the phosphate rock, phosphate and ammonium ions are released. Contrary to the leaching of very soluble phosphate that established equilibrium, the controlled-release phosphate in fertilisers (such as super phosphate) is released as a result of a particular chemical process in soil. By altering the proportion of P rock to zeolite, the rate of phosphate release is regulated. Allen et al. (1996) conducted an experiment to look at the solubility and cation-exchange in mixtures of rock phosphate and NH4+. K-saturated clinoptilolite showed that mixing phosphate rock and zeolite had the ability for slow-release fertilisation of plants in synthetic soils through dissolution and Ion exchange processes. As the zeolite absorbs Ca2+ from the phosphate rock, phosphate and ammonium ions are released. His controlled-release phosphate in fertilisers (such super phosphate) is released as a result of a specific chemical reaction in soil, unlike the leaching of very soluble phosphate that created equilibrium. The rate of phosphate release is controlled by varying the ratio of P rock to zeolite. In a percolation reactor, SharmilaRahale (2011) examined the PO4- release patterns of surfaces treated with various nanoclays and zeolite. It has been shown that while conventional fertilizers only release nutrients for a maximum of 10–12 days, nano-formulations release phosphate for 40–50 days.

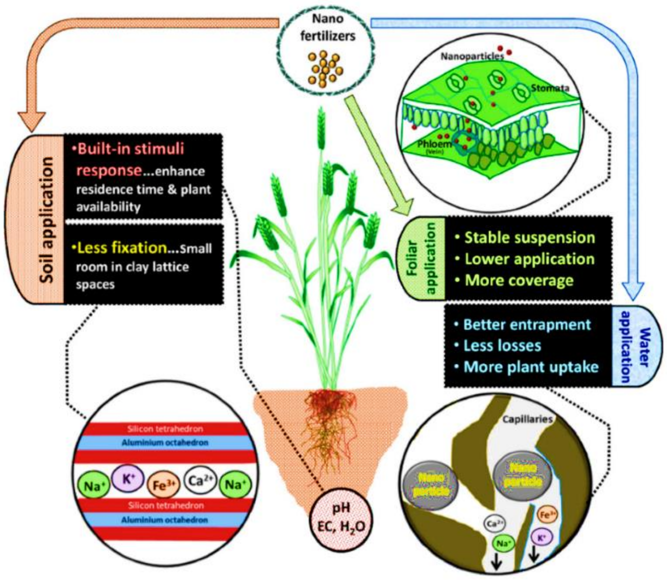


Figure 6: Potential benefits of Nano fertilizers under different modes of application for crop production. In under Creative Commons Attribution License (CC BY).

3. Potassic Nano Fertilizer: Some naturally occurring zeolites have high exchangeable K+ concentrations that can promote plant development in potting soil medium. Zhou and Huang (2007), by supplying more vital cations and anions to plant roots, zeolites can develop into a superior substrate for plant growth. This is because zeolites have the potential to exchange ions with specific nutrient cations.

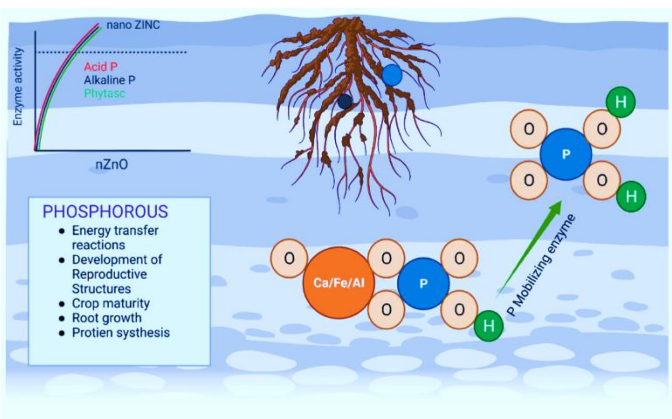


Fig 7: Functions of Phosphorus Nano Fertilizers in Plants

II. Secondary Nano Fertilizers: Secondary nutrients such as sulphur (S), calcium (Ca), and magnesium (Mg) need to be present in relatively high amounts for crop development to be healthy. Zeolite demonstrated a slowrelease fertilizer for calcium and magnesium, according to Supapronet al. (2007). They said that zeolite improved the magnesium and calcium content of the soil. Fansuriet al. (2008), stated that zeolite may freely exchange nutrient ions like calcium and magnesium.

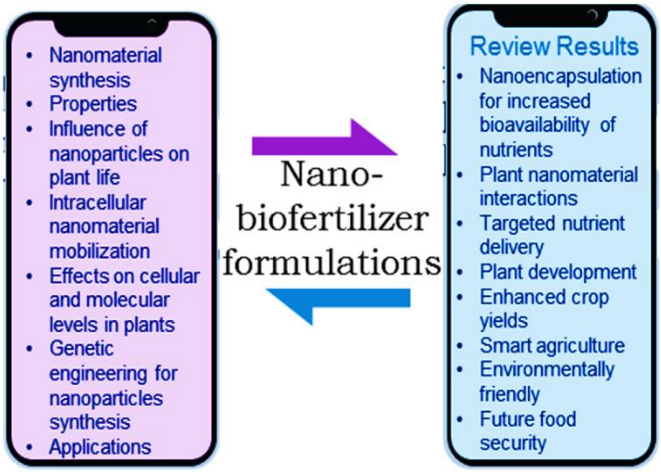


Fig 8: The use of nanotechnology in the creation of Nano-pesticides is another key application that is helping horticulture crops to thrive. Thus, the use of nanotechnology in agriculture methods will undoubtedly set the standard for achieving the long-term goal of agro-technologically producing sustainable crops. *Sources: Diksha Garg et al, 2023*

III. Micronutrient Nano-fertilizers: Compared to macronutrients, micronutrients provide plants with relatively small amounts of essential nutrients. They are key elements to activate enzymes and the synthesize biomolecules involved in plant defence. Therefore, as well as, macronutrient Nano-fertilizers, it is also necessary to apply micronutrient Nano-fertilizers to plants, including boron (B), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), zinc (Zn) and chloride (Cl). The capacity of five naturally occurring zeolites and bentonite minerals to adsorb and release zinc and iron was studied by Shetaet al.(2003). The Langmuir and Freundlich equations were used to determine the potential for sorption of these ions. According to the findings, natural zeolites, particularly minerals like chabazite and bentonite, have a great potential for sorption of Zn and Fe as well as a high capacity for slow-release fertilisers. According to Pandey et al. (2010), zinc-rich ZnO NPs raised the amount of IAA in roots (sprouts), which suggests that plants are growing more quickly because zinc is a necessary nutrient for plants.

Advantages of Nano-fertilizers

- A Nano-fertilizer releases nutrients in a slow and steady rate for a longer period thereby reducing the nutrient losses and improving the nutrient use efficiency.
- Increased crop yields: Nanotechnology can be used to improve plant growth and yield, allowing farmers to produce more food with less land and resources.
- Reduced use of pesticides and fertilizers: By using targeted delivery systems for pesticides and fertilizers, farmers can reduce the amount of these chemicals needed and minimize their impact on the environment.
- Enhanced food safety: Nanotechnology can be used to develop sensors and monitoring devices that can detect contaminants and pathogens in food, improving food safety and reducing the risk of foodborne illness.
- Soil remediation: Nanoparticles can be used to remove pollutants and heavy metals from soil, improving soil health and reducing contamination of crops.
- Integration of biosensors to the Nano-fertilizers will help in selective release of nutrients according to soil nutrient status, crop growth period and environmental conditions.
- Nano-biofertilizers: Encapsulation of beneficial microorganisms by nanotechnology can enhance plant health. As this could include bacteria or fungi that can improve nitrogen, phosphorus and potassium availability in the root zone.
- Reduction in the emission of greenhouse gases

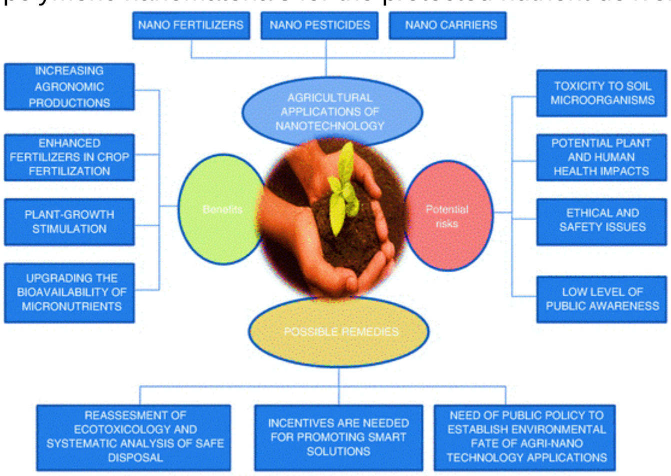
Limitations of Nano-fertilizers

- Environmental risks: The use of nanoparticles in agriculture may pose environmental risks, such as soil contamination or unintended impacts on non-target organisms.

- Health risks: There is still limited understanding of the potential health risks associated with exposure to nanoparticles, particularly over the long term.
- Regulatory challenges: The regulation of nanotechnology in agriculture is still evolving, and it can be difficult to assess the safety and efficacy of new nanotechnology-based products.
- Ethical concerns: There are also ethical concerns related to the use of nanotechnology in agriculture, such as potential impacts on small farmers or the exacerbation of social inequalities.

5. Nano-technology in the field of nutrition

Nanotechnology has revolutionized the world and contributed to various fields including pharmacy, food processing industries, agriculture sectors, and nutrition (Nile et al., 2020). In the past few decades, research in the field of nutrition incorporating nano-science has grown dynamically and stimulated a strong urge for targeted delivery of micronutrients (Dudefoi et al., 2017). Nano-capsules are being used for the increased delivery of drugs and micronutrients (vitamins & minerals) in the body (Koo et al., 2005; McClements, 2020; Yan & Gilbert, 2004). In different methods, nano-composite, nano-structuration, and nano-emulsification are used to encapsulate the materials in miniature forms to deliver bioactive compounds more efficiently. Encapsulated bioactive constituents (e.g., flavonoids and vitamins) can be formulated with polymeric nanomaterials for the protected nutrient delivery (Singh et al., 2017).



(Santosh Kumar Sanivada et al, 2017) **Fig 9: Nano fertilizers for Sustainable Soil Management**

Nutrition-be-nanotech and nanoceuticals are names of some commercial supplements. Vitamin spray-dispersed nano-droplets are considered for improved absorption of nutrients, for example, iron, curcumin, and folic acid. Nano-sized powders are also used for enhancing the absorption of nutrients as nano-cochleate. These are revealed to be an effective tool for nutrient distribution to cells without affecting the taste and color of the food products. The supplement production mostly involves encapsulation techniques where the desirable probiotics and other products are directed into the human body with the help of Zn and Fe nano-structured capsules. The NPs in food supplements are more active than commonly used supplements because they respond more effectively with human cells due to their special size (Koo et al., 2005; McClements et al., 2015).

Nano-capsules are adapted as carriers for antioxidants, essential oils, flavors, coenzyme Q_{10}, vitamins, phytochemicals, and minerals to improve their bioavailability in the human system (Ognik et al., 2016). The encapsulation of polyphenols with NPs may prevent any oxidative actions and providing them with an acceptable taste (Heller, 2006). In the food industry, liposomal nano-vesicles have found applications for the supply and encapsulation of nutrients, enzymes, and antimicrobial compounds (Singh et al., 2017; Wen et al., 2006).

The role of nanotechnology is also assumed to improve the characteristics of bioactive particles in spices and herbs by enhancing their bioavailability, water solubility, and antioxidant properties enabling the active ingredients to dissolve homogeneously (Samah et al., 2017). The nano-materials are considered to increase the bioavailability of important phytochemicals, for example, genistein and curcumin (Yen et al., 2010; Zhang et al., 2008). Moreover, nano-nutraceuticals are available as dietary supplements, herbal products, and bioactive particles in nano-formulations (He et al., 2019).

6. Micronutrient bioavailability

According to Jafari and Mc Clements (2017), the bioavailability of a nutrient is the fraction of ingested bioactive ingredient which is absorbed and consequently used for the essential physiological functions of the body. The bioavailability of bioactive compounds such as vitamins (A, D, and E), carotenoids, curcumin, conjugated linoleic acids, omega-3 fatty acids, and coenzyme Q_{10} reduces after oral ingestion (Zhang & McClements, 2016). It happens due to physiological and physiochemical factors such as bioavailability, absorption, and transformation (Figure 1).

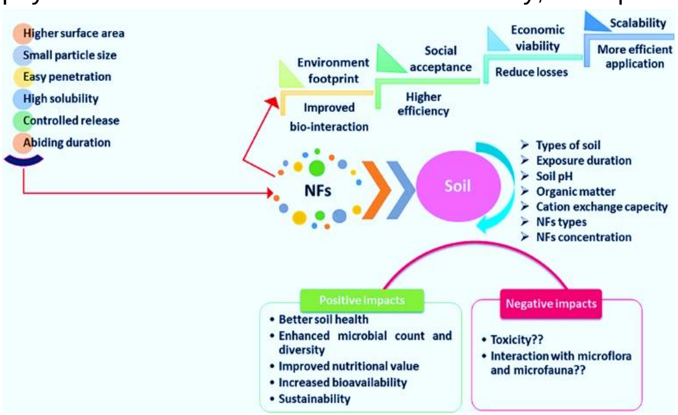
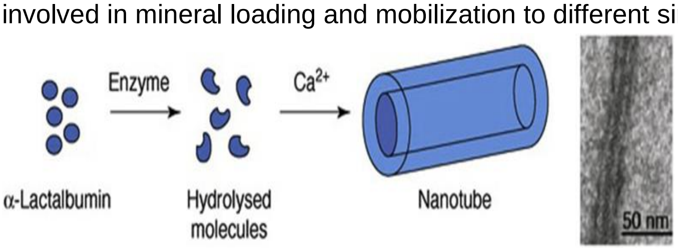


Fig 10: The role of Nano fertilizers in soil (*Krishan Kumar Verma et al, 2022*)

7. Molecular Mechanisms of Mineral Acquisition and Transport

In order to maximize the bioavailability of nutrients, it is essential to understand the process of mineral acquisition, transport, and accumulation in legume seeds. Each of these processes is probably controlled by some genes, many of which are yet to be identified. Several studies have identified genes involved in translocation to different vegetative tissues and ultimately to seeds (Sperotto et al., 2014; Jeong et al., 2017). However, there is very limited knowledge of phloem-expressed genes involved in mineral loading and mobilization to different sink tissues (Braun et al., 2014).



Sources: Heliyon 2021 Dec4;7(12)

Fig 11: Representation of the self-assembly of partially hydrolyzed α -lactalbumin into nanotubes in the presence of calcium ions (Ca^{2+})

Therefore, while studies on specific transporters help us understand their function, whole-plant studies are required to ascertain transporters most relevant to seed mineral delivery. The acquisition and the mobilization of minerals in plants have been broadly studied (Walker and Waters, 2011; González-Guerrero et al., 2016; Xue et al., 2016). Several stresses can lead to the non-availability of key nutrition factors and result in improper crop growth. Details about these different stresses and their effect and a potential solution are provided in Table 2.

Table 1: Constraints to nutrient uptake, transport, storage, and effective survival strategies.

Stress condition	Constraint	Potential solution	References
High pH, salinity, and carbonate content of soil	Iron non-availability leading to Iron deficiency chlorosis (IDC) Limited ion movement to transpiration stream Reduced shoot growth	Coordinate expression of an active proton pump to increase solubility of Fe^{+3}, a ferric chelate reductase to generate the more soluble Fe^{+2}, and finally an iron transporter	Hell and Stephan, 2003
Mineral toxicity	Cytotoxicity Limited uptake	Compartmentalization of minerals Outflow of organic ions for chelation of toxic ions	Socha and Guerinot, 2014
Mn toxicity	Mn toxicity can arise in acidic and poorly drained soil Mn can compete and prevent uptake of other essential elements (Ca, Mg, Fe, and P)	Sequestering of Mn in the apoplast or vacuole	Millaleo et al., 2013
Mineral deficiency in soil	Inadequate nutrient acquisition	Enhanced uptake by transporters and developmental adaptation Root architecture re-modeling for efficient acquisition of minerals Partitioning for storage of minerals	Mickelbart et al., 2015

Stress condition	Constraint	Potential solution	References
Nutrient retention and bioavailability	Inadequate nutrient in seeds	Improved post-harvest processing and cooking methods and conditions and duration of storage Screening of promising lines for micronutrient bioavailability Detect and understand plant biosynthetic genes and pathways of nutritional importance, including those for nutrient absorption enhancers and inhibitors	Nestel et al., 2006
Anti-nutrients (Phytic acid, Trypsin inhibitors, etc.)	Low bioavailability	Soaking of legumes before cooking Food diversification Development of genotypes with low anti-nutrients	Xie et al., 2017
Lack or deficiency of promoters like inulin, histidine, lysine, etc.	Low bioavailability of nutrients	Selection of genotypes with high level of promoters Development of genotypes with high promoters, like inulin, etc.	White and Broadley, 2005

7.1. Iron (Fe) Transport

Legumes are "strategy I" plants that acidify the rhizosphere through an H^+-ATPase (the enzyme of HA2, H^+-ATPase family) to increase Fe^{3+} solubility (Santi and Schmidt, 2009). Then they reduce Fe^{3+} to Fe^{2+} with the help of chelate reductase, ferric reduction oxidase (*FRO2*)and finally Fe^{2+} taken up by root's plasma membrane through a Fe^{2+} iron-regulated transporter (*IRT1*) or its homologues such as natural resistance-associated macrophage protein 1 (*NRAMP1*) or divalent metal-ion transporter 1 (*DMT1*) (Figure 2). Rhizosphere acidification is mainly associated with the release of protons followed by surplus uptake of cations (Fe^+) over anions during nitrogen fixation (Sinclair and Krämer, 2012). Membrane recycling of *IRT1* is controlled by ubiquitination in strategy I plants (Barberon et al., 2011). In legumes, Fe uptake and transportation to roots are mainly carried out by protein *HA2*, *FRO2*, and *IRT1* (Walker and Connolly, 2008; Santi and Schmidt, 2009). Putative homologs for the transport of Fe from the leaf to the root through nutrient transporting genes such as *FIT1*, *IRT1*, *OPT3*, and *bZIP23* have been identified in many legumes including peanut (*AhIRT1*; Xiong et al., 2012), *Medicago truncatula* (*MtNRAMP1*; Tejada-Jiménez et al., 2015), soybean (*NRAMP* genes; Qin et al., 2017), lentil (*Ferritin-1*, *BHLH-1*, and FER-like transcription factor protein and *IRT1*), and chickpea (*CaFer1*; Parveen et al., 2016). Relatively very little is known about Fe uptake, and regulation in legumes shoots (Thomine and Vert, 2013). Fe uptake in shoots is mediated by *IRT*-like transporters, and its movement in the xylem as ferric-citrate complexes has been observed in soybean (Palmer and Guerinot, 2009). Xylem unloading is a crucial step in the distribution and transportation of Fe to different tissues and sinks cell (Figure 2). Expression patterns show that *ZIP* transporters and *YSL* transporters are involved in metal unloading from xylem (Küpper and Kochian, 2010). Oligopeptide transporter (*OPT*) has been suggested to play a significant role in accurate long-distance Fe signaling from shoots to roots and in importing Fe into phloem companion cells in *Arabidopsis* (Kumar et al., 2017). Due to the abundance of nicotianamine (NA) in shoot tissues and its affinity to various ions, it can be assumed that *YSL* transporters are essential for metal transfer from the xylem to the leaves and the seeds, as evident from the expression of *Arabidopsis* genes *AtYSL1* and *AtYSL3* that increased during leaf senescence (Waters et al., 2006). *NRAMP* family genes are known to play a significant role in Fe homeostasis whereas *YSL* and *OPTs* play a major role in loading and unloading of Fe^{2+} NA complexes into and out of phloem (Palmer and Guerinot, 2009). Fe uptake and transportation in plants have been reviewed in several articles (Kobayashi and Nishizawa, 2012; Curie and Mari, 2017).

FIGURE 2.

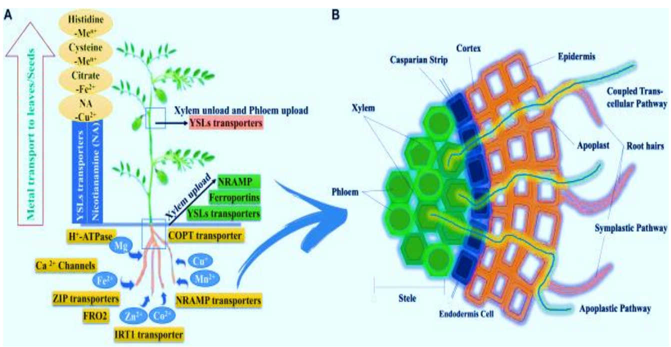


Fig 12: (A) **The different transporters in the uptake of nutrients from the soil and their translocation to aerial parts.** (B) **A schematic representation of mineral transport to roots through different pathways.**

7.2. Zinc (Zn) Transport

Efficient uptake, transport, and accumulation of Zn in seeds are equally crucial for developing nutrient-rich crops (Astudillo et al., 2013). In legumes, Zn is mostly taken up across the plasma membrane of root cells as Zn^{2+}. *ZIP* transporters have been involved in Zn uptake and transport from root to seeds (Colangelo and Guerinot, 2006; Palmgren et al., 2008). *ZRT*, *IRT*-like protein (*ZIP*), HMA heavy metal ATPase (*HMA*), Zinc-induced facilitator (*ZIF*), and metal tolerance protein (*MTP*) have been involved in Zn transport (Hussain et al., 2004). *MTP*s play a role in the mobilization of many metal ions such as Zn, Mn, Fe, Ni, Cd, and Co in the cytoplasm. In the case of *M. truncatula*, *MtZIP1*, *MtZIP3*, *MtZIP4*, *MtZIP5*, *MtZIP6*,and *MtZIP7* genes were found to be upregulated under Zn deficiency in both roots and leaves, suggesting their active role in Zn transport (Hussain et al., 2004). The *bZIP* family is another important gene family involved in Zn transport in legumes. Studies in many dicots such as *Arabidopsis*, soybean (*GmZIP1*), common bean (*PvZIP12*, *PvZIP13*, *PvZIP16*, and *PvbZIP1*), *Medicago* (seven ZIP transporters), and *Lotus japonicus* have identified *ZIP* genes in different tissues like roots, leaves, and seeds (Lin et al., 2009; Astudillo et al., 2013). Mostly, Zn is transported through the symplastic pathway, but a considerable fraction may follow the apoplastic pathway through roots to reach the xylem (White et al., 2002; Figure 2). The cation diffusion facilitator (CDF) family members such as *MTP1* and *ZIF1* transporter play a role in Zn transport to the vacuole while *NRAMPs* have been identified in Zn mobilization from the vacuole (Haydon and Cobbett, 2007). Zn loading to the xylem is mediated through *HMA*, while within the xylem, is transverse as Zn^{2+} or in complex with histidines or Nicotianamine (Palmgren et al., 2008). While *ZIP* family members are actively involved in mediating Zn^{2+} influx to leaf tissue and also to the phloem, *YSL* is involved in loading Zn to the phloem and unloading to the seeds as Zn-NA complex (Haydon and Cobbett, 2007; Waters and Grusak, 2008).

7.3. Manganese (Mn) Transport

Manganese is an essential trace element in plants as it serves as a cofactor in many vital processes such as photosynthesis and lipid biosynthesis. Mn is available in the soil as Mn^{2+} for plant uptake (Figure 2). Very few transporters have been identified exclusively for Mn transport in plants. However, there are many transporters such as *NRAMP*, *YSL*, *IRT1*, *CDF/MTP*, P-Type-ATPase and *VIT* (vacuolar iron transporter) (Xia et al., 2010; Socha and Guerinot, 2014) that help in Mn transport. Transporters in Mn have broad specificity for other divalent cations such as Cd, Ca, Co, Zn, Fe, Cu, and Ni. In *Arabidopsis*, *AtNRAMP1* was reported to be a high-affinity transporter for Mn transport in roots, and knockout lines for *AtNRAMP1* showed susceptibility toward Mn deficiency (Cailliatte et al., 2010). *ZIP1* remobilizes Mn from vacuoles to allow Mn translocation to the shoot through root vasculature (Milner et al., 2013). However, *ZIP2* transporters do not seem to be the primary transporters of Mn in roots of many species, including *M. truncatula*. In the case of field pea and *M. truncatula*, *PsIRT1*, *MtZIP4*, and *MtZIP7* genes can reestablish growth to the Mn uptake defective *smf1* mutant in Mn-limited media indicating *IRT/ZIP* as a direct transporter of Mn in strategy I plants (Milner et al., 2013). A subset of cation channels such as Ca^{2+}-permeable channels transport Mn^{2+} in the apical plasma membrane of *Arabidopsis* root hairs (Véry and Davies, 2000; Socha and Guerinot, 2014). Involvement of other routes in Mn transport can be plausible because of the presence of many transporters associated with Mn transport even in the absence of vacuolar iron transporter 1 (*VIT1*).

7.4. Phosphorus (P) Transport

Phosphorus uptake of plants from the soil is in the form of phosphate (P_i) either via root epidermal cells impelled through a proton gradient produced by plasma membrane H^+-ATPases or with the help of arbuscular mycorrhizal fungi (AMF) found in legumes (Bucher, 2007; Figure 2). Several *Pht1* genes are expressed in roots, aerial parts, and seeds, implying their potential involvement in internal P_i translocation. In the case of *M. truncatula*, P_i-transporters genes (*MtPT1* and *MtPT2*) from the *Pht1* family were found to be highly expressed in P_i-deprived roots (Liu et al., 2008). However, only *MtPT5* showed high affinity for P_i uptake among the reported five (*MtPT1*, *MtPT2*, *MtPT3*, *MtPT4*, and *MtPT5*) *Pht1* family genes in *M. truncatula* (Liu et al., 2008). In *L. japonicus*, three P_i transporter genes of the *Pht1* family have been isolated (Maeda et al., 2006). In the case of soybean, 14 *Pht1* genes (*GmPT1-GmPT14*) were identified in response to P_i availability in various tissues associated with its uptake and translocation (Qin et al., 2012). A high-affinity P_i transporter, *GmPT5* helps in maintaining P_i homeostasis by regulating movement from roots to the region of aerial plant tissues in nodules of soybean (Qin et al., 2012). In chickpea, *CaPHO1*, *CaPHO2*, *CaPHT1; 4*, *CaPAP17*, *CaPPase4*, and *CaDGD1* were involved in P_i uptake, transport, allocation, and the mobilization/remobilization from roots and leaves to nodules (Esfahani et al., 2016). *Pht1* transporters are mostly involved in transferring P_i into cells while other members of the *Pht2*, *Pht3*, and *Pht4* families are associated with the transfer of P_i in the intercellular membrane.

7.5. Copper (Cu) Transport

Copper uptake from the soil follows similar strategies like Fe, entering the root cell through copper transporters (COPT) family transporter (Gayomba et al., 2013; Ryan et al., 2013). Cu is mostly available in the soil as Cu^{2+}, which is transported to the root cell in its reduced form "Cu^{+}" (Figure 2). Ferric reductase, *FRO2*, helps in reduction activity and also in Cu^+ uptake by roots (Bernal et al., 2012). In *Arabidopsis*, Cu stress induces high Cu^{2+} chelate reductase activity regulated by SPL7, and this reductase was encoded by *FRO4/5* at the root tips (Bernal et al., 2012; Ryan et al., 2013). After reduction, Cu^+ is transported through the roots by copper transporter (*COPT*) proteins. *COPT* proteins have not been studied in detail in legumes. However, in *Arabidopsis*, *COPT1* (in roots) and *COPT2* (in shoots) are the core uptake transporters whereas *COPT3* and *COPT5* might be involved in intracellular Cu mobilization (Gayomba et al., 2013). Besides, *COPT* transporters *ZIP2* and *ZIP4* are also believed to support Cu uptake in plant cells in *Arabidopsis*. In *Arabidopsis*, the cysteine-rich metallothionein proteins (MT proteins) were upregulated during Cu stress, whereas in field pea, MT mRNA levels were mildly upregulated in Cu stress conditions.

Metabolic Pathways for Vitamins (β-Carotene, Folate, and Vitamin E) in Legumes. Understanding the pathways to and rate-limiting steps in the accumulation of various seed nutrients is a major challenge. Initial efforts in developing nutrient-rich crops have focused on overexpression of single genes that affect nutrient biosynthesis/uptake, transport or storage. Various studies have suggested that overexpression of a single gene is not sufficient to increase the accumulation of nutrients in seeds (Ishimaru et al., 2010). Considering the complex nature of nutrient accumulation in plants, multiple genes at different steps of translocation or biosynthetic pathways need to be manipulated simultaneously to increase seed nutrient concentrations. To enhance vitamins' content in legumes, a cohesive understanding of the genetics of nutritional traits along with a knowledge of regulatory biochemical and molecular processes in the accumulation of nutrients are required (Asensi-

Fabado and Munné-Bosch, 2010; Bhullar and Gruissem, 2013). A brief description of vitamins such as β-carotene, folate, tocopherol and anti-nutritional components such as phytic acid and raffinose biosynthesis are discussed below.

7.6. Beta (β)-Carotene Biosynthesis

Plant carotenoids are the generic name for C_{40} tetraterpenoids with a conserved biosynthetic pathway that play a significant role in different processes including photosynthesis (DellaPenna and Pogson, 2006). There are two major groups of carotenoids; the first is oxygenated or xanthophyll that consists of lutein, violaxanthin, and neoxanthin, and the second is non-oxygenated or carotenes that include β-carotene and lycopene (DellaPenna and Pogson, 2006). Seeds of legumes are rich in carotenoids such as β-carotene, cryptoxanthin, lutein, and zeaxanthin (Abbo et al., 2005). For instance, β-carotene concentration in chickpea was higher than in genetically engineered "golden rice" endosperm but lower than in Golden Rice2, where β-carotene concentration was increased up to 23-fold (Abbo et al., 2005). In legumes, plastid-confined MEP (2-C-methyl-D-erythritol 4-phosphate) pathway produces carbon flux, which is used for carotenoid biosynthesis (Giuliano, 2014). Carotenoid concentration is a highly heritable trait which is least affected by the environment (Owens et al., 2014). Identifying the metabolic bottlenecks associated with the carotenoid pathway can help in modifying strategies to develop carotenoid-rich crops. The key regulator gene of the carotenoid pathway is *PSY*; the overexpression of this gene or phytoene desaturase gene individually or a in combination has been practiced in several crops including soybean (Schmidt et al., 2015). In soybean, a 1500-fold increase in β-carotene content in dry seeds was observed compared to wild-type by introducing a chimeric gene from pea and a *crtB* gene from bacterium *Pantoea* using a biolistic method (Schmidt et al., 2015). In chickpea, four members of the *PSY* family that might have a positive effect on carotenoid concentration for various cotyledon colors were reported. A total of 32 genes for isoprenoid and carotenoid pathways in chickpea distributed across all eight chromosomes were also identified (Rezaei et al., 2016). Phytoene synthase and desaturase were found to have a major impact on pro-vitamin A and total carotenoid concentration through genetic transformation or overexpression of these genes. Xanthophylls are produced by converting pro-vitamin A compound with the help of β-carotene hydroxylation and can help in developing cultivars with higher pro-vitamin A as seen in potato, where silencing of β-carotene hydroxylase increased β-carotene concentration (da Silva Messias et al., 2014). Lutein, one of the main carotenoid types in chickpea, showed higher concentration in desi compared to kabuli type and was found to be adversely associated with seed weight (Abbo et al., 2005; Ashokkumar et al., 2014). Carotenoid concentration was higher in genotypes with green cotyledons in both pea and chickpea; a similar trend for lutein was observed in pea. Similarly, in transgenic soybean, increased concentration of β-carotene and seed protein content, with a decreased level of abscisic acid in cotyledons by overexpressing a seed-specific bacterial phytoene synthase gene was observed (Schmidt et al., 2015).

7.7. Folate Biosynthesis

Folates (Tetrahydrofolate and derivatives) are water-soluble B vitamins that act as cofactors in many vital metabolic functions, including the metabolism of amino acids, biosynthesis of nucleic acids in the human body. Legumes are a rich source of folates. A high concentration has been estimated in chickpea (351–589 μg/100 g), common bean (165–232 μg/100 g), and lentil (136–182 μg/100 g), (Blancquaert et al., 2014; Jha et al., 2015). Plants are the only source of folate for humans as the human body cannot synthesize it. Folate biosynthesis takes place in three subcellular compartments. Firstly, the Pterin and pABA moieties are synthesized in cytosol and plastids, respectively, while the rest of the reactions take place in the mitochondria. Pterin moiety synthesizes by converting GTP into dihydroneopterin triphosphate and formate with the help of GTP cyclohydrolase-I (Hossain et al., 2004). In legumes, pABA is synthesized from chorismate through two reactions in plastids. In mitochondria, after pyrophosphorylation of 6-hydroxymethyldihydropterin (HMDHP), it combines with pABA to form dihydropteroate with the help of enzymes HMDHP pyrophosphokinase and dihydropteroate synthase. After this reaction, glutamate residue is combined with the carboxy part of the pABA moiety of dihydropteroate to produce dihydrofolate with the help of enzyme dihydrofolate synthetase. Finally, folate is formed by the attachment of a glutamate tail to THF molecule catalyzed by dihydrofolate reductase.

Considering the complex nature of folate biosynthesis, metabolic engineering has emerged as a better approach to increase folate concentration in plants, such as by the overexpression of genes involved in pterin biosynthesis, a folate biosynthesis precursor (Hossain et al., 2004; Storozhenko et al., 2007; Blancquaert et al., 2014). Around a 150-fold increase in biosynthetic pteridines was reported in transformed lines of the common bean by introducing GTP cyclohydrolase I from *Arabidopsis* in three cultivars by particle bombardment (Rivera et al., 2016).

7.8. Vitamin E Biosynthesis

Tocopherol and tocotrienol derivatives are collectively called vitamin E. Improvement for vitamin E mostly focuses on enhancing vitamin E content in edible parts by regulating the activity of various enzymes involved in different steps of the synthesis, such as p-hydroxyphenylpyruvate dioxygenase, homogentisate phytyltransferase, homogentisate geranylgeranyl transferase, homogentisate solanesyltransferase2-methyl-6-phytyl-benzoquinol methyltransferase, tocopherol cyclase, and γ-tocopherol methyltransferase (Tang et al., 2016). Overexpression of γ-*TMT* resulted in an increased proportion of α-tocopherol in soybean (Sattler et al., 2004; Tavva et al., 2007) while overexpression of both MT and γ-*TMT* increased α-tocopherol 5-folds in soybean (Tavva et al., 2007). Overexpression for the combination of tyrA, HPPD, GGPP reductase and HPT resulted in an 11-fold increase in vitamin E content in soybean (Karunanandaa et al., 2005).

8. Metabolic Pathways of Anti-nutrients (Phytic Acid and Raffinose)

Phytic acid binds to mineral cations to form a mixed salt called phytate and sequesters inorganic phosphate in legumes. Myo-inositol is the precursor for many metabolites, including phytate, which plays an important role in plant stress adaptation. In addition to stress response, phytate plays a major role during seed germination to develop embryos and defense against oxidative stress. Considering its anti-nutritional role, breeding and transgenic approaches were used to reduce phytic acid in legumes (see Panzeri et al., 2011; Joshi-Saha and Reddy, 2015). In common bean, genes *PvMIPSs* and *PvMIPSv* (coding for myo-inositol 1phosphate), *PvIMP* (inositolmonophosphatase), *PvMIK* (myo-inositol kinase), *PvIPK2* (inositol 1,4,5-tris-phosphate kinase), *PvITPKa* and *PvITPKb* (inositol 1,3,4-triphosphate 5/6-kinase), and *PvIPK1* (inositol 1,3,4,5,6 pentakisphosphate 2-kinase) have been identified and mapped on a reference genetic map through virtual mapping strategy (Fileppi et al., 2010). In common bean, a low phytic acid line (*lpa*1) 280-10 was selected and used for the identification of *Mrp1* gene that down-regulates the phytic acid pathway at the transcriptional level (Panzeri et al., 2011). *lpa* mutants have also been identified in other legumes such as field pea and soybean using EMS-based mutagenesis (Warkentin et al., 2012). In chickpea, *CaMIPS2* gene was found to be regulating the phytic acid biosynthesis pathway (Kaur et al., 2008). In soybean, identification of consistent metabolic changes in *lpa* mutants showed decreased content of myo-inositol and raffinose compared to the wild type and reported a significant role in reducing phytic acid (Frank et al., 2009). Silencing expression of multidrug resistance-associated protein (MRP) ATP-binding cassette (ABC) transporters in an embryo-specific manner resulted in low phytic acid and high inorganic phosphate in transgenic maize and soybean (using homologous soybean MRP gene) (Shi et al., 2007). Raffinose is another major anti-nutrient affecting plant nutrition potential. In chickpea, raffinose content varied from 0.38 g/100 g to 0.99 g/100 g, while stachyose content ranged from 0.79 g/100 g to 1.87 g/100 g. Synthesis of galactinol is a key requirement for entering into the pathway of the raffinose family of oligosaccharides (RFO) biosynthesis. The key enzyme galactinol synthase synthesizes galactinol using UDP Galactose. Raffinose synthase helps to synthesize raffinose, and stachyose synthase helps to produce tetrasaccharide stachyose by utilizing galactinol, and both these reactions are reversible.

Understanding interactions between micronutrients, such as the synergic effect of Fe and pro-vitamin A carotenoids or the competitive effect of Fe and Zn and bioconversion factors, are essential for the development of nutrient-rich crops. Bioavailability of nutrients depends on endogenous (phytic acid, fiber, amino acids, and proteins) and exogenous factors in seeds. Legumes contain some promoters that enhance the bioavailability of minerals, even in the presence of anti-nutrients. Some promoter compounds are natural plant metabolites, and only minor changes in its accumulation in seeds may be necessary to impact the bioavailability of micronutrients. Inulin is a fructooligosaccharide found in small amounts in raw samples of lentil, chickpea, red kidney bean, common white bean, white bean and faba bean (Rastall and Gibson, 2015). It has a significant positive effect on improving the bioavailability of mineral nutrients in legumes.

Further studies are required to understand the types and amounts of prebiotics concerning in relation to increased bioavailability of minerals. Nicotianamine levels in plants have also shown a positive effect on enhancing Fe concentrations in seeds. Breeders should focus on enhancing the level of promoters such as inulin, β-carotene, histidine, lysine, riboflavin, and selenium, which can increase the bioavailability of Ca, Fe, Zn, Mg, and I (White and Broadley, 2005).

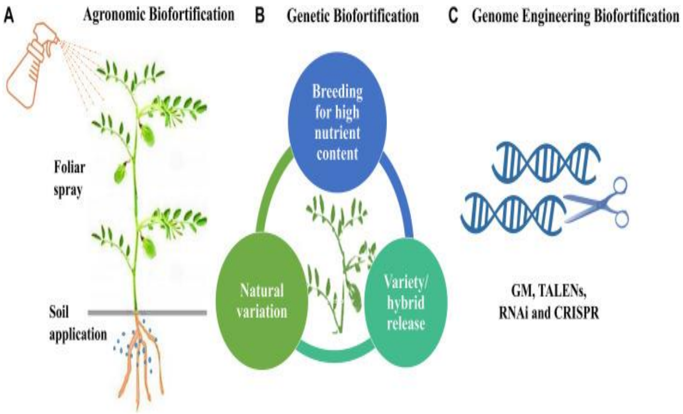


Fig 13: The three approaches for bio fortification. (A) **Agronomic Bio fortification using soil and foliar spray.** (B) **Genetic Bio fortification through breeding using conventional and genomics-assisted breeding.** (C) **Genome Engineering Biofortification including GM and DNA alteration technologies such as TALENs, RNAi and CRISPR.**

9. Agricultural Interventions through Bio fortification

Biofortification is the most sustainable approach to increase nutrient concentration and bioavailability in staple food crops. It refers to the procedure of improving the concentration of essential minerals, vitamins, essential amino acids, and fatty acids and reduces anti-nutritional factors enabling nutrient bioavailability in crop plants (Garcia-Casal et al., 2017). Biofortification approaches include the application of fertilizer to the soil or leaves, plant breeding, and genetic engineering (genetic modification and transgenesis) (Figure 3). It is the most economical and cost-effective way to provide nutrient-rich food to most vulnerable people and gives better yield and profit to farmers (Garcia-Casal et al., 2017).

10. Interaction of nanoparticles with plant-associated microorganisms

The potential use of nanoparticles as nanofertilizers and nanopesticides for precision and sustainable agriculture is still in its infancy and is currently under rigorous investigation (Zulfiqar et al., 2019; Hazarika et al., 2022; Zain et al., 2024). The application of nanofertilizers and nanopesticides may impact various plant growth characteristics (such as seed germination, root and shoot growth, chlorophyll content, photosynthesis, flowering, fruit formation, as well as crop yield), depending on the plant's genetic makeup, soil and plant microbiology, soil nutrients (macronutrients and micronutrients), soil pH, moisture, and other environmental factors (Juo and Franzluebbers, 2003; Bratovcic et al., 2021; Okey-Onyesolu et al., 2021). Nanoparticles introduced in soil and plants could directly or indirectly affect the type of microorganisms present and alter their functions (Mosquera et al., 2018; Kibbey and Strevett, 2019). The effects of nanoparticles on plant-associated microbial communities are highly dependent on the plant type, nanoparticle type (physical characteristics and chemical composition), soil properties (i.e., clay and organic matter content), as well as soil physicochemical characteristics (texture, organic matter content, pH, etc.) (Kumar et al., 2018; Kibbey and Strevett, 2019; Peng et al., 2020). In the rhizosphere, plants release a variety of exudates that promote microbial growth. Meanwhile, microorganisms work in concert with plant roots to support plant growth by facilitating a variety of nutrient cycles (Zhang N. et al., 2014). The presence of nanoparticles in soil dramatically affects the microbial communities in the rhizosphere, plant exudates, and extracellular materials produced by the microorganisms (Gao et al., 2018). Additionally, nanoparticles can enter the plant directly through root and stomata pores on leaf surfaces, with diameters ranging from a few tens of nanometers to a few hundred (Carpita et al., 1979; Eichert and Goldbach, 2008; Eichert et al., 2008). Subsequently, nanoparticles are transported by plasmodesmata from cell to cell within the plant, where they affect various physiological functions as well as plant endophytes (Zambryski, 2004). Nanoparticle-microbe interactions within the plant and soil play a significant role in disease management and subsequent plant improvement. However, this is influenced by either negative or positive nanoparticle effects as antimicrobial agents or microbial growth promoters, respectively. The mechanism in which nanoparticles hinder the development of various microorganisms involves the release of metal ions that interact with cellular components through various pathways. These pathways include generation of reactive oxygen species (ROS), formation of pores in the cell membrane, damage to cell walls, DNA damage, and cell cycle arrest. Ultimately, all these lead to the inhibition of cell growth and in some cases, phytopathogen inhibition (Singh et al., 2019).

While many studies may have focused on nanoparticle mechanisms as antimicrobials, it has also been shown that nanoparticles can play a positive role on microbial metabolism and functions. The beneficial nanoparticle-microbe interactions include nanoparticles' high bioavailability due to increased specific surface areas. This helps in nutrient uptake by the microbes as nanoparticles provide microorganisms with essential nutrients that stimulate growth and metabolic activity. Nanoparticles can also act as nano-tools for electron transfer, chemotaxis, and storage units (Mansor and Xu, 2020). Learning about the mechanisms in which microorganisms interact with nanoparticles might help in the development of nanomaterials that are safe for the environment. This can include development of green synthesis approach for nanoparticle production. Overall, the use of nanoparticles as agricultural amendments requires further investigation as it may directly or indirectly affect plant growth by influencing plant-associated microorganisms.

11. Application of nanoparticles in agriculture

Nanotechnology has been described as the understanding and control of matter in the range of 1 to 100 nm (Rajput et al., 2018). Particle dimensions within this range are considered nanoparticles (NPs) (Taghavi et al., 2013). Nanoparticles are distinguished based on their core material (organic or inorganic). Inorganic NPs are further divided into metal (Al, Bi, Co, Cu, Au, Fe, In, Mo, Ni, Si, Ag, Sn, Ti, W, Zn), metal oxide (Al_2O_3, CeO_2, CuO, Cu_2O, In_2O_3, La_2O_3, MgO, NiO, SiO_2, TiO_2, SnO_2, ZnO, ZrO_2), of which Ag, ZnO, TiO2, FeO, and CuO are often utilized and their harmful effects on the activity, diversity, and abundance of flora and fauna are closely observed (Rajput et al., 2018). Nanoparticles can be used in agriculture as fertilizers or pesticides and are generally regarded as nanofertilizers and nanopesticides, respectively. The use of nanoparticles as nanofertilizers in agriculture has the potential to improve the efficiency of nutrient consumption (Toksha et al., 2021; Ndaba et al., 2022; Rabalao et al., 2022). Additionally, the use of nanoparticles in the form of nanopesticides may protect crops from fungal and bacterial infections (Yadav S. A. et al., 2022). However, the impact of continued use of nanoparticles on plant-associated microorganisms remains unclear. Studies on the effects of nanoparticles on soil and plant microbiomes remain rare, even though microbial communities are important and sensitive determinants of the environmental hazards of nanoparticles (Brookes, 1995; Holden et al., 2014).

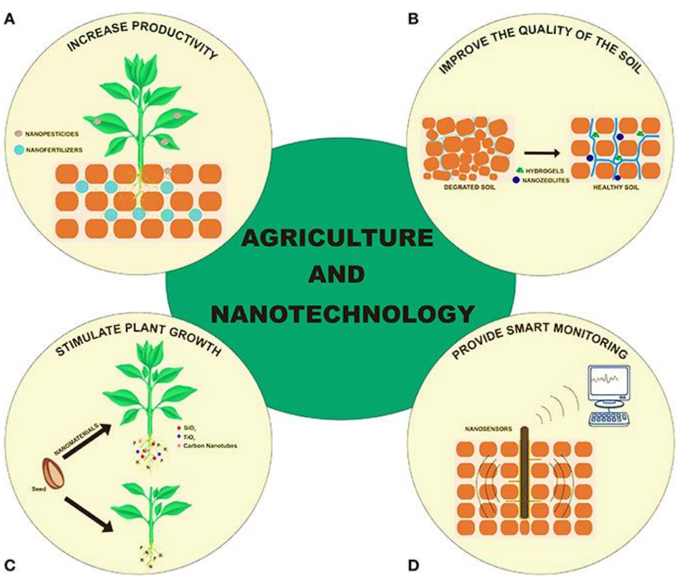


Figure 14: Potential applications of nanotechnology in agriculture. (A) **Increase the productivity using nanopesticides and nanofertilizers;** (B) **Improve the quality of the soil using nanozeolites and hydrogels;** (C) **Stimulate plant growth using nanomaterials (SiO_2, TiO_2, and carbon nanotubes);** (D) **Provide smart monitoring using nanosensors by wireless communication devices.**

Despite the potential benefits of applying nanotechnology to agriculture, some researchers have cautioned and expressed concern about the consequences of nanoparticle applications in agriculture (Khan et al., 2022). Table 3 provides a summary of the benefits and drawbacks of using nanoparticles in agriculture. Nanoparticles are introduced into the agroecosystem via the application of nano-based agriculture amendments as well as the direct release of waste from industries and households (Weir et al., 2012; Sánchez-Quiles and Tovar-Sánchez, 2014). The impact of direct exposure of plants to nanoparticles should not be ignored as they may pose both negative and/or positive effects on soil health as well as crop growth and quality. The factors that influence the effects of nanoparticles include the type and size of the nanoparticle, plant species, nanoparticle concentration, and length of time that the soil/crop was exposed to the nanoparticles (Duan and Li, 2013). In a study done by An et al. (2008) silver nanoparticles boosted ascorbate and chlorophyll in the leaves of asparagus (*Asparagus officinalis* L.). These findings provide examples of the beneficial effects of nanoparticles. In a different study, silica nanoparticles applied to maize seedlings increased seed germination, root and shoot length, photosynthesis, and dry weight (Suriyaprabha et al., 2012). On the other hand, some reports on metal nanoparticles (MNPs) suggest negative impacts on the growth and physiology of internationally significant crops like maize (*Zea may* L.), wheat (*Triticum aestivum*), rice (*Oryza sativa* L.) and soybean (Dimkpa et al., 2012; Nair and Chung, 2014; Thuesombat et al., 2014). The toxic effects of nanoparticle application on crops are both physical and physiological, and examples include a reduction in fruit yield, plant growth, and biomass. Nanoparticles may also cause indirect toxicity to plants by damaging plant roots, enhancing uptake of contaminants by plants, and by altering plant-associated microbial communities (Anjum et al., 2013; Ge et al., 2014). The mechanisms by which nanoparticles interact and impact plant associated microorganisms, following their application, is discussed in the following sections.

Table 2: Advantages and disadvantages of nanoparticle application in agriculture (Sindhu et al., 2020).

Advantages	
Properties	**Effects**
Facilitate higher nutrient use efficiency	• Small particle size than the pore size of root and leaves leads to more penetration into the plant. • Increase the efficiency with which crop plants absorb nutrients. • Nutrient loss prevention.
Nutrient content and health	• The growth of plant components and metabolic processes like photosynthesis are accelerated by nanofertilizers, increasing yield. • Increased nutrient availability contributes to higher crop quality indicators such as protein, oil content, sugar content, etc. • More readily available nanonutrients protect plants from disease, nutrient shortages, and other biotic and abiotic stresses, resulting in higher yields and higher-quality food products for consumption by humans and other animals.
Slow/controlled release	• For greater uptake by crop plants, nanofertilizers regulate the rate and

Advantages	
	dosage of encapsulated nutrients and fertilizers. • Increased availability as a result of nutrients' gradual release. • Extend the real time that nutrients are supplied for.
Reduces loss	• The slower rate of release ensures constant nutrient availability. • Plants can absorb nutrients without wasting them by leaching and/or leaking. • Decrease the need for fertilizers.
Enhance the soil's quality	• Improve soil quality and water-holding capacity. • Improves microbial activity.
Disadvantages	
Transformation of NPs	• Nanomaterials can interact and modify various elements of the environment due to their reactivity. • Nanomaterials may cause toxicity when they interact with soil components.
Accumulation of NPs	• Nano-fertilizers can build up in plant tissues, which can limit growth, produce reactive oxygen species, and cause cell death. • May build up in food components and, when consumed, may have negative effects on human health.
Safety concerns for farm workers	• Reactivity and unpredictability of Nano-materials have prompted safety issues for personnel who may become exposed during their fabrication and deployment in the field.

11. Impact of Nano fertilizer on plant-associated microorganisms

Nanoparticles, when used in the form of nanofertilizer, have been proven to enhance crop growth and quality (Merghany et al., 2019; Babu et al., 2022). Unlike bulk chemical fertilizers, which are required in high doses, nanofertilizers can be applied in relatively smaller quantities. Applying a lower dosage of nanofertilizer can minimize the potential for nutrient loss through leaching and volatilization, and thereby improves nutrient use efficiency (Raliya et al., 2018).

Three factors – intrinsic, extrinsic, and mode of administration – affect the efficiency of nanofertilizers. Nano-formulation techniques, particle size, and surface coating are examples of intrinsic variables. While extrinsic factors include soil texture, depth, pH, temperature, organic matter, and microbial activity (Zulfiqar et al., 2019). Moreover, the mechanism of delivery through plant roots or leaves (foliar) has a considerable impact on the uptake, behavior, and bioavailability of nanofertilizers (Mahil and Kumar, 2019). Due to their interaction with organic materials in the soil, nanofertilizers may change the soil

surface chemistry, which could have an impact on plants and microorganisms. On the other hand, microorganisms and their actions can potentially alter how nanoparticles behave (Frenk et al., 2013; Zulfiqar et al., 2019; Toksha et al., 2021).
In a study conducted by Kaur et al. (2022), the effect of titanium dioxide (TiO_2) NPs on the soil rhizosphere of mung bean crop was evaluated. The TiO_2 NPs were shown to stimulate growth of soil microflora (N-fixers and ammonia oxidizers) as well as increase enzymatic activity for dehydrogenase, phosphatase, protease, urease, and catalase at low concentrations (1.0, 2.5, 5.0, and 10.0 mg/L) compared to the higher concentration (20 mg/L). In addition, the nitrate-N content increased with days after treatment and TiO_2 NP concentration. An experiment conducted by Helal et al. (2023) demonstrated that the tomato plant (*Lycopersicon Esculentum* L.) treated with a controlled-release nano-urea (CRU) fertilizer showed better plant growth, yield, and fruit quality compared to the conventional fertilizers. In another study, an increase in nutritional value of spinach (*Spinacia oleracea*) after treatment with ZnO NPs (500 and 1,000 ppm) was indicated by higher values of protein and dietary fiber, as well as overall leaf quality (width, length, color, and surface area) (Revanappa and Pramod, 2015). Table 4 highlights some of the impacts of different nanofertilizers on microbial processes and related microorganisms in plants.

Table 3: Impact of Nano fertilizers on microbial functions and related microorganisms in plants.

Nanomaterial	Plant name	Effect on microorganisms	Effect on microbial function	Effect on the plant	References
Metallic silver (Ag)	*Cucumis sativus*	Increased growth-promoting bacterial activity	Improved carbon, nitrogen, and other biogeochemical cycles	An increase in the length of the roots and shoots as well as biochemical indicators like proline, protein, and antioxidants	Nawaz and Bano (2019)
Titanium dioxide (TiO2)	*Triticum aestivum*	Increased actinobacterial and planctomycete abundance	Efficiency of nitrogen fixation increased	Improvement in phenotypic characteristics	Moll et al. (2017)
ZnO NPs	*Phoenix dactylifera*	Number of fungal and bacterial cultivable heterotrophic colony-forming units reduced significantly	Reduction in carbon and nitrogen mineralization efficiency	Decrease in dissolved organic carbon and mineral nitrogen	Rashid et al. (2017)
Iron oxide (FeO)	*Zea mays*	An increase in *Bradyrhizobium* and ammonia-oxidizing bacteria activity	Improved nitrification	Improved plant growth and yield.	He et al. (2016)
Iron oxide (Fe_3O_4)	*Triticum aestivum*	Increased actinobacteria and planctomyces population	Improved nitrogen fixation efficiency	Improvement in phenotypic characteristics	Zhang et al. (2020)

Nanomaterial	Plant name	Effect on microorganisms	Effect on microbial function	Effect on the plant	References
Pristine and sulfidized ZnO NPs	*Glycine max*	Significant effects on bacterial communities	Drastic impact on carbon and nitrogen metabolism	Overexposure to zinc may have an impact on the development and growth of soybeans	Chen et al. (2023)
Zinc oxide (ZnO)	*Lactuca sativa*	Increased abundance of cyanobacteria, bacteria, and protozoa	Enhancement of organic matter decomposition and nitrogen fixing	Fresh biomass and net photosynthetic rate both increased by 6.2%	Xu et al. (2018)
Cu and Zn NPs	*Raphanus sativus*	Reduced Azotobacter genus abundance in the soil	Decrease in catalase and dehydrogenase activities	Decrease in germination and roots length	Kolesnikov et al. (2019)
Silica	*Zea mays*	P solubilizing and nitrogen-fixing bacteria were more abundant, but silicate-solubilizing bacteria were less abundant	N/A	Increased germination and absorption of silica	Rangaraj et al. (2014)
High dose of ZnO NPs	*Medicago sativa*	Reduction in the quantity of bacteroids and in the diversity and relative abundance of soil microorganisms	Decreased nitrogen-fixing ability	Decrease in root nodules and plant biomass	Sun et al. (2022)

Despite the many benefits of nanofertilizers, the antibacterial potential of nanoparticles in general has also received substantial attention (Nath et al., 2008; Ramírez Aguirre et al., 2020; Thakral et al., 2021). The applied nanofertilizers may inadvertently have negative impacts on the beneficial microbial populations in the soil and on plants. The concentration and identity of nanoparticles, soil type, pH, and biological factors including root exudates and microbial diversity all have a significant impact on how nanoparticles affect the soil. A study conducted by Xu et al. (2015) investigating the effect of CuO NPs on soil microbes in flooded paddy soil reported CuO NPs (500 and 1,000 mg/kg) to have a negative impact on the soil microbes as was indicated by a significant decrease in microbial biomass and decrease in enzyme activity for urease, phosphatases, and dehydrogenase. The application of silver nanoparticles (Ag NPs) at 100 mg/kg significantly increased the soil pH and altered bacterial groups associated with carbon, nitrogen, and phosphorus cycling both in the absence or presence of cucumber (*Cucumis sativus*) plants (Zhang et al., 2020). Metal oxide nanoparticles, namely ZnO and CeO_2, were observed to inhibit enzymatic activity and reduced the numbers of K-solubilizing and P-solubilizing bacteria as well as soil Azotobacter (Zhang et al., 2018; Kaur et al., 2022). In another study, the activity of soil dehydrogenase was demonstrated to be adversely affected by high quantities of nanoparticles (García-Gómez et al., 2018). Dehydrogenase activity directly correlates with soil microbial biomass, and plays a significant role in the oxidation of organic materials. Therefore, the microbial biomass was impacted by the dose of nanoparticles applied (García-Gómez et al., 2018). Another study by Shah et al. (2014) examining the response of the soil microbial community to nanoparticle application showed that silver nanomaterial caused changes in the microbial community structure, however, zinc oxide and zero-valent copper oxide did not significantly alter the structure of the microbial community.

12. Impact of Nano pesticides on plant-associated microorganisms

Plant diseases and insect pests are effectively managed in agriculture by the application of pesticides. However, the high concentrations of chemical components applied per hectare has given rise to several issues, including environmental deterioration, pest resistance, bioaccumulation, and health risks (Yadav J. et al., 2022). Due to microbial activity, air drift, soil leaching, degradation processes including photolysis and hydrolysis, amongst other factors, more than 90% of the pesticides that are applied are lost. It is only a small amount of the remaining 10% that eventually reaches the target site (Yadav J. et al., 2022). This necessitates repeated application which eventually results in high costs and environmental pollution. Moreover, certain pesticides have been shown to have adverse effects on human health such as cancer, birth defects, reproductive defect, neurological and developmental impairment, immunotoxicity, and disruption of the endocrine system, when ingested through the consumption of pesticide-contaminated food (Toksha et al., 2021).

Although some environment-specific nanopesticides are on the market (Smith et al., 2008), nano-formulations with effective delivery mechanisms which result in application of modest amounts of nanopesticides are required. Nanopesticides provide innovative strategies for delivering the active ingredient of pesticides to the target site (Ahmed et al., 2023). Slow-releasing qualities, enhanced stability, permeability, solubility, and specificity are all features of Nano-encapsulated pesticide formulations (Narayanan et al., 2017). They are specifically created to make the active ingredient (AI) more soluble and release it at the target site in a controlled manner. Due to this, only a small amount of the AI needs to be applied for it to be effective for an extended period of time (Oliveira et al., 2019).

Nano pesticides are classified into two types. Type 1 Nano pesticides are metal-based, whereas Type 2 materials contain AIs that are enclosed by Nano carriers, such as polymers, clays, and zein nanoparticles. The most prevalent analytes for Type 1 Nano pesticides are Ag-, Ti-, and Cu-based nanomaterials (NMs). These nanopesticides can suppress a variety of plant pathogens, including fungal (such as *Candida* and *Fusarium*), as well as bacterial (such as Escherichia coli and Staphylococcus) (Wang et al., 2022).

If properly applied, nanopesticides could increase crop output, food safety, and nutritional value. For several plants treated with Type 1 nanopesticides (such as Ag-, Ti-, Cu-, and Zn-based NMs), improvements in the concentration of sugar, fatty acids, chlorophyll, carotenes, and important elements (such as P, K, Ca, Mg, S, Fe, Si, Mn, and Zn) have been documented (Gomez et al., 2021; Ma et al., 2021; Rawat et al., 2021; Shang et al., 2021; Yadav J. et al., 2022). Suppression of pathogenic activity is one of the factors contributing to these enhancements.

The abundance, structure, and network functioning of the plant-associated microbiome, which includes archaea, bacteria, and fungi, can be changed by adding metal-based nanopesticides to soil and plant. This in turn may change the bioavailability and recycling of macronutrients (such as C, N, P, and S). More importantly, in order to fully utilize nanopesticides, it is necessary to comprehend how they interact with nutrients, soil, plant-associated microbiota, and other factors. Nanopesticides have obvious pesticidal activity and as such can exhibit toxicity toward non-target organisms. Studies show that, in comparison to their non-nanoscale equivalents, nanopesticides are 43.1% less toxic (Wang et al., 2020). This is primarily due to their AI delivery system, which is target-specific, and thereby minimizes the exposure to non-target organisms.

$Cu(OH)_2$ nanopesticides applied to target soil agroecosystems for 365 days, had only minor negative effects on non-target wetland systems and the bacterial and fungal communities that live there (Carley et al., 2020). However, a few studies have shown negative impacts related to nanopesticide exposure. Zhai et al. (2020) showed that long-term exposure to high concentrations of atrazine-containing nanopesticides (NPATZs) dramatically reduced the metabolic capability of bacterial communities in the rhizosphere and changed the makeup of those communities in comparison to conventional ATZ. An investigation into the long-term (117 days) effects of Ag nanopesticides (100 mg/kg) on the microbiome of the maize rhizosphere revealed negative effects on microbial diversity, the nitrogen cycle, and crop output (Sillen et al., 2020). Low concentrations (0.5, 1.0, and 2.0 mg/g) of zinc oxide (ZnO) applied directly to soil enhanced the relative abundance of the essential bacterial group *Bacillus* in comparison to the control, but the higher concentrations had harmful effects on the bacterial population (You et al., 2018). A study by Zhao et al. (2017), discovered that exposure of spinach to $Cu(OH)_2$ nanopesticide resulted in a significant reduction in antioxidant or defence-associated metabolites such as ascorbic acid, α-tocopherol, threonic acid, β sitosterol, 4-hydroxybutyric acid, ferulic acid, and total phenolics (Peixoto et al., 2021). Another study showed that captan@ZnO35-45 nm and captan@SiO2 20–30nm nanofungicides influenced soil microorganisms by altering numerous microbial characteristics (Sułowicz et al., 2023).

Overall, literature suggests that nanopesticides may be more effective, resilient, and sustainable than their traditional analogues, with fewer negative environmental effects. However, future research is required to comprehend the effects of realistic nanopesticide doses on the rhizosphere microbiota, crop yield, and agroecosystem health in field settings.

13. Effect of Nano-fertilizers on plant growth:

The development of zeolite-based nano-fertilizer has attracted significant economic interest due to the rising awareness and the availability of low-cost natural zeolites worldwide. Chuprova et al. (2004) stated that zeolite fertilisers have positive impacts on Chernozem's mobile humus components and the biological productivity of maize. In a different study, it was discovered that a patented nano-composite of N, P, K, micronutrients, mannose, and amino acids increased the uptake and utilisation of nutrients by grain crops (Jinghua, 2004). Bhattacharya et al. (2004), found that a balanced application of NPK coupled with S, Zn, B, and Mo will be a successful strategy for increasing pulses' grain yield in red and lateritic soils. With adequate NPK treatment Green and black gram yield gets increased by 13% and 38% in comparison to control. Liu et al. (2006) demonstrated that the organic material (polystyrene) intercalated in the layers of kaolinite clay produces a cementing of Nano and sub Nano-composites that can control the release of nutrients from the fertilizer capsule. Nanoparticles could therefore be employed to control the release of nutrients across membranes. The efficacy of natural and artificial nutrient sources can be increased by the use of nanotechnology. The efficiency of crops' fertilizer use is increased via Nano-fertilizer technology. Since the public has become increasingly concerned about the negative effects of chemical fertilizers on the agro-ecosystem, there has been an increase in interest in the usage of Nano-porous zeolites in farming (Ramesh et al., 2010). These findings and patented goods strongly imply that there is a huge potential market for the creation of nano-fertilizers (De Rosa et al., 2010). The use of nano-fertilizer could be a tactic to increase crop productivity and nutrient use efficiency.

13.1. Important of Nano fertilizer for Food Security?

- It has been estimated that the world's population (currently eight billion people) will increase to approximately nine billion by 2050. Food production will need to double (compared with 2009 production) to meet the rising demand for food. Currently, an estimated 811 million people go to bed hungry each night globally.
- Global agricultural systems will need to rapidly respond to the growing population by producing higher volumes of food; if not, millions more people will go hungry. Food systems, however, are facing numerous unprecedented challenges, including rapid climatic changes.
- Fertilizers play a vital role in increasing agricultural production, but excessive use of chemical fertilizers irreversibly damages the chemical ecology of soil and reduces the available area for crop production. Chemical fertilizers, therefore, inadvertently contribute to food insecurity in the long term by damaging fertile land.
- Agricultural practices that do not harm the planet must be implemented globally so that food production can be guaranteed for generations to come. One solution may come from Nano fertilizers, which do not rely on the heavy use of harmful chemicals.

13.2. Nano fertilizers Benefit Agriculture?

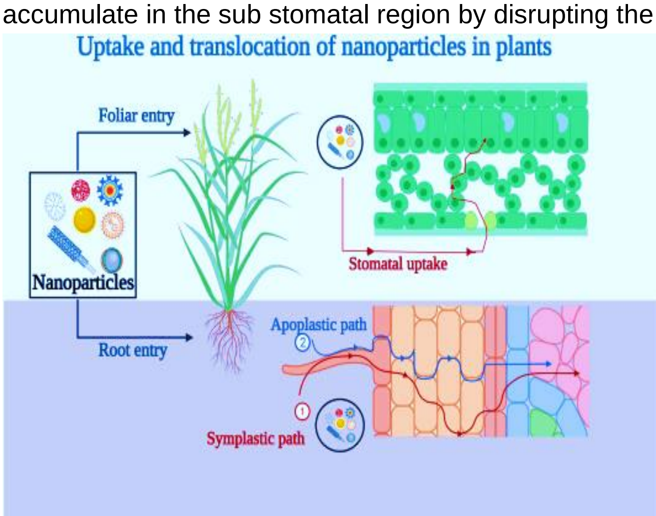
In conventional agriculture, an excess of fertilizer is applied directly into the soil or sprayed on the leaves, surpassing the plant's nutritional need. This is because a very low percentage of fertilizer reaches its target site due to leaching of chemicals, evaporation, drift, hydrolysis, run-off, and photolytic or microbial degradation.

This excess of chemical fertilizer negatively affects the nutrient equilibrium of the soil and causes contamination of local water supplies due to the leaching of toxic materials into water bodies.

Switching from a conventional fertilizer to Nano fertilizer could reduce the amount of chemicals used while simultaneously increasing crop yield. Nano fertilizers do this via various mechanisms, including increasing nutrient uptake, controlling the release of nutrients, and targeting nutrient delivery. Using a Nano fertilizer can also reduce the environmental impact of agriculture.

13.3. Uptake, translocation and accumulation of nanoparticles

The current knowledge about exact mechanisms and accurate details related to uptake, translocation and accumulation of nanoparticles is very limited. However, the existing literature provides a brief picture of the entry, transport and movement of NPs. Entry of nanoparticles into plants occurs mainly through roots (root entry) or leaves (foliar entry) and sometimes through other vegetative parts. Direct injection of NPs, incubating NPs with seeds, biolistic delivery, irrigating with NPs, hydroponic treatment are some other ways of nanoparticle application that are under study. Examples include the introduction of NPs in Lactuca sativa (lettuce) , Cucurbita pepo (field pumpkin), *Raphanus sativus* (radish), *Oryza sativa* (rice), *Cucumis sativus* (cucumber) by seed incubation. Introduction of silver nanoparticles (Ag NPS) in Gerbera jamesonii (Barberton daisy) and *Rosa hybrida* (hybrid tea rose) and magnetite (Fe_3O_4) nanoparticles in Cucurbita maxima (pumpkin) are the examples included under hydroponic treatment. Once the plant is treated with NPs, uptake occurs through natural plant openings (stomata, bark, lenticels, damages, wounds) passively. The dynamics of NPs-plant interactions are affected by many factors such as chemical composition, root anatomy, and soil nature. Uptake, translocation and accumulation of NPs are also dependent on the size of NPs. Nanoparticles with a size lesser than the cellular pore size get entry easily. However, the size exclusion limits (SELs) of cell walls and other parts vary based on abiotic stress factors and other physicochemical factors. For example, 4 to 100 nm-sized NPs have the ability to accumulate in the sub stomatal region by disrupting the wax layer and cuticle.



Sources: ***Golla Nagaraju Gari Saritha et al, 2022***

Fig. 2. Uptake and translocation of nanoparticles in plants.

Once delivered, mobilization of NPs occurs in two ways and they are apoplastic and symplastic pathways. The former promotes the radial movement of nanoparticles while the latter makes intracellular movement possible. Through these two pathways, NPs move to different parts and accumulate in the plants. Apoplastic movement is determined by capillary forces and osmotic pressure. This can make way for NPs to reach endodermis surpassing the cortex and epidermis. In order to enter the stele and associated vascular tissues, NPs must take up a symplastic route through aquaporins, endocytosis, ion channels or carrier proteins. After cellular internalization, the movement of NPs to neighboring cells is channeled by plasmodesmata. Although it is not an easy task to overcome the cellular integrity maintained by the cytoskeleton, studies on the model organism Arabidopsis thaliana have proposed that NPs disrupt the micro tubular network and with the help of Rab proteins, they pass through plasmodesmata.

13.4. Nano fertilizers: Controlled Nutrient Release

Using Nano fertilizers instead of conventional fertilizers can also improve the stability and predictability of nutrient delivery. This is achieved by engineering the nanoparticles used in Nano fertilizer so that they can release nutrients over long periods. Several researchers have reported that the small size of nanoparticles used in Nano fertilizers enables the absorption of abundant nutrient ions that is later desorbed slowly and steadily for an extended period. Therefore, formulations of Nano fertilizers can provide balanced nutrition for crops throughout the growth cycle, improving agricultural production.

13.5. Nano fertilizers: Reduced Environmental Impact

Due to the reduced volume of Nano fertilizers required to achieve the same or better crop yields than conventional fertilizes, the use of Nano fertilizers reduces the environmental impact of agriculture. Using reduced volumes of fertilizer lessens the volume of harmful chemicals that the environment is exposed to. Therefore, Nano fertilizers, to some extent, can help mitigate the negative impact of fertilizer use, such as damage to soil and water pollution caused by fertilizer run-off. While Nano fertilizers are not inherently environmentally friendly, they may offer a less damaging alternative to the agricultural industry.

13.6. Nano fertilizers: Additional Benefits

Nano fertilizers can suppress crop diseases by acting directly on phytopathogens through various mechanisms, including the production of reactive oxygen species. These materials also enhance crop production indirectly by improving crop nutrition and boosting plant defence pathways. In addition, the efficient use of Nano fertilizers can improve crop productivity by enhancing the rate of seed germination, seedling growth and photosynthetic activity. Finally, Nano biosensors that react with specific root exudates are also being explored. These techniques are relatively new and have numerous ethical and safety issues that must be carefully studied before implementation.

14. The global agricultural landscape of Nano fertilizers in Agriculture

The global agricultural landscape has radically changed since the revolution of green nanotechnology. Nano fertilizers are now being used in specific concentrations in accordance with the nutritional requirements of the crops, ensuring minimal differential losses. There are three types of Nano fertilizers: nanoscale fertilizers, nanoscale additive fertilizers, and nanoscale coating fertilizers. Nanoscale fertilizers are made of nanoparticles that contain nutrients. Nanoscale additive fertilizers are traditional fertilizers with nanoscale additives. Nanoscale coating fertilizers are traditional fertilizers coated or loaded with nanoparticles. The encapsulation of nutrients most commonly produces Nano fertilizers with nanomaterials. Preliminary nanomaterials are produced using physical (top-down) and chemical (bottom-up) approaches. More recently, the targeted nutrients are either encapsulated inside nonporous materials, coated with a thin polymer film particle, or coated with emulsions of nanoscale dimension. Encapsulation of beneficial microorganisms, such as bacteria or fungi, has shown promise as it can enhance the availability of nitrogen, phosphorus, and potassium in the root zone, thereby improving plant growth. Nano fertilizers can also be classified based on their actions: control or slow-release fertilizers; control loss fertilizers; magnetic fertilizers or nanocomposite fertilizers (which use a Nano device to supply a wide range of macronutrient and micronutrients in desirable concentration). Porous nanomaterials significantly reduce nitrogen loss by regulating demand-based release and by enhancing the plant uptake process. Examples of porous nanomaterials include:

Ammonium charged zeolites, which can enhance the solubility of phosphate minerals, showing an improvement in phosphorus availability and uptake by crops. Graphene oxide films, a carbon-based nanomaterial, can prolong potassium nitrate release, extending the time of function and minimizing losses by leaching. Nano calcite ($CaCO_3$-40%) with Nano SiO_2 (4%), MgO (1%), and Fe_2O_3 (1%) not only improve the uptake of calcium, magnesium and iron, but also notably enhance the intake of phosphorous with micronutrients zinc and manganese.

15. Agriculture in the 21st Century

Inhumane levels of hunger currently affect over 800 million people, and by 2050, the global population is projected to be close to 9.7 billion. A rapid increase in food poverty has the potential to spark conflict, ecological instability, and economic unpredictability. Reduced agricultural productivity, nutritional scarcity, and climate change are some of the biggest challenges agricultural scientists face today. Consequently, it is believed that current agricultural output need to be increased by as much as 50–70% to fulfill both present and future food requirements. Heavy fertilization of agricultural soils, tillage methods, fossil fuel usage, and livestock manure are the principal sources of greenhouse gas emissions, and hence represent a major contributor to climate change. Soil fertility, food security, and the environment have all declined as a result of extensive crop production coupled with an overreliance on chemical fertilizers and pesticides. Increases in temperature and atmospheric CO_2 levels, as well as changes in rainfall patterns, pose a danger to agricultural productivity and lead to drastically reduced crop yields. As a result, individuals experience a wide range of health issues due to the instability and poor quality of the food they consume. Unpredictable seasonal and geographical changes interrupt plant life cycles, which means that climate change affects crop nutritional quality. One of the greatest issues facing contemporary agriculture is meeting the world's present and projected food needs. Defending natural resources to support increased agriculture while reducing adverse environmental consequences is a huge challenge that will require a concerted effort from interdisciplinary researchers.

Crops that are subjected to biotic and abiotic stressors experience a broad variety of diseases, many of which negatively affect crop output and nutritional quality. Over the past sixty years, artificial chemical fertilizers have been at the forefront of efforts to revive agricultural output and meet surging global food demand. Scientific and agricultural studies show that using agrochemicals like phosphate, ammonia, nitrate, or urea compounds in farming has disastrous effects on ecological health when used extensively and over extended periods. This has become a significant contributor to issues such as soil and water contamination, eroded landscapes, hunger, low fertility, inefficient water retention, and the disturbance of native soil biodiversity. Unfortunately, these agrochemicals do not stay out of the hydrosphere and contribute to eutrophication. Even more problematic is the fact that water constraint compounds the impact of nutrient pollution on soil quality, in addition to increasing emissions of greenhouse gases, eutrophication in aquatic environments, and soil salinization, all of which pose serious threats to food safety and quality. The latest research has shown that a sizeable fraction of synthetic fertilizers are not consumed by plants but instead escape into the environment or drainage sources like waterways. Plant-growth-promoting rhizobacteria (PGPR) as bio fertilizers have been advocated as being among the most sustainable and resilient methods to boost crop production. By providing essential nutrients, they stimulate plant growth via several direct and indirect pathways. Nitrogen fixation, exopolysaccharide synthesis, the production of siderophores and phytohormones along with nutrient solubilization are all examples of direct mechanisms. Through colonization of the rhizosphere, they provide plants with stress tolerance and resilience. The development of sustainable agricultural techniques should be prioritized, since we cannot entirely remove the use of agrochemicals; nevertheless, we may pick other ways to make crop production more efficient. Designing, characterizing, and manufacturing substances by controlling their sizes and shapes at the nanoscale constitute what the Royal Society calls "nanotechnology".

Nanotechnology is a relatively recent scientific idea that makes use of methods and materials that change the physio-chemical properties of a substance. The integration of these two fields has led to revolutionary developments in the agricultural sector. Due to the nature of climate change, nanotechnology has a wide range of possible uses and benefits. This new paradigm has matured to the point that it can be used in real-world settings. Soil structure, insects, infections, pollutants, and the distribution of pesticides, fertilizers, nutrients, and genetic components will be managed, all to exert a significant impact on agriculture. Nanoparticles (NPs) operate as triggers, kicking off several defensive mechanisms in plants subjected to stress. Many different fields of application have welcomed this fast-developing technology, including plant regulatory surveillance, improved fertilizer usage efficiency, accelerated plant development, and regular pesticide release. Surprisingly, a nanoparticle-derived strategy has gained favour and effectiveness in agriculture for crop sustainability, beating out bio-pesticides and other fertilizers due to the particular features of nanoparticles, such as their large surface area, high solubility, and light weight.

16. Applications of nanotechnology in pests and plant diseases management:

Now a day's use of chemicals such as pesticides, fungicides and herbicides is the fastest and cheapest way to control pests and diseases. Indiscriminate use of pesticides has caused many problems such as: adverse effects on human health and on pollinating insects and domestic animals, and entering this material directly or indirectly in ecosystems. Intelligent use of chemicals on the nano scale can be an appropriate solution for this problem. These materials are used as carriers in nano scale has self-regulation, this means that the medication on the necessary amount only be delivered into plant tissue. Nanoparticles for liberation of active ingredients or drug molecules will be at its helm in near future for therapy of all pathological sufferings of crop plants. There are myriad of nano materials including polymeric nanoparticles, iron oxide nanoparticles and gold nanoparticles which can be easily synthesized and exploited as pesticide, fertilizer or drug delivery piggybacks (Sharon et al., 2010) . Rao and Paria (2013) used sulfur nanoparticles (SNPs) as a green Nano pesticide on Fusarium solani and Venturia inaequalis Phytopathogens. It has been found that small sized particles of

SNP (35 nm) are very effective in prevention of the fungal growth and can be useful for the protection of important crops such as tomato, potato, apple, grape etc., from different diseases, mainly for organic farming because of antimicrobial Property of silver. Nano-based viral diagnostics, including multiplexed diagnostic kit development, have taken momentum in order to detect the exact strain of virus or other pathogens and stage of application of some therapeutic to stop the disease. Rouhani et al. (2012) investigated the insecticidal activity of Ag nanoparticles against the A. nerii. Nanoparticles of Ag and Ag-Zn were synthesized through a solvothermal method, and using them, insecticidal solutions of different Concentrations were prepared and tested on A. nerii. For comparison purposes, imidacloprid was also used as a conventional insecticide. The result showed that Ag nanoparticles can be used as a valuable tool in pest management programs of A. nerii. Additionally, the study showed that Imidacloprid at 1 μL Ml^{-1} and nanoparticles at 700 mg mL^{-1} had the highest insect mortality effect.

17. Future prospects and Conclusions:

Nanotechnology offers promising applications in agriculture, potentially revolutionizing crop production and management. However, challenges remain, including potential environmental and health risks associated with nanoparticles. Thus, we need to develop regulatory frameworks to ensure the safe and responsible development and use of nanomaterials in agriculture. Proper Risk Assessment can be conducted as suggested in the guidelines by the Department of Biotechnology (DBT), and FCO order 2021. The application of nanotechnologies as well as the introduction of nanomaterials in agriculture, potentially can greatly contribute to address the issue of sustainability. In fact, the efficient use of fertilizers and pesticides can be enhanced by the use of nanoscale carriers and compounds, reducing the amount to be applied without impairing productivity. Nanotechnologies can also have an impact on the reduction of waste, both contributing to a more efficient production as well as to the reuse of waste, while Nano sensors technology can encourage the diffusion of precision agriculture, for an efficient management of resources, including energy (FAO and WHO, 2013).However, as with the application of all new technologies, there is the need to perform a reliable risk-benefit assessment, as well as a full cost accounting evaluation. In the case of nanotechnologies, this requires also the development of reliable methods for the characterization and quantification of nanomaterials in different matrices and for the evaluation of their impact on the environment (Servin and White, 2016) as well as on human health (EFSA Scientific Committee, 2011). Furthermore, it is very important to engage all stakeholders, including non-governmental and consumer associations, in an open dialogue to acquire consumer acceptance and public support for this technology.

18. Government Initiatives on Nanotechnology in Agriculture

1. Mission on Nano Science and Technology (Nano Mission): Launched in 2007, under the Department of Science & Technology (DST), with funding spanned multiple areas like basic research in nanotechnology including Agriculture.
2. Guidelines for evaluating nano-agri inputs and products: Developed by the Department of Biotechnology to ensure the safe and effective use of nanomaterials in agriculture and address the regulatory framework for commercialization.
3. National Agricultural Innovation Project (NAIP): Several projects have been initiated to explore the applications of nanotechnology in agriculture.
4. Skill development training programme on nanotechnology: By Indian Council for Agriculture Research (ICAR), in line with the Government of India's Skill Development Initiative, to impart hands-on training on the synthesis & characterization of nanomaterials
5. Nano Fertilizer Plant (NFP): Established by IFFCO at Phulpur, Prayagraj.

18. Author Contributions

All the authors participated in the drafting the manuscript and discussion of all topics related to this perspective manuscript.

19. Conflict of Interest Statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

20. Availability of data and material

All relevant data and material are presented in the Research Review Paper.

21. Funding

Not Applicable.

22. Consent for publication

Not applicable.

23. Ethics approval and consent to participate

Not applicable

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