Nano Fertilizers: Revolutionizing Agriculture for a Sustainable Future

Abstract

Nanotechnology, one of the advanced fields of study, is currently the focus of contemporary science and one of the most important ones in physics, chemistry, agriculture, and other fields. Nanotechnology provides superior quality, environmental safety, biological support, and financial stability as an environmentally sound substitute for traditional agriculture. Utilizing nanoparticles (NPs) in agriculture has introduced recently; examples like biosynthesis, the use of Nano pesticides and fertilizers, improving biological function, and reducing heavy metal toxicity and abiotic stress. To focuson safe use and positive response of nano-particles, more research is required. There are gaps in the food supply compare to food production, which get worse over time due to rising food demands and nutrient depletion. Environmental degradation, changes in soil ecology, and problems with agricultural output are all brought on by synthetic fertilizer inputs.Adapting advanced agriculturetechnologyfor a sustainable future will be the main topic of this review.

Keywords:-Sustainable agriculture, nanotechnology, Nano fertilizers, nanofertilizers application, fertilizer inputs

INTRODUCTION:-

As we know that there are three categories of nanotechnologies: Nano-fertilizer, Nano-additives and Nano-coatings, for use in fertilizer inputs and plant protection.The application of nanoparticles to bridge the gap between bulk materials and their atomic or molecular structures is of tremendous scientific interest. Application of fertilizer is essential for raising agricultural yield, excess fertilizer application reduces the amount of land that can be used for crop production. Agrochemical use in sustainable agriculture must be kept to a minimum in order to maintain biodiversity and the ecosystem. Maintaining the health and quality of the soil and plants is beneficial for climate conservation and sustainable agriculture. Another cutting-edge agricultural technique that can make it possible to produce agricultural fields efficiently is nanotechnology [2].The field of nanotechnology has made it possible to use nanoscale or nanostructured materials as controlled-release or fertilizer carriers, thereby creating "smart fertilizers" that lower environmental protection expenditures (Chinnamuthu and Boopathi, 2009). Fertilizers that have been designed to the nanoscale, or commonly between 1 and 100 nanometers in at least one dimension, are referred to as Nano fertilizers. Nutrients like potassium, phosphorus, nitrogen, and other micronutrients are present in this type of fertilizer.[4]. When high analysis chemical fertilizers are added to soil, a significant amount of them are wasted and are not available to plants. For instance, 40–70%, 80–90%, and 50–90% of fertilizers, including potassium (K), phosphorus (P), and nitrogen (N), are lost or fixed in soils, causing financial losses for the farmers. (Ombódi and Saigusa, 2000).

When used as Nano-fertilizers, Nano-scale nutrients should lessen nutrient leaching and volatilization losses because their formulation may enable selective release correlated with time and environmental factors and may time the release of nutrients with crop uptake [6].The particles of Nano fertilizers are small enough for plants to absorb and increase agricultural production[7]. Such a carrier complex may or may not contain nanostructured elements, which could be nanomaterials. It is integrated through either adsorption or absorption into a matrix made of zeolite, chitosan, polyacrylic acid, or clay [8]. They can be categorized according to their consistency, activity, and nutrient makeup. These categories comprise nutrient-loaded, inorganic and organic, hybrid, controlled-release, targeted delivery, plant growth-stimulating, water- and nutrient-loss-controlling, and different consistency-based Nano fertilizers like surface-coated, synthetic polymer-coated, biological product-coated, and Nano carrier-based options.Promising Nano fertilizers with granular structures that supply essential nutrients to plants over a prolonged period of time—weeks to months—are called controlled-releasefertilizers (CRFs) [67-69]. Because of their special qualities, nanomaterials like graphene, carbon nanotubes, and quantum dots are perfect for controlled-release applications [7]. In comparison to conventional fertilizers, Nano-fertilizers have advantages in terms of application and small requirements, slow release mechanism, transportation and application cost savings, and relatively minimal salt accumulation in the soil. These enhance the bioavailability of nutrients, thus successfully meeting crop nutritional requirements. Through bio fortification, foliar-applied Nano-fertilizers improve crop nutritional quality [9]. Whether applying liquid fertilizer for macronutrients or micronutrients, the method is highly successful (Popko *et al.* 2018). According to El-Ghamry*et al.* (2018), Nano fertilizers can: (1) lower the chemical load in the soil, (2) increase nutrient use efficiency (NUE), (3) reduce the adverse effects of conventional bulky fertilizers, and (4) decrease the frequency of application.

Nanotechnology in Agriculture: -

Nanotechnology, one of the innovative research areas, is now the center of attention for modern science and one of the most significant areas in physics, chemistry, agriculture and other disciplines [12]. Applications of nanotechnology in agriculture include Nano-encapsulated flavor enhancers, Nano sensors, Nano-fertilizers, Nano films in packaging to stop spoiling and oxygen absorption and Nano-chip use tracking and identification [13]. The food industry, biomedicine, environmental engineering, safety and security, water resources, energy conversion and many other fields could undergo a revolution thanks to nanotechnology, which focuses on unique properties of materials arising from nanometric size (Baruah *et al.,* 2008).

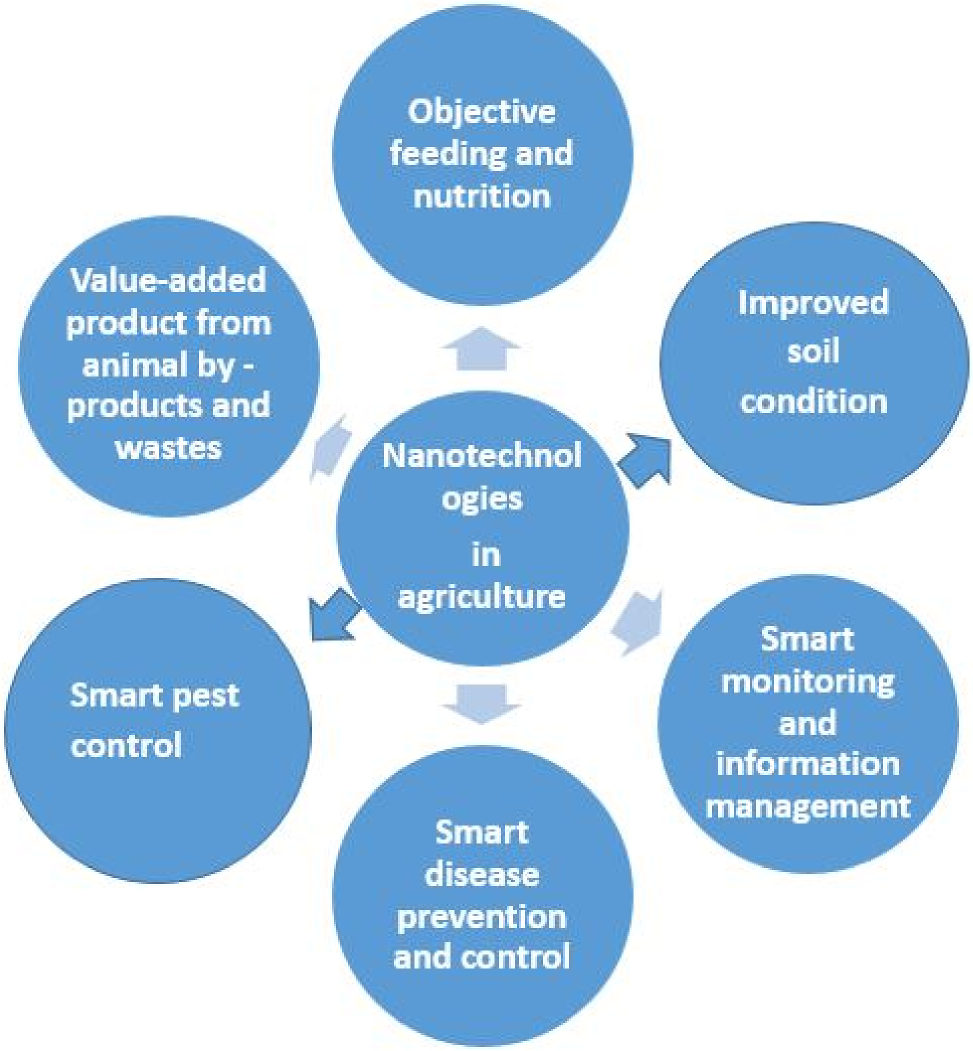

Fig 1 :The role of nanotechnologies in improving agriculture practices(Vijayakumar *et al* 2022)**.**

In order to preserve the natural resources that agriculture depends on and guarantee food security for the world's expanding population, sustainable food production methods are required (Meena *et al*. 2018). The **food demand** is rising daily due to the growing world population, which has forced growers to employ fertilizers on a vast scale (Ghorbanpour *et al.* 2020)**.**

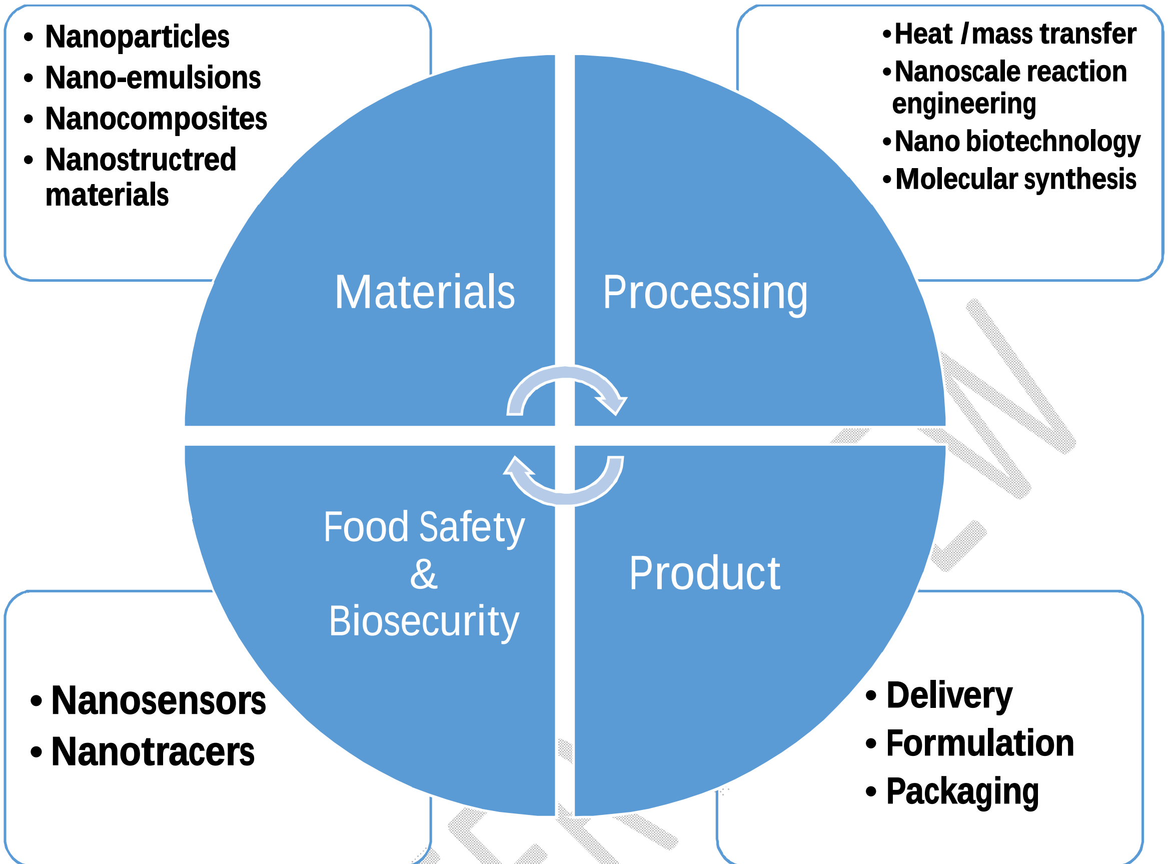

Fig 2 :The role of nanotechnologies in improving food industry(Tipu *et al* 2022).

The role of nanotechnologies in soil sciencefield: -The processes of industrialization and urbanization deplete natural resources and produce toxic waste that contaminates the air, water, and land. An economical and energy-efficient method of treating these wastes is provided by nanotechnology. Treatment of the soil, water, and air is advantageous. Nanomaterials can also be used to treat bioaerosols, greenhouse gases, and polluted water [53]. Pollution buildup in food chains, however, impact on both people and wildlife at serious risk."Nanotechnology" is a group of emerging technologies that operate on the nanometer scale, or range between 1 and 100 nm, to produce materials, devices, and systems with fundamentally new properties and functions by controlling the size and shape of matter. This is one of the most promising avenues to revolutionize environmental remediation techniques (Ramsden 2009).A viable strategy for creating cost-effective, environmentally friendly, and sustainable solutions to remove hazardous pollutants from the environment is nanotechnology. Nanotechnology creates systems, technologies, and materials with novel features and capabilities by operating on a nanoscale

scale. It's possible uses in the treatment of pollution, including as disinfectants, sensors, membranes, and Nano adsorbents, present leapfrogging opportunities for the advancement of traditional remediation technologies. To develop environmentally sound, resilient, and cost-effective methods for remediating soil, water, and air pollution, immediate action is required[53]. Due to its potential applications in a variety of pollution treatment disciplines, nanotechnology has gained significant traction globally and is providing leapfrogging opportunities for the advancement and transformation of traditional remediation technologies (Brame *et al*. 2011).

Table 1 :Potential applications in a variety of pollution treatment disciplines

Nanoparticles Type	**Application**	**Usage**	**Soil Applications**
Silica based	Germination of seeds	Content of chlorophyll together with buildup of proline	The makeup of the soil also improved.
Iron sulfate	cultivars without flowers	exceptional resilience to the shock of salinity	The Layering and Composition of Soil
Nano zeolite	For sustained nutrition and mineral supply	Additionally, agricultural practices strengthen tolerance to drought.	The composition of soil also improved.
Nano-Si	Remediation	Regulating Cd accumulation	Remediation of Soils
Nano-fertilizers	efficient in reducing soil deterioration	abundant metals that are simple to remove	The composition of soil also improved.

The Soils Improvement through Nanotechnology (Azam *et al* 2022)

The role of nanotechnologies in Agronomy field: -Agronomy, the study of crops grown for food and fiber, is mother branch of agricultural science. It is essential since, in the majority of developing nations, it powers the economies and provides both direct and indirect food for people (Chhipa and Joshi, 2016). Population expansion, climate change, diseases, soil erosion, nutrient shortages, urbanization, and industrialization are some of the issues facing agriculture. Crop output and growth are directly impacted by the overuse of synthetic fertilizers (Manjunatha *et al*. 2016). Due to an excessuse of water and a rise in hazardous chemicals, pesticide-induced crop disease and traditional irrigation techniques are two factors that contribute to soil and water depletion (Rodell *et al*. 2009). Effective nanomaterials are used in nanotechnology to protect crops, monitor plant growth, diagnose disease-causing organisms, increase food production, and boost agricultural and livestock productivity (Batsmanova*et al*. 2013). Food production and crop protection are the two main applications of nanotechnology, which offers novel instruments for the safe, regulated distribution of agrochemicals without upsetting ecosystems or lowering the concentration of pesticides in the environment (Ghormade*et al*. 2011; González *et al*. 2014).

The role of nanotechnologies in horticulture field:-High-yield crops are promoted by nanofertilizers in horticulture, which is advantageous for sustainable farming. However, the absence of risk management, monitoring, and formulations impedes their advancement. Though they can affect how well plants absorb nutrients, nanomaterials also pose a risk to human health because they can penetrate cell membranes and enter biological processes (Suppan, 2017 ;Iqbal, 2019 and Singh, 2017). The study emphasizes how harmful nanofertilizers are to ecosystems, food security, human health, and ecosystems. To ensure safety, it demands the use of established crop formulations and guidelines. However, there are drawbacks to using nanotechnology in horticulture, such as worries about environmental impact and safety. Cost is a constraint, and safety regulations are becoming more and more necessary due to changing regulations[65].

Nano Fertilizer Synthesis Method:-It is possible to create nanoparticles by physical, chemical, biological, and aerosol methods.

Fig 3 :Nano Fertilizer Synthesis Method

1. **Synthesis of Nano fertilizer using physical means:-**By milling, crushing, or grinding bulk materials into Nano sized materials, the top-down technique is a physical method for creating nanomaterials (De Castro and Mitchell 2002). Etching technology, high-energy ball milling, cryo-milling, cold milling, mechanical polishing, nanoimprint lithography and sliding wear are a few examples of top-down processes. The most popular top-down technique is high-energy ball milling, formerly known as mechanical milling. This process entails severely plastically deforming large particles into nanosized particles in order to decrease material size and increase the surface area and reactivity of the particles[20]. An attrition mill is used in high-energy ball milling, which was developed in an effort to create homogenous composite particles or alloys (Benjamin 1970). Other mills, like shaker mills, mixer mills, ball mills and planetary ball mills, are then used. The results of Benjamin's research in the 1970s prompted research into the various phases involved in

high-energy ball milling (Benjamin and Volin 1974). The primary disadvantage of the high-energy ball milling technique is the uneven surface structure that is produced, making it unsuitable for the preparation of materials with consistent shapes. Shaker mills, attrition mills and planetary ball mills are the three types of high-energy ball milling equipment (Suryanarayana, 2001). In shaker mills, the sample and grinding media—that is, the milling balls and sample—are violently spun to and fro multiple times, forcing the milling balls to collide. The sample and the vial wall ultimately cause the size reduction in the final result. By lowering the precursor size to nanoparticle size or by milling two or more types of precursors to create a nanocarrier or nanosensor, high-energy ball milling produces nanofertilizer[24].

2. **Synthesis of nanofertilizer using chemical means: -**Chemical techniques known as "bottom-up methods" are used to create nanomaterials by combining basic units to form more stable, bigger structures. Entails assembling the substance atom by atom and cluster by cluster until a nanoscale material is formed. It involves the production of ultrafine particles through their dissolved molecular state using appropriate solvents, as well as positional assembly, self-assembly and chemical synthesis[24].The bottom-up approach uses a number of techniques, including sol-gel, inert gas condensation, arc discharge, fast solidification, arc plasma and physical and chemical vapor deposition. The advantages of the bottom-up technique lie in its ability to generate uniform nanomaterials in terms of size, shape and distribution. For the synthesis of nanoparticles to be applied to plants, bottom-up methods are frequently used (Chalenko 2010; Dutta *et al.* 2014; Tarafdar 2015; Poopathi*et al.* 2015; Saha and Gupta 2017).

3. **Synthesis of Nano fertilizer using biological means:-**The application of biosynthetic, or "green," technologies-which are low-cost, eco-friendly, and produce less contamination-is essential to nanotechnology. Metal nanoparticles (NPs) can be produced in an environmentally friendly way by promoting biological molecules to move through carefully regulated hierarchical assemblages. Biosynthesis is the result of the actions of many different biological organisms, including bacteria, fungus, algae and different plants that include leaves, fruits, roots, flowers and seeds. These organisms have the unusual capacity to concentrate and absorb metallic ions from their surroundings, which makes them plausible mediators of NP production.

- **Synthesis Mediated by Microbes: -**As energy-efficient, inexpensive and non-toxic technologies that can create MNPs more quickly than physicochemical procedures, microorganisms as nanofactories hold out a great deal of potential. There are two ways to extract the nanomaterials from the microbes: intracellularly and extracellularly. Because of its negative charge, the cell wall plays a significant role in the unique transport systems involved in intracellular biosynthesis in microorganisms[30]. Positively charged metal ions are deposited on negatively charged cell walls through electrostatic interactions. Following entry into the microorganism's cells, ions undergo reduction through metabolic processes facilitated by enzymes such as nitrate reductase, resulting in the formation of MNPs[31]. During the extracellular mechanism, the nitrate-reductase production pathway converts the metal ions to their corresponding NPs[30].
- **Synthesis Mediated by Plants: -**Plants are readily available natural sources that yield larger amounts of bimolecular reducing agents than microorganisms do. Metallic NPs have been created using extracts from a variety of plant materials, including fruits, stalks, leaflets, roots and blossoms [32]. Plant material is cleaned, dried, boiled and then filtered to create plant extract. After that, a metallic salt solution is mixed with the plant filtrate and the mixture is further incubated to yield metallic nanoparticles. The phytochemicals contained in plant extracts, such as terpenoids, flavones, quinones, ketones and aldehydes, function as electron donors to transform metal ions into nanoparticles (NPs) in aqueous solutions[30].

4. **Synthesis of nanofertilizer using aerosol means: -**The gas flow rate, heater size and diffusion drier size must all be precisely controlled in order to manufacture nanoparticles using the aerosol approach[33]. These methods mainly consist of evaporating a zinc source inside a chamber using resistive heat. There are other heat sources that are employed, such as lasers, radio frequencies, and electron beams. The vapors are forced to transfer from the heating chamber into the inert-gas chamber, which is cooler, and are collected there for more consolidation [34].There are five distinct aerosol processes used to create nanoparticles. These include the following[33]:

i. **Flame method: -** The flame approach can successfully create TiO2 nanoparticles, but it must be handled with appropriate caution.

ii. **Furnace method: -**It is extremely difficult to generate particles smaller than 100 nm using the furnace approach.

iii. **Electrospray chemical method:** - The yield of electro spraying is quite modest (1 g per year), but it is a highly valuable approach for producing nanoparticles with precise size and form.

iv. **Chemical vapor deposition method:-** vapor deposition of chemicals (with catalytic interaction).

v. **Physical vapor deposition method: -**physical vapor deposition (in the absence of catalysis).

Table 2 :Properties of Nono Fertilizers

Sr. No.	**Properties**	**Nano fertilize**	**Inorganic fertilizer**
1.	Rate of nutrient loss	**minimum** loss of fertilizer nutrients	**tendency of frequent**loss by runoff, leaching, and drifting
2.	Controlled release	Release pattern and rate are carefully regulated.	High toxicity and soil imbalance result from excessive nutrient release.
3.	Solubility	**Highly soluble**	**Less soluble**
4.	Bioavailability	High	Low
5.	Dispersion of mineral micronutrients	enhanced insoluble nutrient dispersion	Reduced solubility as a result of the big particle
6.	Effective duration of release	Effective and extended duration	Utilized by the plant **in small amount** when and where it is applied, the **remaining** is transformed into an insoluble form.

7.	The efficiency of nutrients uptake	increased uptake ratio and reduced need for fertilizer	Roots cannot access it, and nutrient uptake efficiency is poor.
8.	Soil adsorption and fixation	Reduced	High

Properties of Nano Fertilizers **(**Singh *et al* 2023).

Application method of Nano fertilizers: -Application of nanofertilizer can be done in three main ways: foliar, seed nanopriming, and root application. By directly spraying nanofertilizers onto plant leaves, a technique known as foliar application, nutrients can be absorbed by the leaves more quickly. This approach works especially well in areas with poor soil fertility or when nutrients are needed urgently. Before sowing, seeds are coated or soaked in a solution containing nanofertilizers, a process known as seed nanopriming. Rapid germination, robust seedlings, and improved nutrient uptake over the course of the plant's life are all encouraged by this strategy. It is possible to apply nanofertilizers to the soil by traditional methods like side-dressing, broadcasting, or fertigation. After entering the soil, the NPs engage in interactions with plant roots by either adhering to the root surface or entering the root cells by means of endocytosis[7].

1. **Foliar: -** Plant physiology influences how well nanoparticles are absorbed by plants. Generally, trichomes, stomata, stigma and hydathodes absorb NPs, which are then carried by the phloem and xylem throughout the plant. There are two ways that NPs can translocate: apoplastic and symplastic pathways. The apoplast, or cell wall and other intercellular spaces, is where macromolecules (NPs, water, etc.) go through during the apoplastic route. The size exclusion limits (SELs) of cell walls, which range from 5 to 20 nm, restrict the amount of such macromolecules that can travel during this transport[36]. On the other hand, in the symplastic pathway, plasmodesmata—the inner side of the plasma membrane—are the mechanism by which macromolecules (NPs) are transferred from one cell to another. To control phytopathogens, NFs can also be mixed with nanoparticles. Enzymes that stress plant cells have the ability to sever chemical connections within the polymer wall's nanocapsule. The plant releases mucilage to stave off infection when it senses an attack by plant pathogens. Additionally, the buildup

ofnanoparticles on the leaflets' surface may result in foliar heating, which could modify gas exchange because it would impede the stomata[35].

2. **Seed Nanopriming: -** A pre-sowing process known as "seed priming" modifies the physiology of seeds to hasten germination and stimulate plant growth and development by controlling metabolic and signaling cascades. The technique, which entails soaking seeds in nanofertilizers, has been demonstrated to cut fertilizer application in half while producing superior outcomes. Nanobiofertilizers work as growth-promoting hormone-stimulating agents, entering seed pores and spreading throughout, thus promoting germination and development.Utilizing nanofertilizer during seed priming reduces reactive oxygen species and controls plant growth hormones to enhance seed germination. In addition to increasing resistance, seed priming also promotes the expression of several genes during germination, especially those linked to plant resilience. Traditional techniques for seed priming involve the use of water, nutrients, or hormones to break down the seed coat. Advanced seed nano-priming methods, on the other hand, apply nanofertilizers directly to the seed surface, leaving a significant portion that prevents disease penetration.Absorption of nanocompounds at the cellular level minimizes input and avoids molecular interactions, resulting in the generation of extremely resilient seeds with enhanced germination and growth of seedlings, particularly in stressful conditions. By boosting antioxidants, controlling internal hormone activity in crops, and lowering the production of reactive oxygen species (ROS), nanofertilizers lessen plant stress[7].

3. **Roots: -** NPs enter the plant through the root's epidermis, pass through the endodermis and enter the xylem, where they are carried to the aerial portion of the plant. When NPs are between 3 and 8 nm in size, they pierce the cell wall through pores[37]. Because the Casparian strip has wounds, NPs can also enter at the root tip meristem or at the locations of lateral root development. NPs must break through cell walls and plasma membranes in order to reach the epidermal layers of the roots. They then penetrate the vascular tissues (xylem) from there. The cell walls have pores that range in size from 3 to 8 nm, which is extremely small for NPs to enter. Nevertheless, it has been demonstrated that NPs cause the creation of huge pores in cell walls so that they can internalize[35].

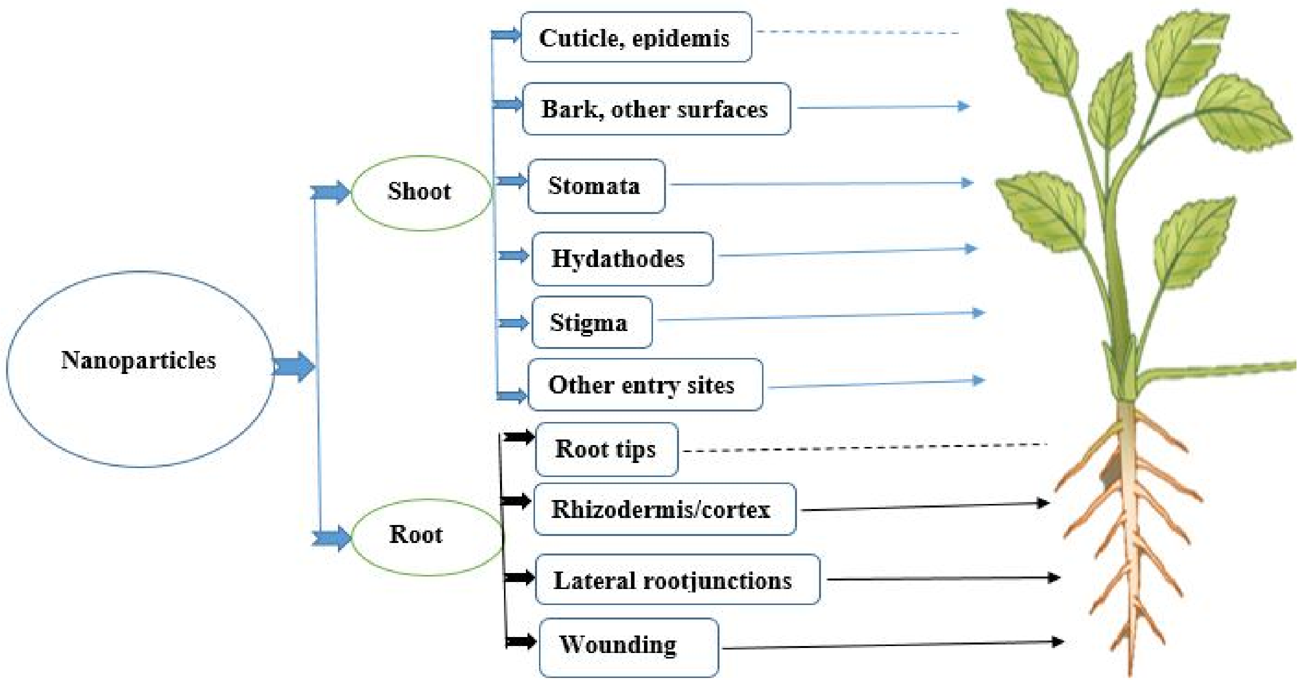

Fig.4 :Path ways of nanoparticle association, uptake and translocation in plants. Broken lines indicate the assumption of very low rates of transport**Tarafdar JC (2015)**.

Mechanisms of Action: - Comparing NMs to traditional fertilizers, their high reactivity guarantees maximum usage efficacy and high and efficient plant nutrient absorption with minimal waste[39]. In addition to characteristics intrinsic to the nanoparticle, such as size and coating, the efficiency of the absorption, distribution and accumulation of NFs is dependent on exposure to numerous conditions, including the pH of the soil, the amount of organic matter and the texture of the soil. Effects of many variables on the uptake, penetration, transport and absorption of nanoparticles in plants[35].

(A) The characteristics of nanoparticles impact on both the application technique and their absorption and translocation in plants.

(b) Nanoparticles can interact with chemicals and bacteria in the soil, which may help or hinder their absorption.

(c) Nanomaterials can travel up and down the plant using the Apo plastic and symplastic pathways and they can also migrate radially to switch between pathways.

(d) Endocytosis, pore formation, carrier protein-mediated internalization and plasmodesmata are a few of the mechanisms that have been postulated to explain how nanoparticles enter cells.

Benefits: - NFs have several advantages for environmentally responsible and sustainable crop production. The following are a few of these in particular[35]:

- **i.** Improved nutrition absorption and effective use without losses.
- **ii.** Substantial decrease in the danger of environmental contamination as a result of the reduction in nutrient losses.
- **iii.** When considering the solubility and diffusion rate of natural fibers (NFs) in comparison to traditional synthetic fertilizers,
- **iv.** Regulated nutrient release in NFs as opposed to chemical fertilizers, where nutrient release occurs very quickly and spontaneously.
- **v.** NFs are needed in smaller quantities than with synthetic fertilizers because of increased absorption and decreased loss.
- **vi.** Both an increase in soil fertility and the creation of a suitable environment for microorganisms.

Table 3 :The effects of several nanomaterials on growth and yield enhancement {Iqbal, M. A. (2019)}

Sr. No.	**Crops**	**Nano fertilizers**	**Yield increment (%)**
1.	Paddy	Nano fertilizer + urea	10.2
2.	Paddy	Nano fertilizer + urea	8.5
3.	Wheat	Nano fertilizer + urea	6.5
4	Wheat	Nano fertilizer + urea	7.3
5.	Soybean	Nano-encapsulated phosphorous	16.7
6.	Maize	Nano-encapsulated phosphorous	10.9
7.	Wheat	Nano-encapsulated phosphorous	28.8
8.	Wheat	Nano-encapsulated phosphorous	14.6
9.	Vegetables	Nano chitosan-NPK fertilizers	12.0–19.7

10.	Wheat	Nano-encapsulated phosphorous	28.8
11.	Vegetables	Nano-encapsulated phosphorous	12.0–19.7
12.	Wheat	Nano chitosan-NPK fertilizers	14.6
13.	Tomato	Nano chitosan	20.0
14.	Cucumber	Nano chitosan	9.3
15.	Pea	Nano chitosan	20
16.	Capsicum	Nano chitosan	11.5
17.	Beet-root	Nano chitosan	8.4
18.	Sweet potato	Nanopowder of cotton seed and ammonium fertilizer	16
19.	Cereals	Aqueous solution on nanoiron	8–17
20.	Peanut	Nanoparticles of ZnO	4.8
21.	Cabbage	Nanoparticles of ZnO	9.1
22.	Cucumber	Nanoparticles of ZnO	6.3
23.	Chickpea	Nanoparticles of ZnO	14.9
24.	Cauliflower	Nanoparticles of ZnO	8.3
25.	Cereals	Nanosilver + allicin	4–8.5
26.	Vegetables	Rare earth oxides nanoparticles	7–45
27.	Cereals	Sulfur nanoparticles + silicon dioxide nanoparticles + synthetic fertilizer	3.4–45%
28.	Cereals	Iron oxide nanoparticles + calcium carbonate nanoparticles + peat	14.8–23.1

Challenges in Nanofertilizers Application: -The introduction of nanofertilizers in India is not without challenges, as is the case with any new technology. Nano-based products are becoming more and more popular for field applications in agriculture as a means of overcoming this. It is considered vital to carefully assess the optimal activity and concentration of NFs before applying them in the field in order to achieve the best outcomes possible, taking into account high yields and low losses. Remaining levels of NFs should be measured during plant studies to lessen the possibility of impacting other biotic components in the ecosystem. Simultaneously designing and implementing safety measures is crucial. This is to specify the kind, dimension, and form of nanoparticles suitable for crop production. These elements, together with solubility, stability, surface reactivity, and charges, are crucial to agricultural productivity. NFs' reactivity in plants remains non-specific, regardless of the species being studied. This could be due to the lack of established guidelines for their practical use in the field. Naturally, there is still much to learn about the mechanisms underlying the absorption of NFs and other nano-based agrochemicals by plants[46].

FarmersChallenges in Nanofertilizers Application: -

Cost: Nanofertilizers might now be more expensive than regular fertilizers because of the intricate production processes required. Making them affordable and efficient for small-scale farmers is the main goal.

Research and Awareness: To improve application techniques and formulations for widespread usage, extensive research and development are needed. Teaching farmers about the benefits and correct use of nanofertilizers is also essential to a successful deployment.

- Lack of a risk management framework for nanofertilizers
- Lack of necessary quantities of nanofertilizers' manufacture and availability. This restricts the use of nanofertilizers as a broader source of plant nutrition.
- The pricey nature of nanopowders
- The formulation method is not standardized. This leads to varied outcomes for the same nanomaterial in different pedoclimatic settings.

Government Initiatives: - Realizing the promise of nanofertilizers, the Indian government has taken significant steps to promote their use. Research funding, public-private partnerships, and other programs designed to advance the national development and availability of nanofertilizers[49].

Environmental impact and Safety: - Since our current understanding is insufficient to predict the potential environmental effects of nanoparticles, caution is needed when synthesizing and using them in agriculture for commercial or industrial products (Bernhardt *et al*., 2010; Nowack and Bucheli, 2007). The market has seen a number of ethical and social issues about the safety of consumer items enabled by nanotechnology, particularly in relation to health and the environment.

In order to identify health and environmental concerns with Nano-enabled products, the public expects appropriate labeling and safety standards on packages (Throne-Holst and Rip, 2011).Government and regulatory authorities (certification bodies, regulatory agencies), environmental, health, and safety councils (like Environment Health Services), non-governmental organizations, and scientific authorities worldwide are all required to recognize the significance of risk assessment of nanotechnology (Sharma *et al*., 2012). Nanoparticles in fertilizers can improve crop productivity and reduce environmental impact. Researchers are exploring nanomaterials like nanozeolites, nanochitosan, and metal oxide nanoparticles to improve nutrient absorption and retention. Controlled-release nanofertilizers have been developed, reducing application frequency and potential nutrient losses[7].

Regulatory framework and future outlook of Nano fertilizers: -In order to address major themes like the synthesis of nanoparticles for agricultural use, quick diagnostic kits for early disease and pest detection, nanopheromones for effective pest control, Nano-agri-inputs for enhanced use efficiencies, precision water management, stabilization of organic matter in soil, nanofood systems, and biosafety, as well as establish a policy framework, the Indian Council of Agricultural Research (ICAR) has opened up an exclusive platform. For use in agriculture, the green or microbial synthesis of nanomaterials that are naturally encapsulated in mother proteins is thought to be more stable and safer for the biological system[43]. Future research should focus on eco-friendly synthesis methods, optimizing properties, and minimizing risks. Green technology innovation and IoT technologies are needed to create sustainable products and "smart technology"of nanofertilizers that respond to environmental issue.

Conclusion:-

The development of novel nanofertilizer products in accordance with needs, efficient legislation, and related risk management are only a few of the factors that will determine the future of nanofertilizers for sustainable crop production and the length of time required for their widespread adaption as a source of plant nutrients.Nano fertilisers promise to transform the way we nurture our crops and preserve the environment, bringing in an era of change in agricultural sciences.They can boost agricultural productivity, conserve water, and minimise environmental effects, they are a useful tool for sustainable farming. The next generation of agriculture seems to be more than ever. This innovative technology is bringing out a new era of ecological balance and food security. Lastly, in order to optimise the use of nanofertilizers for sustainable crop production in a changing climate with the potential for environmental damage, researchers and regulators must take responsibility to provide further insights.

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References

1. Mastronardi E, Tsae P, Zhang X, Monreal C, DeRosa MC (2015). Strategic role of nanotechnology in fertilizers: potential and limitations. In: Nanotechnologies in food and agriculture. *Springer*, Cham. https://doi.org/10.1007/978-3-319-14024-7_2
2. Al-Juthery, H. W., Lahmod, N. R., & Al-Taee, R. A. (2021). Intelligent, Nano-fertilizers: a new technology for improvement nutrient use efficiency (article review). In *IOP Conference Series: Earth and Environmental Science* (Vol. 735, No. 1, p. 012086). IOP Publishing.
3. Chinnamuthu CR, Boopathi PM. (2009). Nanotechnology and Agroecosystem. Madras. Agric. J.; 96:17-31.
4. Ninama, J., Sachan, K., Yadav, B., Satapathy, S. N., Kumar, J., & Singh, B. V. (2023). Effects and consequences of Nano fertilizer application on plant growth and developments: a review. *International Journal of Environment and Climate Change*, *13*(10), 2288-2298.
5. Ombódi, A., &Saigusa, M. (2000). Broadcast application versus band application of polyolefin□coated fertilizer on green peppers grown on andisol. *Journal of plant nutrition*, *23*(10), 1485-1493.
6. Chaitra, A. K. P., Ahuja, R., Sidhu, S. P. K., & Sikka, R. (2021). Importance of Nano fertilizers in sustainable agriculture. *Environ. Sci. Ecol. Curr. Res. (ESECR)*, *5*, 1029.
7. Yadav, A., Yadav, K., & Abd-Elsalam, K. A. (2023). Nanofertilizers: Types, Delivery and Advantages in Agricultural Sustainability. *Agrochemicals*, 2(2), 296-336.
8. Mahanta, N., Dambale, A., Rajkhowa, M., Mahanta, C., & Mahanta, N. (2019). Nutrient use efficiency through Nano fertilizers. *Int J Chem Stud*, *7*(3), 2839-2842.

9. Kumar, Y., Tiwari, K. N., Singh, T., & Raliya, R. (2021). Nanofertilizers and their role in sustainable agriculture. *Annals of Plant and Soil Research*, *23*(3), 238-255.
10. Khatri, A., & Bhateria, R. (2023). Efficacy of Nano fertilizers over chemical fertilizers in boosting agronomic production. *Nature Environment and Pollution Technology*, *22*(2), 767-776.
11. El-Ghamry, A., Mosa, A. A., Alshaal, T., & El-Ramady, H. (2018). Nanofertilizers vs. biofertilizers: new insights. *Environment, Biodiversity and Soil Security*, *2*(2018), 51-72.
12. Al-Hchami, S. H. J., & Alrawi, T. K. (2020). NANO FERTILIZER, BENEFITS AND EFFECTS ON FRUIT TREES: A. *Plant Archives*, *20*(1), 1085-1088.
13. Pohshna, C., Mailapalli, D. R., & Laha, T. (2020). Synthesis of Nano fertilizers by planetary ball milling. *Sustainable Agriculture Reviews 40*, 75-112.
14. Baruah S, Warad HC, Chindaduang A, Tumcharern G, and Dutta J. (2008). Studies on chitosan stabilisedZns: Mn2 + Nanoparticles, *J Bio Nano Sc* in press.
15. Vijayakumar, M. D., Surendhar, G. J., Natrayan, L., Patil, P. P., Ram, P. M., & Paramasivam, P. (2022). Evolution and recent scenario of nanotechnology in agriculture and food industries. *Journal of Nanomaterials*, *2022*.
16. Meena, R.S., Das, A., Yadav, G.S. and Lal, R. eds., (2018). Legumes for soil health and sustainable management (p. 541). Singapore: *Springer*. https://doi.org/10.1007/978-981-13- 0253-4
17. Ghorbanpour, M., Bhargava, P., Varma, A. and Choudhary, D.K. eds., (2020). Biogenic Nano- particles and their use in agro-ecosystems. Singapore: *Springer*. https://doi.org/10.1007/978- 981-15-2985-6
18. Tipu, M. M. H., Baroi, A., Rana, J., Islam, S., Jahan, R., Miah, M. S., &Asaduzzaman, M. (2021). Potential applications of nanotechnology in agriculture: A smart tool for sustainable agriculture. In *Agricultural Development in Asia-potential use of Nano-materials and Nano-technology*. London, UK: IntechOpen.
19. De Castro CL, Mitchell BS (2002). Nanoparticles from mechanical attrition. Synth Funct Surf Treat Nanoparticles: 1–15.
20. https://pdfs.semanticscholar.org/4279/540565f0e0860db9eb9e3041 d18a8c65f11c.pdf

21. Pohshna, C., Mailapalli, D. R., & Laha, T. (2020). Synthesis of Nano fertilizers by planetary ball milling. *Sustainable Agriculture Reviews 40*, 75-112.
22. Benjamin JS (1970). Dispersion strengthened superalloys by mechanical alloying. Met Trans 1(10):2943–2951. https://doi.org/10.1007/BF03037835
23. Benjamin JS, Volin TE (1974). Mechanism of mechanical alloying. Met Trans. https://doi. org/10.1007/BF02644161
24. Suryanarayana C (2001). Mechanical alloying and milling Suryanarayana. Mater Sci 46:1–184. https://doi.org/10.1016/S0079-6425(99)00010-9
25. Pohshna, C., Mailapalli, D. R., & Laha, T. (2020). Synthesis of Nano fertilizers by planetary ball milling. *Sustainable Agriculture Reviews 40*, 75-112.
26. Chalenko GI, Gerasimova NG, Vasyukova NI, Ozeretskovskaya OL, Kovalenko LV, Folmanis GE, Tananaev IG (2010). Metal nanoparticles induce germination and wound healing in potato tubers. *Dokl Biol Sci* 435:428–430. https://doi.org/10.1134/S0012496610060165
27. Dutta N, Mukhopadhyay A, Dasgupta AK, Chakrabarti K (2014). Improved production of reducing sugars from rice husk and rice straw using bacterial cellulase and xylanase activated with hydroxyapatite nanoparticles. Bioresour Technol 153:269–277. https://doi.org/10.1016/j. biortech.2013.12.016
28. Tarafdar JC (2015). Nanoparticle production, characterization and its application to horticultural crops. Winter School – Utilization of Degraded Land and Soil through Horticultural Crops for Agricultural Productivity and Environmental Quality. Ajmer, Rajasthan, pp 222–229
29. Poopathi S, De Britto LJ, Praba VL, Mani C, Praveen M (2015). Synthesis of silver nanoparticles from Azadirachta indica—a most effective method for mosquito control. *Environ Sci Pollut Res* 22(4):2956–2963. https://doi.org/10.1007/s11356-014-3560-x
30. Saha N, Gupta SD (2017). Low-dose toxicity of biogenic silver nanoparticles fabricated by Swertia chirata on root tips and flower buds of Allium cepa. *J Hazard Mater* 330:18–28. https://doi. org/10.1016/j.jhazmat.2017.01.021
31. Bairwa, P., Kumar, N., Devra, V., & Abd-Elsalam, K. A. (2023). Nano-biofertilizers synthesis and applications in agroecosystems. *Agrochemicals*, *2*(1), 118-134.

32. Hulkoti, N. I., &Taranath, T. C. (2014). Biosynthesis of nanoparticles using microbes—a review. *Colloids and surfaces B: Biointerfaces*, *121*, 474-483.

33. Bahrulolum, H., Nooraei, S., Javanshir, N., Tarrahimofrad, H., Mirbagheri, V. S., Easton, A. J., & Ahmadian, G. (2021). Green synthesis of metal nanoparticles using microorganisms and their application in the agrifood sector. *Journal of Nanobiotechnology*, *19*, 1-26.

34. Tarafdar, J. C., Xiang, Y., Wang, W. N., Dong, Q., & Biswas, P. (2012). Nanoparticle synthesis characterization and application to solve some chronic agricultural problems. *Appl Biol Res*, *14*, 138-144.

35. Singh, A., Rajput, V. D., Pandey, D., Sharma, R., Ghazaryan, K., &Minkina, T. (2023). Nano Zinc-Enabled Strategies in Crops for Combatting Zinc Malnutrition in Human Health. *Frontiers in Bioscience-Landmark*, *28*(8), 158.

36. Singh, A., Rajput, V. D., Pandey, D., Sharma, R., Ghazaryan, K., &Minkina, T. (2023). Nano Zinc-Enabled Strategies in Crops for Combatting Zinc Malnutrition in Human Health. *Frontiers in Bioscience-Landmark*, *28*(8), 158.

37. Bernela, M., Rani, R., Malik, P., & Mukherjee, T. K. (2021). Nanofertilizers: applications and future prospects. In *Nanotechnology* (pp. 289-332). Jenny Stanford Publishing.

38. Ali, S., Mehmood, A., & Khan, N. (2021). Uptake, translocation, and consequences of nanomaterials on plant growth and stress adaptation. *Journal of Nanomaterials*, *2021*, 1-17.

39. Zahra, Z., Habib, Z., Hyun, H., & Shahzad, H. M. A. (2022). Overview on recent developments in the design, application, and impacts of Nano fertilizers in agriculture. *Sustainability*, *14*(15), 9397.

40. Fatima, F., Hashim, A., & Anees, S. (2021). Efficacy of nanoparticles as nanofertilizer production: a review. *Environmental Science and Pollution Research*, *28*(2), 1292-1303.

41. Iqbal, M. A. (2019). Nano-fertilizers for sustainable crop production under changing climate: a global perspective. *Sustainable crop production*, *8*, 1-13.

42. Bernhardt, E. S., Colman, B. P., Hochella, M. F., Cardinale, B. J., Nisbet, R. M., Richardson, C. J., & Yin, L. (2010). An ecological perspective on nanomaterial impacts in the environment. *Journal of environmental quality*, *39*(6), 1954-1965.
43. Nowack, B., & Bucheli, T. D. (2007). Occurrence, behavior and effects of nanoparticles in the environment. *Environmental pollution*, *150*(1), 5-22.
44. Marella, S., Kumar, A. N., & Tollamadugu, N. P. (2021). Nanotechnology-based innovative technologies for high agricultural productivity: Opportunities, challenges, and future perspectives. *Recent Developments in Applied Microbiology and Biochemistry*, 211-220.
45. Throne-Holst, H., Rip, A., (2011). Complexities of labelling of Nano products on the consumer markets. *Eur. J. Law Technol*. 2, 3.
46. Sharma, V., Kumar, A., Dhawan, A., (2012). Nano materials: exposure, effects and toxicity assessment. *Proc. Natl. Acad. Sci. India B: Biol. Sci*. 82, 3–11.
47. Gade, A., Ingle, P., Nimbalkar, U., Rai, M., Raut, R., Vedpathak, M., & Abd-Elsalam, K. A. (2023). Nanofertilizers: the next generation of agrochemicals for long-term impact on sustainability in farming systems. *Agrochemicals*, *2*(2), 257-278.
48. Bose, Priyom. (2023). The Effect of Nanofertilizers on Sustainable Crop Development. AZoNano. Retrieved on March 20, 2024 from https://www.azonano.com/article.aspx?ArticleID=5614.
49. Duddumpudi, Venkata Sri Akshay. (2023). Nano Fertilizers: Transforming Indian Agriculture For A Sustainable Future.
50. Dubey A, Mailapalli DR (2016).Nanofertilisers, nanopesticides, nanosensors of pest and nanotoxicity in agriculture. In: Sustainable agriculture reviews. *Springer*, Cham, pp 307–330
51. Avila-Quezada, G. D., Ingle, A. P., Golińska, P., & Rai, M. (2022). Strategic applications of nano-fertilizers for sustainable agriculture: Benefits and bottlenecks. *Nanotechnology Reviews, 11*(1), 2123-2140.
52. Ramsden J (2009). Essentials of nanotechnology. BookvBoon. books.google.com
53. Brame J, Li Q, Alvarez PJJ (2011). Nanotechnology-enabled water treatment and reuse: emerging opportunities and challenges for developing countries. *Trends Food Sci Technol* 22:618–624

54. Adhikari, T. (2021). Nanotechnology in environmental soil science. *Soil Science: Fundamentals to Recent Advances*, 297-309.
55. Azam, N., Khan, M. W., Sardar, S., Yousaf, I., Zahid, A., Ismail, A., ... & Javed, M. S. (2022). New insights for improving agriculture soils through nanotechnology. *Haya Saudi J Life Sci*, *7*(9), 244-248.
56. Chhipa H, Joshi P (2016).Nanofertilizers, nanopesticides and nanosensors in agriculture. In: Nanoscience in food and agriculture, vol 1. *Springer*, Cham, pp 247–282
57. Manjunatha SB, Biradar DP, Aladakatti YR (2016). Nanotechnology and its applications in agriculture: a review. *J Farm Sci* 29(1):1–13
58. Rodell M, Velicogna I, Famiglietti JS (2009). Satellite-based estimates of groundwater depletion in India. *Nature* 460(7258):999–1002
59. Batsmanova LM, Gonchar LM, Taran NY, Okanenko AA (2013). Using a colloidal solution of metal nanoparticles as micronutrient fertilizer for cereals. Doctoral dissertation, Sumy State University.
60. Ghormade V, Deshpande MV, Paknikar KM (2011). Perspectives for nano-biotechnology enabled protection and nutrition of plants. *Biotechnol Adv* 29(6):792–803
61. González JOW, Gutiérrez MM, Ferrero AA, Band BF (2014). Essential oils nanoformulations for stored-product pest control–characterization and biological properties. *Chemosphere* 100:130–138
62. Ansari, M., Shahzadi, K., & Ahmed, S. (2020). Nanotechnology: a breakthrough in agronomy. *Nanoagronomy*, 1-21.
63. Iqbal MA. (2019). Nano-fertilizers for sustainable crop production under changing climate: A global perspective. *Sustainable crop production*.;8:1-13.
64. Suppan S. (2017). Applying nanotechnology to fertilizer: rationales, research, risks and regulatory challenges. The Institute for Agriculture and Trade Policy works locally and globally, Brazil;.
65. Singh NA. (2017). Nanotechnology innovations, industrial applications and patents. Environ. Chem. Lett.;15(2):185-191.

66. Rana, R. A., Siddiqui, M. N., Skalicky, M., Brestic, M., Hossain, A., Kayesh, E., ... & Islam, T. (2021). Prospects of nanotechnology in improving the productivity and quality of horticultural crops. *Horticulturae*, *7*(10), 332.
67. Jithendar B, Kumar R, Rana N. Revolutionizing Crop Nutrition: Exploring Nano Fertilizers in Agriculture. Int. J. Plant Soil Sci. [Internet]. 2024 May 6 [cited 2024 May 25];36(6):327-39. Available from: https://journalijpss.com/index.php/IJPSS/article/view/4635
68. Chinnappa SA, Krishnamurthy D, Ajayakumar MY, Ramesha YM, Ravi S. Effect of Nano Fertilizers on Growth, Yield, Nutrient Uptake and Soil Microbiology of Kharif Sorghum. Int. J.Environ. Clim. Change. [Internet]. 2023 Sep. 5 [cited 2024 May 25];13(10):2339-48. Available from: https://journalijecc.com/index.php/IJECC/article/view/2899
69. El-Saadony MT, ALmoshadak AS, Shafi ME, Albaqami NM, Saad AM, El-Tahan AM, Desoky ES, Elnahal AS, Almakas A, Abd El-Mageed TA, Taha AE. Vital roles of sustainable nano-fertilizers in improving plant quality and quantity-an updated review. Saudi journal of biological sciences. 2021 Dec 1;28(12):7349-59.