Egypt. J. Soil Sci. **Vol. 64**, No. 4, pp: 1355 - 1378 (2024)

Egyptian Journal of Soil Science

http://ejss.journals.ekb.eg/

Nanotechnology Products in Agriculture and Environmental Protection: Advances and Challenges

Abhishek Singh[1], Sapna Rawat[2], Vishnu D. Rajput[3], Tatiana Minkina[3], Saglara Mandzhieva[3], Arevik Sh. Eloyan[4], Rupesh Kumar Singh[5,6], Omkar Singh[7], Hassan El-Ramady[8*] and **Karen Ghazaryan[1]**

(1)Faculty of Biology, Yerevan State University, Yerevan 0025, Armenia; sinxabishik@ysu.am, kghazaryan@ysu.am
(2) Department of Botany, University of Delhi, India; rawatsapna61@gmail.com
(3)Academy of Biology and Biotechnology, Southern Federal University, Rostov-on-Don, Russia; rajput.vishnu@gmail.com, tminkina@mail.ru, msaglara@mail.ru
(4)Scientific Center of Soil Science, Agrochemistry and Melioration after H. Petrosyan after H. Petrosyan; branch of Armenian National Agrarian University; elarev@mail.ru
(5) Centro de Investigação e Tecnologias Agroambientais e Biológicas (CITAB), Universidade de Trás-os-Montes e Alto Douro, Vila Real, Portugal
(6)Centre of Molecular and Environmental Biology, Department of Biology, University of Minho, Campus of Gualtar, Braga, Portugal; rupesh@utad.pt
(7)Dept. of Soil Science, Sardar Vallabhbhai Patel University of Agriculture and Technology, Meerut, Uttar Pradesh, India-250110; singhomkar.agri@gmail.com
(8) Soil and Water Dept., Faculty of Agriculture, Kafrelsheikh University, 33516 Kafr El-Sheikh, Egypt

THE APPLICATION of nanotechnology (NT) is bringing about an enormous shift in the agricultural and environmental protection industries by providing innovative solutions to old problems. The review article summarizes the latest advancements and challenges in the use of nanotechnology (NT) across various fields. In agriculture, nanotechnology has transformed precision farming by enhancing soil and plant health, which leads to increased crop yields and reduced need for chemical inputs. Nano-pesticides and nano-fertilizers contribute to this by improving the efficiency and precision of pest control and nutrient delivery, thereby minimizing resource waste and environmental pollution. In environmental protection, nanomaterials are used for water filtration, air quality monitoring, and the cleanup of polluted areas, showcasing their broad applications in addressing environmental issues. Adsorbents and catalysts with a nanostructure allow for removing organic impurities, heavy metals, and pollutants with less energy consumption and more efficiency than conventional approaches. Despite these encouraging developments, several challenges remain before nanotechnology (NT) can be fully utilized in agriculture and environmental protection. Key concerns include the potential toxicity of nanoparticles to humans and non-target organisms, the lack of comprehensive regulatory frameworks, and the need for extensive research into the long-term environmental impacts of nanomaterials. Additionally, obstacles such as high costs and the complexity of scaling up manufacturing volumes pose significant barriers to the widespread adoption of nanotechnology. To overcome these obstacles and guarantee the safe and sustainable utilization of nanotechnology's benefits, scientists, legislators, and industry stakeholders must work together across disciplines. This review article shows how nanotechnology might revolutionize our future by making it more sustainable. Furthermore, it is also crucial to deal with regulatory obstacles associated with NT.

Keywords: Nano-enabled products, Environment protection, Crop protection, Soil improvement, Nanotechnology, Sustainable agriculture.

*Corresponding author e-mail: ramady2000@gmail.com
Received: 28/06/2024; Accepted: 04/08/2024
DOI: 10.21608/EJSS.2024.300047.1802

1. Introduction

There are currently around 8 billion people on this planet: most living in emerging nations like Asia. According to Food and Agriculture Organizations (FAO), it is expected to reach 10 billion by 2050 (Balaure et al., 2017). A large section of the population in this region experiences daily food shortages due to natural effects or unpredictable political situations. In contrast, in the industrialized world, the main concern is growing crops that increase agricultural production while also being resistant to pests and drought (Hemathilake et al., 2022). "Zero hunger" is among the goals of sustainable development of the United Nations (Khanal et al., 2021)Therefore, targeted agricultural expansion requires an intelligent strategy to maximize production per unit of natural resources and increase farm revenue by using cutting-edge technology sparingly in the face of limited water and land resources (Steenwerth et al. 2014). Potential yields and agricultural earnings increased significantly during the green revolution era because of the widespread adoption of enhanced high-yielding cultivars and the intense use of fertilizers, irrigation, and pesticides. However, this development frequently disregarded the economic and sustainable use of natural resources (Tadele, 2017). Approximately 60% of Indians rely on agriculture for their livelihoods, yet there has been a discernible drop in agricultural earnings and productivity in recent years (Nadkarni, 2022).

According to recent studies, NT has great promise for enhancing the agricultural industry by increasing the effectiveness of farminputs and providing solutions for environmental and agricultural issues that will improve food security and production (Prasad et al., 2017a). Scientific discoveries also state that NT has surfaced as a potentially transformative technology that can boost the food and agricultural sectors, improving the standard of living for underprivileged populations (Gondal et al., 2023).

The European Commission has identified NT as one of the six "Key Enabling Technologies" essential for sustainable breakthroughs in various industries due to its recognition of its potential (Merzbacher, 2020). The National Nanotechnology Initiative (NNI) was founded by the US Federal Government in 2001 to advance NT. The National Science Foundation (NSF) in the United States established a program specifically focused on NPs in 1991 due to an emerging commitment to technology (Talebian et al., 2021). It was based on prior nanoparticle research that IBM and the NSF funded. With the publication of the "Nanotechnology Research Directions" report, an official document of the US National Science and Technology Council (NSTC), this long-term vision for NT development began to take shape in 1999 (Bayda et al., 2020). Nanotechnological companies are distributed worldwide, with prominent hubs in various countries reflecting their significant contributions to this cutting-edge field. The United States leads the global landscape with a value of 3547, showcasing its robust presence in NT. China follows closely behind with a value of 992, highlighting its rapid advancements in this field. Germany, the UK, and Switzerland also play pivotal roles, with values of 866, 532, and 472, respectively, emphasizing the European strength in nanotechnological innovation. Asian countries such as Japan, South Korea, and India have notable contributions, with 446, 402, and 347 values, reflecting the region's commitment to technological progress (Fig. 1).

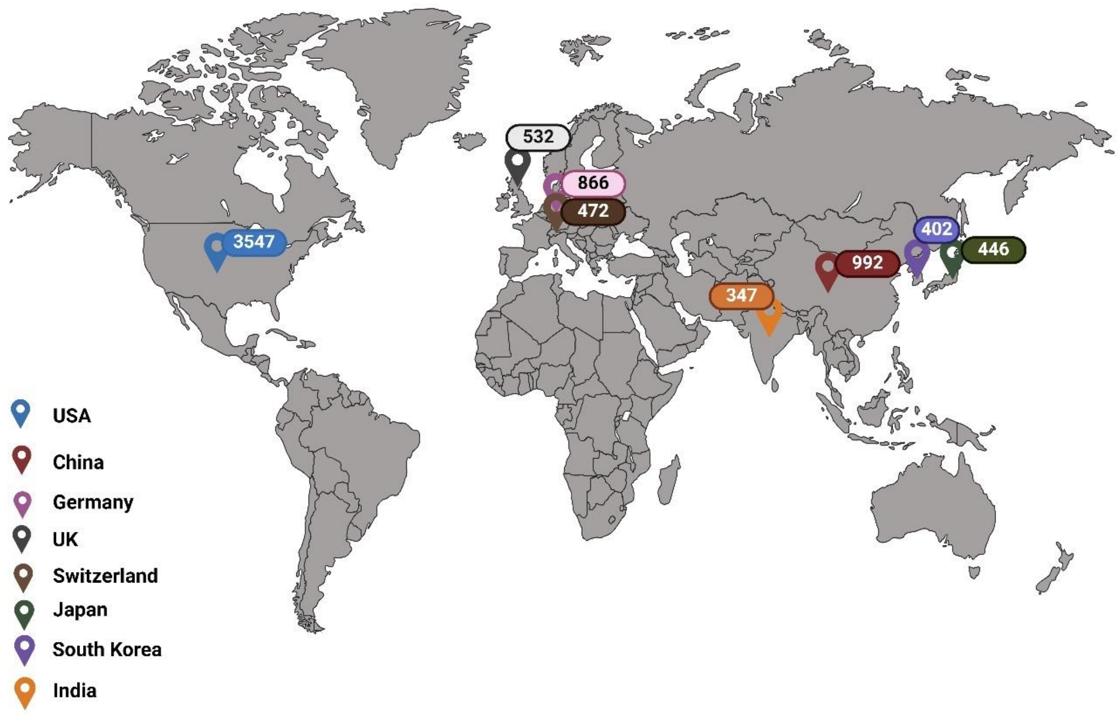

Fig. 1. Map of the global distribution of nano-enabled products in different countries (NPD 2024).

Russia and Canada are among other key players, showcasing the global dispersion of nanotechnological endeavours. This distribution underscores the collaborative and competitive nature of the NT landscape, with various nations actively participating in shaping the future of this transformative industry (Fig. 1; Nanotechnology in Agriculture Industry, NPD 2024).Commercial uses of nano-enabled goods have advanced significantly, especially in sustainable agriculture (Rajput et al., 2021b). These items include various advances, such as soil-improving agents, growth stimulators, nano-fertilizers, and nano-sensors. Due to their potential to serve as intelligent and regulated delivery systems, these nanostructures have drawn interest and may improve agricultural techniques' accuracy and efficiency. Various NPs are crucial in enhancing plant defense against diseases and pests. Silver (Ag)-based NPs boost the plant immune system (Saratale et al., 2017), Cu-based nanomaterials exhibit antibacterial and antifungal activities (Giannousi et al., 2013), and ZnO-NPs effectively control grey-mold disease (Malandrakis et al., 2022). ZnO nanoparticles have been found to improve growth rate and yield of peanuts (Prasad et al., 2012), enhance shoot-root growth and chlorophyll content in cluster beans (Raliya and Tarafdar, 2013), but also decrease chlorophyll in *Pisum sativum* can be attributed to the phytotoxic effects of ZnO NP as evidenced by increased H2O2 levels and lipid peroxidation, and disrupt chlorophyll production, leading to reduced chlorophyll content in the leaves (Mukherjee et al., 2014) and reduce root and stem parameters in *Glycine max* at high concentrations (Yoon et al., 2014). TiO_2 nanoparticles have long been used in agriculture, particularly for heavy metal remediation, stress management, plant growth promotion, and quality enhancement (Kumar et al., 2022). TiO_2 nanoparticles have accelerated seed germination, promoted photosynthesis, and improved growth in spinach (Gordillo-Delgado et al., 2020), increased root elongation in wheat (Dağhan et al., 2020), and enhanced plant biomass in *Pelargonium hortorum* (Gul et al. 2019) due to their ability to improve light absorption, enhance nutrient uptake, stimulate plant hormone production, and mitigate oxidative stress. However, TiO_2 nanoparticles also reduced chlorophyll, carotenoids, and stomatal conductance in *Triticum aestivum* (Dias et al., 2019). The possible reasons for these effects include oxidative stress, as TiO2 nanoparticles can generate reactive oxygen species (ROS) under light exposure, leading to damage of cellular components like chloroplasts. Additionally, the physical blockage of stomata by nanoparticles can reduce gas exchange and affect photosynthesis and transpiration. Furthermore, nutrient imbalances caused by the interaction of nanoparticles with essential nutrients might contribute to these observed reductions. Similarly, silica NPs (SiO_2-NPs), derived from agricultural waste, have also shown promise for plant protection (Snehal et al., 2018). SiO_2 nanoparticles have been shown to enhance plant dry weight and organic compound levels in maize (Suriyaprabha et al., 2012) and improve tomato seed germination (Siddiqui and Al-Whaibi, 2014). Furthermore, Ag-NPs, CuO-NPs, and ZnO-NPs are employed to improve soil physicochemical properties (Mittal et al., 2013; Seleiman et al., 2020), by enhancing soil nutrient availability, increasing water retention, and promoting beneficial microbial activity, offering potential sustainable solutions for agriculture offering potential sustainable agricultural solutions. Additionally, AgNPs increased plant biomass, height, and shoot length in *Solanumlycopersicum* (Noshad et al., 2019) and improved growth metrics in *Trigonellafoenum-graecum* (Sadak, 2019).

Nano-enabled products also have applications in environmental pollution management. Iron (Fe) NPs are extensively used in environmental pollution management due to their small size and high surface area-to-volume ratio, enabling efficient removal of pollutants like Cd, chloroform, DDT, etc.(Zhang, 2003). Carbon nanotubes have improved seed germination and root growth in tomatoes (Khodakovskaya et al., 2009), enhanced root growth in wheat (Wang et al., 2012), and stimulated growth in various other crops (Tripathi et al., 2011). Al_2O_3 nanoparticles have no toxic effect on root elongation in *Arabidopsis thaliana* (Lee et al., 2010). MoO_3 nanoparticles, used as a foliar fertilizer, enhanced the morphological criteria of common dry beans (Osman et al., 2020).They also have applications in *ex-situ* slurry reactors for treating soil, sediment, and solid waste, and anchoring them onto activated carbon can enhance the effectiveness of wastewater treatment (Zhang, 2003). Fe NPs, including bimetallic ones with Pd and Pt coatings, are also helpful in treating soil, sediment, solid waste, and aqueous phase remediation (Elliott and Zhang, 2001). Gold (Au) NPs, due to the quantum size effect, exhibit promising catalytic activity in converting CO to CO_2(Laoufi et al., 2011). Carbon nanotubes (CNTs) are studied for their role in air purification by absorbing gases and causing macroscopic changes in resistance (Demirer et al., 2019). El Gamal et al. (2022) emphasized the potential of CNPs (Chitosan NPs) in affecting the integrity of virus particles, inhibiting their replication and accumulation within plant tissues, and enhancing the production of defense-related factors against Bean yellow mosaic virus in faba beans.

NPs in agriculture, although in their early stages, hold significant potential for reshaping traditional practices. Modified NPs can address persistent issues related to fertilizers, herbicides, and insecticides. Despite being in its infancy, this application has transformative potential (Prasad et al., 2017b). Modified NPs could change public perceptions of agriculture and offer solutions to longstanding challenges through advanced materials and technologies (Prasad et al., 2017b). The unique distribution of NPs in plants provides multiple advantages (Hu et al., 2021). Overall, incorporating NPs in agriculture has the potential to revolutionize the industry by leveraging cutting-edge solutions for long-standing challenges.

Due to their essential properties, including size, optical properties, surface-to-volume ratio, and others, NPs can effectively protect plants (Siddiqi and Husen, 2017). The controlled release of fertilizers and pesticides with nano-encapsulated particles is an excellent example of applying NPs with the critical feature of site-specific slow release (Singh et al., 2023b; Vishwakarma et al., 2018). This very efficient method provides a robust defensive mechanism for plants interacting with pathogens by shielding non-target species and performing other collateral repairs (Naderi and Danesh-Shahraki, 2013). Other uses of NT in agriculture include organic fertilizers, micronutrients, NPs, attenuating biopesticides, and regulating the release of fertilizers in a measured and controlled manner (Singh et al., 2024a, 2024b, 2024c, 2023a; Verma et al., 2022).

The website of the nanotechnology products database (NPD), which maintains current data on products enabled by NT, revealed that there are 11,171 commercially available items in total, produced by 3,910 firms across 68 nations (https://product.statnano.com/; accessed January 20, 2024).

Various nano-enabled products are utilized in several industries, including agriculture. Comparably, 329 companies across 329 countries have produced 844 products to date. These automotive businesses use nano-enabled items linked to auto-additives, auto-parts, and maintenance. Similarly, the construction industry has manufactured around 1170 products by 625 companies across 49 items worldwide. Additionally, there are 1962 products in electronics, 1319 in medicine, 1011 in cosmetics, 591 in renewable energies, and 206 in printing (NPD 2024). In agriculture, more than 260 nano-enabled products have been manufactured by 96 companies in 29 countries worldwide (Fig. 2). These nano-enabled products with NT applications are related to soil enhancement, plant breeding, animal husbandry, fertilizers, and plant protection.

This review addresses and investigates the potential applications of nano-enabled goods in sustainable agriculture and environmental pollution management. It is crucial to find a balance between taking advantage of these developments and ensuring they are used responsibly and safely as the agriculture industry continues using NT for increased productivity and resource utilization. This study aims to produce a responsible and sustainable integration of technology in agriculture by exploring the two sides of the possible benefits and environmental issues related to the usage of nano-enabled goods.

2. Agricultural Applications of Nano-products

Currently, appropriate amounts of nano-enabled products such as nano-fungicides, nano-pesticides, nano-herbicides, and nano-fertilizers can be applied through several methods, such as soil treatment, direct injection into the plants, mixing for sowing, root soaking, and foliar application to the crop (Sharma et al., 2021, 2017). These nano-fungicides, nano-pesticides, nano-herbicides, and nano-fertilizers have applications in controlling pests, microbes, and unwanted herbs that can infect crops and reduce productivity (Nisha Raj et al., 2021). These nano-enabled products are in demand for crop protection in sustainable agriculture. Recently, nano-based stretch films made of polyethylene were used to protect plants from UV rays and thunder storms (Iavicoli et al., 2017; Rajput et al., 2021a). Approximately 49 nano-enabled products manufactured by 25 companies in the commercial market of 12 countries are employed in plant protection. Among them, 18 nano-pesticides and 7 nano-fungicide products are widely used in crop protection and disease management against various pests and diseases (NPD 2024). India has gained its 2^{nd}last position in this market of nano-enabled plant protection products.

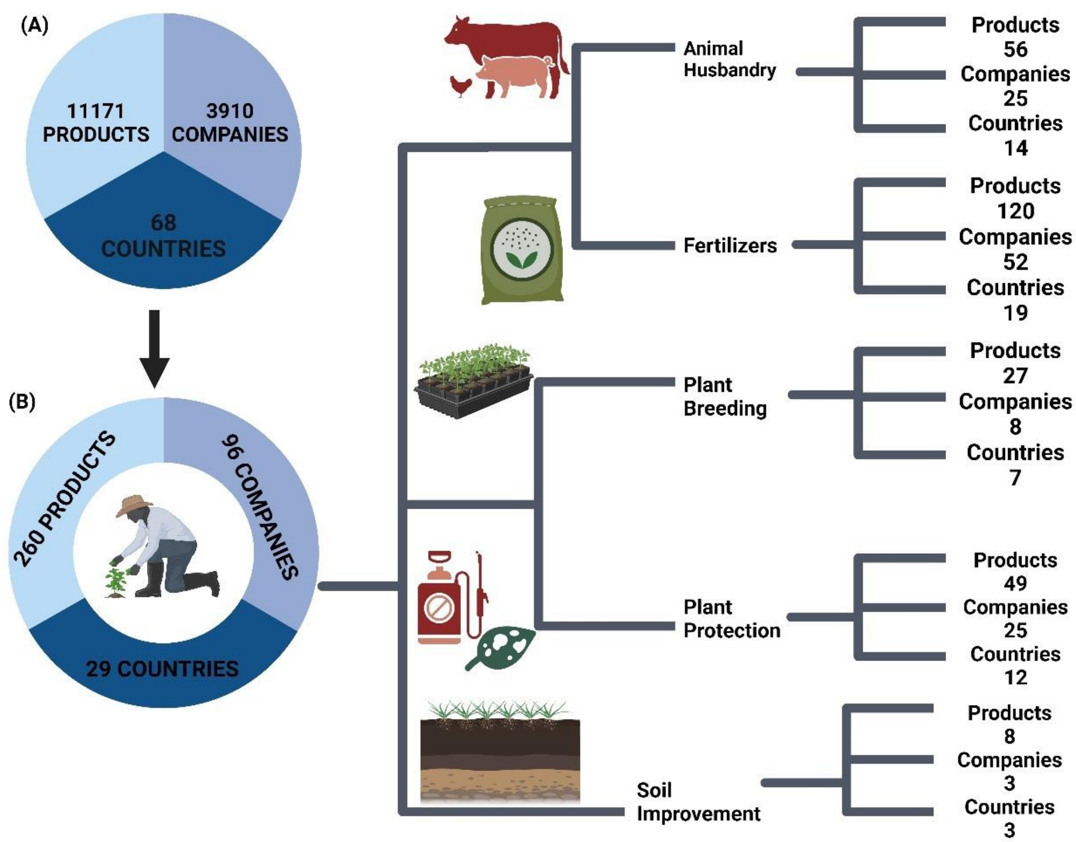

Fig. 2. Worldwide (A) nano products and (B) agriculture products that are utilized for crop protection, production, and soil health improvement.

2.1 Nano-pesticides

Nanotechnology can potentially solve environmental issues and transform the efficacy of pesticides (Fig. 3) (Kumar et al., 2019). Available in a variety of forms, including lipids, polymers and metal-organic frameworks, nano-pesticides use manufactured NPs that possess biocidal capabilities (Garg et al., 2023). These materials give agricultural surfaces precise control over pesticide adhesion and release through various methods. Pesticide stability and persistence are increased using NT to manipulate particle size and structure, frequently by encasing active chemicals in NPs. This allows them to remain on plant surfaces for a more extended period (Zafar et al., 2020).

Additionally, certain nanocarriers may react to changes in their surroundings, improving their targeting skills. Increasing the surface area allows nano-pesticides and plant surfaces to interact more effectively, strengthening the adhesion effects. Because of the increased permeability and accurate release mechanisms, even modest dosages can significantly influence plants while limiting adverse environmental consequences, cutting expenses associated with agricultural production, and improving control sustainability. Similarly, nano-nutrients enhance plant nutrient uptake and utilization due to their high surface area and reactivity, which improves nutrient availability, absorption efficiency, and delivery precision, thus promoting better plant growth and productivity with lower quantities of nutrients. Improved crop yields, precise control over the spread of pests and diseases, and increased environmental friendliness are just a few advantages that nano-pesticides provide to agriculture. Using chiral nanomaterials in nano-pesticides provides better biocompatibility, less toxicity to non-target species, and compliance with sustainability and environmental friendliness (Albanese et al., 2012). This novel strategy highlights a research hotspot in agriculture and shows how nano-pesticides can transform conventional approaches to pest management completely.

Nano-enabled pesticides represent a transformative leap in agricultural practices, addressing concerns about conventional pesticide solubility and environmental impact. Several innovative formulations are emerging globally, each designed with specific properties to enhance effectiveness and sustainability (Table 1; NPD 2024). India's NanoBee BioInnovations introduces the Smart Plant Protector, leveraging fast-acting colloidal NT for contact-based and repellent modes, controlling various stages of pests, and combating plant diseases. In Costa Rica, ClearLeaf offers GotaBlanca® 500, an Ag nano-colloid-based solution for pre- and post-harvest protection (Table 1). These nano-enabled pesticides promise precise control, reduced environmental impact, and enhanced sustainability in agriculture.

2.1.1 Nano-insecticides

The utilization of NPs in insect pest management has emerged as a diverse and promising strategy, offering innovative solutions to challenges associated with conventional chemical pesticides (Fig. 3). Several studies have investigated the efficacy of different NPs and their active ingredients against specific target organisms (Miola et al., 2022). Various concentrations of TiO_2 nanoparticles had varying effects on pupae weight, adult emergence, adult inhibition, and sex ratio, with 75 μg/ml proving to be the most effective concentration for these parameters (Mohamadeen et al., 2024). Chitosan nanoparticles loaded with *Mentha spicata* essential oil (MsEO/CSNPs) demonstrated potent antioxidant properties and effective insecticidal activity against *Callosobruchus maculatus* and *Sitophilus granaries* (Choudhary et al., 2024). Similarly, copper nanoparticles synthesized from extracts of Acacia cornigera and *Annona purpurea* plants have the potential to be biocontrol agents against *Tribolium castaneum*, a significant pest of stored grains with high economic impact. A commonly accepted theory for various NPs is their induction of toxicity by triggering oxidative stress in arthropod tissues (Alengebawy et al., 2021). Additionally, their toxicity may result from nanoparticle penetration through the exoskeleton (Jafir et al., 2023).

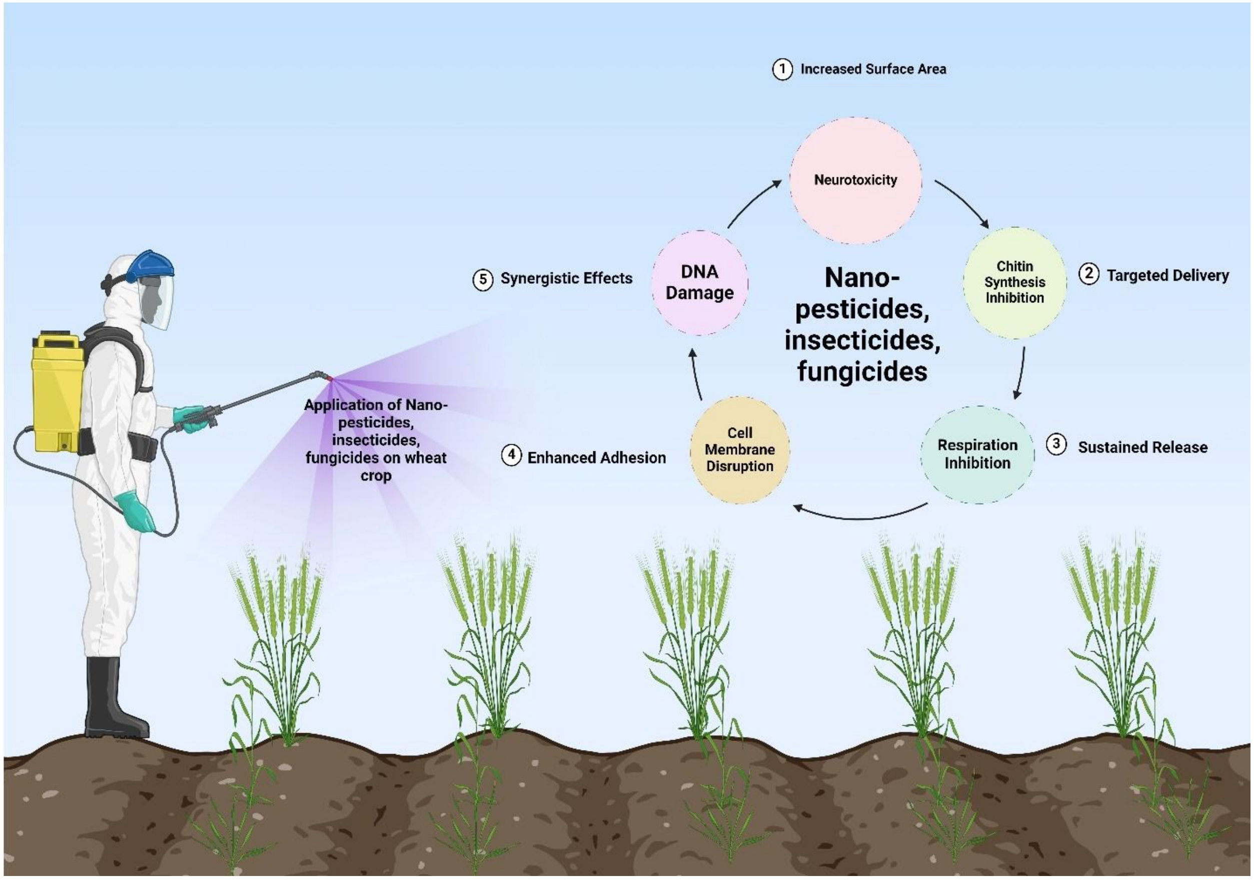

Fig. 3. Application of different nano-enabled pesticides, insecticides, and fungicide products with their mode of action for crop protection.

Within the intracellular space, nanoscale materials bind to sulfur in proteins or phosphorus in DNA, leading to rapid denaturation of organelles and enzymes. Consequently, a decrease in membrane permeability and disturbance in the proton motive force may occur, causing a loss of cellular function and eventual cell death (Mikhailova, 2020). For instance, nanoencapsulation of *Carumcopticum* essential oil has shown effectiveness against the diamondback moth, while myristic acid-chitosan nanogels have demonstrated efficacy in controlling wheat weevils (Ziaee et al., 2023). Polyethylene glycol-coated NPs containing garlic essential oil exhibit potential against the red flour beetle (Mohamed et al., 2020).Nanogels incorporating methyl eugenol effectively manage the Oriental fruit fly (Bhagat et al., 2013). Nano-capsules with pyridinyl target cotton bollworms, while those with azidobenzaldehyde are effective against armyworms (Kumar et al., 2022). Chitosan-coated nano-formulations employing pyrifluquinazon, exhibit promise in controlling green peach aphids (Kang et al., 2012). Chitosan nanocarriers, using Nomuraearileyi, are effective against tobacco cutworms (Feng and Peng, 2012). Nano-dust, particularly nano-Al_2O_3 nanoparticle dust, effectively manages ice weevils (Andrić et al., 2012). Additionally, nano-DEPA demonstrates effectiveness against mosquitoes (Mapossa et al., 2021). These nanoparticle-based approaches offer advantages such as enhanced contact with pests, targeted release of formulations, and reduced environmental pesticide load, positioning them as environmentally sustainable strategies for insect pest management in the context of green agriculture.

2.1.2 Nano-fungicides

To combat fungal diseases, researchers are developing nano-fungicides that contain organic components such as active chemicals, polymer-based inorganic SiO_2-NPs, titanium dioxide (TiO_2), nano-emulsions, and nano-clays (Sivarethinamohan and Sujatha, 2021). Metals such as copper (Cu), zinc (Zn), silver (Ag), titanium dioxide (TiO_2), and various inorganic elements are used in the synthesis of nanofungicides (Venugopalet al., 2024). By delivering the necessary dosage of pesticides into plant tissue, NPs self-regulating properties help reduce the number of pesticides used. Metal NPs (MNPs) exhibit a superior fungitoxic effect compared to their ionic counterparts due to their ability to cause direct mechanical damage through a large surface-to-volume ratio or nanostructure defects. Additionally, MNPs generate H_2O_2, which can penetrate the membrane and cause internal damage. This unique mode of action provides advantages in terms of effectiveness and eco-compatibility, as MNPs require smaller xenobiotic quantities, resulting in a reduced environmental footprint (Malandrakis et al., 2022). One example of a bio-fungicide created and processed using molecular NT is the commercially available "Diyarex Gold"from R.V. Agri Corporation (Abd-Elsalam et al., 2019). It is an effective fungicide and bactericide that is safe for the environment and does not harm economically significant insect populations like bees. Diyarex Gold treats vegetable, herb, grapevine, and orchard diseases such as powdery mildews, downy mildews, rust, and early and late blight (Bhattacharyya et al., 2016).

Similarly, GotaBlanca® 500 (crop protection solution), an Ag nano-colloid-based pesticide by Costa Rica's ClearLeaf, is a versatile solution for crop protection in open fields, greenhouses, and hydroponic systems, offering effective antimicrobial and fungicidal properties (Table. 1) ("Home | Nanotechnology Products Database | NPD,"2024).

2.1.3 Nano-herbicides

Several nano-formulations and their effects on various plant species provide a thorough overview of numerous nano-enabled herbicides and their uses in weed management. Modern nano-herbicides primarily operate by inhibiting the activity of enzymes or proteins within the cell, initiating a series of events that result in either cell death or developmental impairment (Vats, 2015). A variety of nano-formulations, including dendrimer glyphosate, CS alginate NPs, PCL_ATZ NPs, and nano-emulsions containing glyphosate, show encouraging results in terms of decreased toxicity, increased stability, and improved biological efficacy (Forini et al., 2022). The nano-formulations solve issues with traditional herbicide applications by demonstrating regulated release, reduced soil sorption, and higher plant absorption of herbicides (https://product.statnano.com/; accessed: January 20, 2024).

Zn-layered hydroxides, mesoporous silica NPs, halloysite nanotubes (HNTs), and layered double hydroxides (LDHs) are a few examples (Forini et al., 2022). These nano-formulations exhibit stimulus-responsive delivery systems, regulated release of many herbicides at once, and sustained release. The results show that herbicides with inorganic NT can enhance herbicidal effectiveness while reducing side effects.

These formulations show promise for successful and sustainable weed management in agriculture because of their enhanced efficacy, controlled release, and decreased toxicity. The variety of nano-formulations and their intended effects on various plant species highlight the encouraging developments in nano-herbicide research for future agricultural practices.

2.2 Nano-fertilizer

Nano-fertilizers (NFs) present several advantages over conventional fertilizers (CFs), such as NFs demonstrate environmental friendliness by being non-toxic; contribute to improved soil fertility, crop yield, and quality; reduce the overall cost of production; exhibit higher nutrient use efficiency compared to CFs; and provide a targeted, balanced, and slow release of nutrients, contributing to effective nutrient management (Fig. 4). Nanoparticles have shown promising applications in agriculture across various crops. Carbon nanoparticles applied to wheat (*Triticum aestivum*) enhance plant biomass, height, nutrient uptake, and nitrogen utilization efficiency (Zhao et al., 2021). Silica nanoparticles (Si-NPs) increase plant height, fruit weight, leaf area, and overall biomass in cucumber (*Cucumis sativus*) (Yassen et al., 2017). Zinc oxide nanoparticles (ZnONPs) effectively enhance plant growth and alleviate zinc deficiency symptoms in rice (*Oryza sativa*L.) (Bala et al., 2019). These findings highlight the potential of nanoparticle use in agriculture to enhance crop productivity and nutrient efficiency. Nano-coated fertilizers enhance nutrient delivery by exploiting their tiny size to improve penetration through plant stomata and cell walls. Due to their diameter being smaller than cell wall pores, nanoparticles can easily pass through these openings and reach the plasma membrane of plant cells. This enables more efficient entry into the plant tissue and direct access to the cells. The small size of nanoparticles allows them to navigate through the stomatal openings and traverse the cell wall's pores more effectively than larger particles. Once inside the plant, nano-coated fertilizers facilitate targeted and controlled nutrient delivery, improving nutrient uptake, reducing waste, and enhancing overall plant growth and productivity.(Joshua et al., 2023). Application through foliar methods facilitates the transportation of NPs to heterotrophic cells from the application site through plasmodesmata, characterized by a diameter of 40 nm (Etxeberria et al., 2016). The uptake of NPs involves binding to carrier proteins, aquaporins, ion channels, and endocytosis. Table 2 outlines various nano-enabled fertilizers developed by multiple companies across different countries, each boasting distinctive properties and targeted applications. Dr. Vivasayam Crop Care Services in India offers Nano Potash Liquid Fertilizer, emphasizing plant growth acceleration and soil nutrition enhancement. Groagro 1 by Microwell Bio Solutions in Malaysia introduces a controlled-release organic fertilizer that is rich in potassium, magnesium, and boron, which is recommended for peat soil. Fosvit K30 from the Kimitec Group in Spain focuses on agricultural self-defence enhancement against invasive fungal infections. AFME Trading Group in the UK contributes with nano-potassium chelate and nano-Zn chelate fertilizers, emphasizing plant growth regulation and nutritional benefits.

Table 1. Nano-enabled pesticides and their applications in agriculture (NPD 2024).

Nano-enabled pesticides	Company	Country	Properties	Applications
Smart Plant Protector	NanoBeeBio Innovations (ReAgri)	India	Pesticide Removal and Plant health Improvement	They are fast-acting and unique. Colloidal NT acts both on contact and as a repellent, controlling eggs, larvae, and adult pests' stages while also managing plant diseases with its antibacterial and antifungal properties.
Nano Shield	Anand Agro Care	India	Antibiotic, Virucidal and Fungicide	Nano Shield is a synergy of hydrogen peroxide stabilized with nano-Ag particles in the presence of a catalyst. This unique product is effective on an extensive range of microorganisms. Nano Shield is an excellent fungicide, antibiotic, and virucide.
GotaBlanca® 500	ClearLeaf	Costa Rica	Antibacterial Activity and Fungicide	Ag nano-colloid-based pre-harvest solutions are for protection in open fields, greenhouses, and hydroponics, and post-harvest solutions are for better conservation during the long transit.
NANOCU	Bio Nano Technology	Egypt	Plant Growth Acceleration	Cu products manufactured by nanotechnology used as a fungicide and a bactericide contain Cu in the form of NPs,
Nano Ag 2000 ppm For Plant Protection & Disinfection	YK Laboratories	India	Anti-microbial activity	Nano-Ag ions can bind to the microbial cell's molecular component, further deactivating the metabolic system and inhibiting further reproducing the microbes and eventually killing them.
Kopsil-Agri	Filo life sciences pvt. Ltd.	India	Antibacterial, Activity Anti-fungal Activity, Antiviral and Anti-Germ	These are Ag-based and Cu-based nano-colloids. These are mixed with waterand can be sprayed directly onto plants and shrubs. Its action works outside of the plants to effectively destroy bacteria, viruses, fungi, etc. It leaves no residue on food plants sprayed with it, as do poison sprays and is safe for human consumption.
Bee-Sico	Nanobeebioinnovations (reagri)	India	Antibacterial Activity Anti-microbial activity Antiviral Fungicide	BEE-SICO is a colloid of NPs of pure Ag and Cu encapsulated in a biopolymer. Encapsulation improves stability and has an anti-microbial effect.Our unique proprietary NT process prepares it, which reduces Ag^{+} to Ag^{0} and Cu^{+} to Cu^{0}(metallic copper). It contains 250 ppm of nano-Ag and 250 ppm of nano-Cu.

Nano cube® marinus complete plus	Dennerle	Germany	Algae Resistance	Nano Cube Marinus Complete Plus contains everything you need to get off to a good start.
Blue lagoon uv-block	Dennerle	Germany	Lagoon	This is used to prevent green and thread algae. It controls algae growth by reducing light penetration using a special blue dye. It is ideal for all garden ponds, koi ponds, and swimming ponds. Gives the water an attractive, blue lagoon coloration. It makes the colors of fish and plants appear more intense. Perfectly biologically harmless for fish, plants, and all other pond inhabitants (crayfish, mussels, snails, frogs, newts, dragonfly larvae, etc.) Pond water treated with Blue Lagoon is harmless to all pets (dogs, cats, and birds).
Antialgae Direct	Dennerle	Germany	Non-toxic Environmentally Friendly Algae Resistance PH Control	Ag nanoparticle-based product provides a swift and simple means of killing off irksome thread algae, which tend to grow around the pond's edge or float on large mats on the water's surface. The powder is sprinkled directly onto the algae. The active oxygen that is released destroys the algae cells. The dead algae are broken down by the bacteria living in the pond. The active component, hydrogen peroxide, quickly decomposes into oxygen and water.
Algaestop	Dennerle	Germany	Non-toxic Environmentally Friendly Algae Resistance pH Control	Ag nanoparticle-based barley straw isan effective and reliable agent to treat thread algae, which can be used as a preventative and fight algae. Barley straw inhibits algae growth through its decomposition and causes any algae present to die off. Dennerle Algae Stop also includes humic peat, oak bark, and alder fruit. These reduce and regulate the pH, as algae require high pH values. A slightly golden-brown colour also filters algae, promoting UV light. Prevents new algae growth. For clear, healthy pond water Made from renewable raw materials

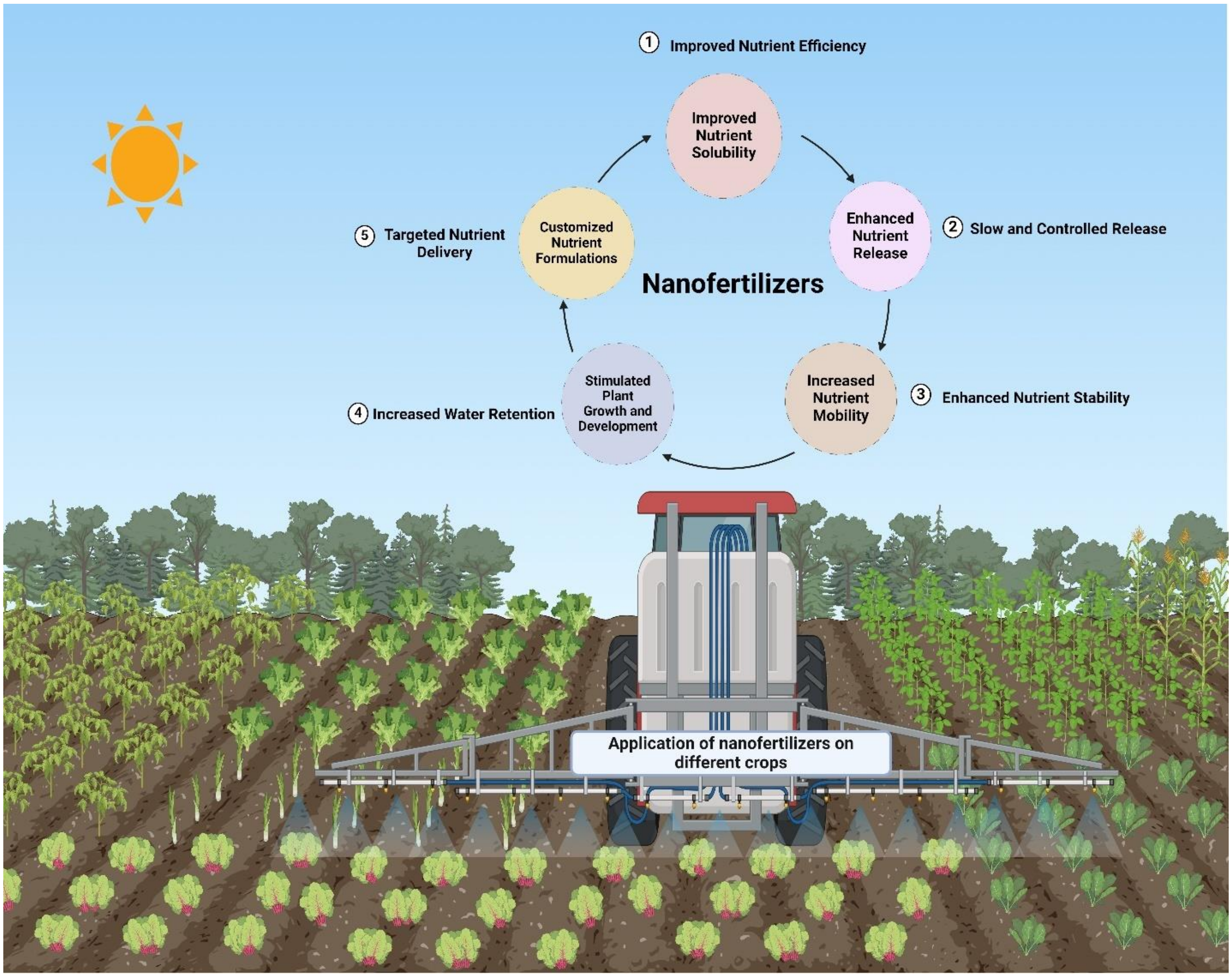

Fig. 4. Application of nano-enabled fertilizers and their mode of action for crop production.

Bioteksa in Mexico presents Nubiotek® Ultra Ca, promoting crop tolerance to climatic stress and pests. The litho plant in Brazil introduces lithocal, enhancing nutritional absorption through calcium and magnesium elements. Alert Biotech in India provides nano-Zn, which is vital for protein synthesis and plant growth. Additionally, table 2 features fertilizers like Shoot Food, an NT-based foliar liquid fertilizer by NanoBeeBioInnovations in India, and High-Tech Nano Chelated Manganese Fertilizer 12% from Trademax Corporation FzeLlc in the UAE, aimed at enzyme activation and photosynthesis increase. AgroArgentum® Bor by Hortus Supplies International B.V. in the Netherlands stresses optimized photosynthesis, reduced plant stress, and enhanced growth. AFME Trading Group in the UK also offers Nano Fe Chelate Fertilizer for plant growth regulation and acceleration. Each fertilizer caters to specific agricultural needs, ranging from nutrient enrichment to stress resilience, showcasing the evolving landscape of nano-agricultural innovations globally "Nanotechnology in Agriculture Industry | NPD," 2024.).

Table 2. Nano-enabled fertilizers and their applications for plant growth (NPD 2024).

Nano-enabled Fertilizers	Company	Country	Properties	Applications
Nano Potash Liquid Fertilizer	Dr. Vivasayam Crop Care Services	India	Plant Growth Acceleration Soil nutritious	Nano Potash enhances root growth and development, contributing to a more robust, healthier root system.
Groagro 1: Super Nano-Catalyst Kalium + T. E	Microwell Bio Solutions SdnBhd	Malaysia	Controlled-release organic fertilizer for K, Mg, and B High of organic K (max 25%) High of alkalinity property (pH<11) Highly recommended for peat soil.	Advanced material formulation compounds contain high organic potassium, magnesium, boron, and essential trace elements.
Fosvit K30	Kimitec Group	Spain	Agriculture Invasive fungal infections Integrated Production	Provide self-defence enhancement
Nano potassium chelate fertilizer	AFME trading group	UK	Plant Growth Regulation Plant Growth Acceleration	Acceleration of plant growth
Nubiotek ® Ultra Ca	Bioteksa	Mexico	Effectively helps the crop generally tolerate different scenarios of climatic stress the aggressive presence of pests, or diseases with excellent performance.	Plant growth regulation and nutritional plant growth acceleration
Lithocal	Litho Plant	Brazil	Nutritional absorption enhancement	Calcium (Ca) and Magnesium (Mg) in formulation are essential elements for all crops. They promote an increase in the root system where the plant absorbs more water and nutrients from the soil, better resisting periods of drought, and increasing tillering sprouts and vegetative vigor.
Nano Zn (chelated)	Alert Biotech	India	pH stability Nutritional	Nano Zn is an essential micronutrient and a vital constituent of various enzyme systems. The element regulates protein synthesis, energy production, and plant growth.
Nano Zn chelate fertilizer	AFME Trading Group	India	Plant growth regulation plant growth acceleration	Chelated fertilizers provide one or more nutrient metal elements to plants, in which deficiencies will result in the yellowing of leaves, retarded growth, and general low-quality corps.
Shoot Food	NanoBeeBioInnovations (ReAgri)	India	NT based Essential Primary, Secondary & Micronutrients	Provide foliar liquid fertilizer, fast absorbing used for all plants

High-Tech Nano chelated manganese fertilizer 12%	Trademax Corporation FzeLlc	UAE	enzymes activation & photosynthesis increase	This nano fertilizer is in powder form, completely soluble in water, and absorbable through foliar spraying (1.5 g/L) and soil application (2-5 kg/ha).
AgroArgentum® Bor	Hortus Supplies International B.V.	Netherlands	Pesticide removal plant growth regulation plant stress reduction	Optimized photosynthesis can boost the plant's growth and development and more flowering and harvest. It also provides the necessary elements. Thus, the plant becomes, more robust and more tolerant to stress.
Nano Fe chelate fertilizer	AFME trading group	UK	Plant growth regulation plant growth acceleration	Using these fertilizers will increase plant growth while assuring adequate development and efficient crop production.

2.3. NPs-Based Soil Improvement

By altering the pore fluid and strengthening the bonds between soil particles, nanomaterials are essential for increasing soil strength. Because of their tiny size, NPs can spread into the pore space more efficiently, especially in fine soil particles that are not under much pressure. The inclusion of nanomaterials affects the soil's microstructure. For example, the two-dimensional structure of CNT and other NPs has a different effect on the soil than that of three-dimensional NPs like colloidal silica (Etxeberria et al., 2016) Titanium dioxide nanoparticles show promise in boosting wheat yields when used as a foliar application. Hydroxyapatite nanoparticles are highly effective in acidic soil conditions. Zinc oxide nanoparticles, integrated into urea fertilizers, offer agricultural benefits for wheat by increasing zinc levels and impacting the growth of rice and maize (Hadri et al., 2024). Copper oxide nanoparticles demonstrate resilience to environmental stressors and effectively manage nutrient deficiencies (Hadri et al., 2024).

Rheological suspension qualities impact the architecture of NPs in soil-water suspension, which is essential for their ability to strengthen soil (Kannan and Sujatha, 2022). The specific surface area of NPs increases with decreasing particle size. As a result, the atomic surface becomes more extensive, improving interactions with other particles and ion exchange capacity. In soils containing these particles, increased plastic and liquid limits result from the facilitation of pore water collection by NPs. When characterizing the energy and motion state of particles at the nanoscale, NPs in the soil brings complications that are more in line with models from quantum mechanics than classical mechanics, provides a comprehensive overview of various engineered NPs (ENPs). These include various materials such as fullerenes, including Buckminster fullerenes, CNTs, and nano-cones. Metal ENPs are also covered, featuring elemental metals like Ag, Au, and Fe. Oxides, including TiO_2, CuO, FeO_2, ZnO, aluminium oxide (Al_2O_3), SiO_2, and cerium dioxide (CeO_2), are described in the context of ENPs. Complex compounds like Co-Zn-Fe oxide and quantum dots, often coated with polymers such as cadmium-selenide (CdSe), and organic polymers like dendrimers and polystyrene, are also outlined. This classification emphasizes the vast array of engineered nanomaterials recognized and studied by the authority. This demonstrates the unique and complex interaction between soil mechanics and nanomaterials, offering new perspectives on creative methods for improving soil in various applications.

2.4 NPs-Based Plant Growth Enhancers

In biology, applying nanomaterials may significantly improve plant development, growth, and production. With NT, agricultural productivity may be increased by maximizing input efficiency and reducing losses caused by various causes. The capacity of NPs to offer agrochemicals to a broader and more targeted surface area, acting as special carriers that improve nutrient absorption, is one of their main characteristics. Consequently, this leads to an elevated buildup of vital nutrients in crop plants.

Gold Nanoparticles (Au NPs) applied at concentrations of 10 µg/mL and 80 µg/mL via foliar spray on *Brassica juncea*, resulted in a positive increase in seed yield (Arora et al., 2012). Silver Nanoparticles (Ag NPs) at concentrations of 50 mg/L and 75 mg/L showed effective fungicidal activity and improved growth and heat stress tolerance in *Triticum aestivum* (Chavan and Shelar, 2015). Zinc Oxide Nanoparticles (ZnO NPs) enhanced grain yield and biomass accumulation while decreasing shoot chlorophyll content in *Triticum aestivum* (Afify et al., 2019). Titanium dioxide Nanoparticles (TiO_2 NPs) applied at 100-1,000 mg/kg in pots with soil on *Solanum lycopersicum*, improved plant height, root length, biomass, and lycopene content (Eddy et al., 2020).

In addition to improving nutrition, NPs are essential for crop protection. Because of their unique qualities, NPs can effectively transport agrochemicals with controlled release and targeted delivery. This focused strategy reduces the adverse effects on the environment while increasing the effectiveness of crop protection methods. Using nanomaterials in agriculture has enormous potential to maximize crop protection, enhance nutrient management, and optimize resource usage. This creative way of incorporating NT into biological systems can improve overall productivity and sustainability in agriculture. Boron is essential for maintaining a balance between sugar and starch in plants and plays a crucial role in translocating sugars and carbohydrates. Specifically, boron influences sugar metabolism and carbohydrate distribution related to sugar and starch synthesis, transport, and utilization. Thus, their nano-boron product is a versatile solution for plant growth regulation, primarily functioning as an herbicide, algaecide, and pest controller. It employs boron NPs to target impaired cell expansion in rapidly growing organs, leading to malformation, shorter roots, and sterility in male and female flowers, ultimately reducing seed set (NPD 2024).

The Nano-Molybdenum product focuses on plant growth regulation, leveraging molybdenum’s role in essential enzymes like nitrate reductase and nitrogenase. Symptoms resembling nitrogen deficiency, such as pale green color and stunted growth, can be alleviated with this nano-enhanced solution. Nano-Magnesium, another offering from Kanak Biotech, uses magnesium-based nano-capsules to address issues like yellowing between leaf veins and reddish-brown tints, which are symptoms of magnesium deficiency. Magnesium is vital in phosphorus translocation and is a crucial constituent of the chlorophyll molecule. For plants experiencing stunted growth and fruit development issues, nano-iron provides a solution. Fe NPs address symptoms like reduced leaf size, discoloration, premature leaf fall, and chlorosis, enhancing plant growth acceleration. Kanak Biotech's nano-potassium product tackles challenges such as brown scorching, leaf curling, chlorosis, and overall poor resistance to environmental stressors. The potassium nano-powder promotes healthy root development and robust plant growth. Nano-phosphorous is designed to combat reduced growth, stunted internodes, smaller leaves, and poor seed development by utilizing phosphorous NPs. It addresses symptoms like dark green or purple leaves, promoting tillering in cereals.

Nano-Zn addresses stunted growth and fruit development, like nano-Fe, by mitigating issues such as reduced leaf size, discoloration, premature leaf fall, and chlorosis, ultimately supporting overall plant health and growth acceleration. The Kanak Biotech products showcase NT's versatility in optimizing plant nutrition and growth regulation.

3. Integrating Approaches of Nanotechnological Products into Sustainable Agriculture and Environmental Management Practices

In several areas of environmental remediation, such as soil, air, and wastewater treatment, NPs are essential. Nanomaterials improve nutrient delivery, strengthen mechanical strength, and make removing contaminants from soil easier. Fertilizers using NT provide targeted and regulated releases of nutrients, promoting agricultural output and plant development. Because of their antibacterial, antiviral, and antimicrobial characteristics, NPs are essential to air purification technology for air remediation. Particulate matter is successfully removed from air purification systems using nanofiber-coated filter media, which increases filtering efficiency. NPs, particularly MNPs, and nano-sorbents, are helpful in the treatment of wastewater because they help get rid of organic solutes, bacteria, viruses, and hazardous metal ions. In sophisticated oxidation systems, photocatalytic NPs are essential for breaking down pollutants in wastewater (Regmi et al., 2018). Membrane technologies that enhance mass transfer and selectively filter impurities, such as zeolite and graphene-embedded membranes, also aid in the purification of water (Gao et al., 2022). The adaptability and specific uses of NPs highlight their importance in putting into practice long-term and successful environmental restoration plans.

3.1 Soil Improvement

With various NT uses, nano-remediation is an emerging technology with enormous potential for treating soil pollution. These include immobilization, adsorption, Fenton-type oxidation, reduction reactions, surface assimilation, and integration with bioremediation methods such as phytoremediation (Mukhopadhyay et al., 2022). Biochar-treated soil exhibited higher pH and organic carbon content, increased labile carbon, total nitrogen, and available phosphorus concentrations. NP-biochar combinations enhanced soil fertility reduced sodicity risk, and boosted ryegrass biomass (Forján et al., 2024). Nano-enabled soil remediation solutions offer innovative approaches to address various soil challenges. According to Madhura et al. (Madhura et al., 2018), the use of magnetite NPs and nano-zerovalent Fe assisted in readily degrading organic contaminants in the soil. Additionally, nano-TiO_2 and PEI-Cu NPs were reported to shorten the half-lives of atrazine and phenanthrene in the soil, respectively (Kalidhasan et al., 2017; Li et al., 2016).Moreover, magnetite nanomaterials modified with polyacrylamide can potentially promote soil degradation and arsenate leaching (Zheng et al., 2020).Research also suggested that adding nZVI to soil contaminated with pyrene produced strong reducing conditions that made it possible to eliminate pyrene via reduction. According to the study, 80% of soil-bound Cr (VI) could be eliminated by using sodium carboxymethyl cellulose-stabilized nZVI(Usman et al., 2020). Polycyclic aromatic hydrocarbons (PAHs) were bioremediation using a lipid derivative of choline-coated silica NPs. In addition, Fe sulfide, and stabilized by carboxymethylcellulose, was investigated for its ability to consolidate mercury in soils severely polluted with PAHs (Gong et al., 2012). In 2007, Yu et al. Click or tap here to enter text. conducted research on the degradation of organochlorine pesticides, including α-, β-, γ-, and δ-hexachlorobenzene, dicofol, and cypermethrin, using nano-scale TiO_2 and ZnO as superior photocatalysts. According to research by Rui et al. (Fan et al., 2014) (2010), organophosphorus and carbamate insecticides exhibited 15–30% photocatalytic degradation. This photocatalytic degradation was achieved using nano-TiO_2 containing rhenium (Re^{+3}) in the leaves of tomato plants. Due to complete oxidation and increased electron release, nanoscale zerovalent Fe reduces DDT and detoxifies CBs and organochlorine pesticides from soil (El-Temsah et al., 2016; Pan and Xing, 2012).

Another solution is the liquid nano-clay treatment by Desert Control LNC in Norway. This technology significantly reduces water usage by saturating the soil and retaining water effectively by up to 50-65% compared to traditional irrigation methods. In Australia, Richgro's Natural Sand to Soil introduces a zeolite nanoporous product that transforms sandy soil into nutrient-rich garden soil with improved drainage and water-holding capacity. Meanwhile, Zoiltech™ Soil Treatment by Enviro Veritas in the USA provides non-toxic deodorization, nutrient balancing, and moisture retention, promoting a healthy soil environment. Grigg Brothers' Zeopro™ utilizes zeolite to enhance soil physical properties, aiding turfgrass establishment (NPD 2024).

Zeomax® Gardenaid, from Zeotech Corporation in the USA, is a long-lasting soil amendment that improves nutrient retention, aeration, and moisture content. Another Canadian solution, the BRZ Soil Amendment by Bear River Zeolite Co., reduces irrigation needs, prevents compaction, and enhances root system aeration. Bear River Zeolite Co. offers the BRZ High Salinity Soils solution for challenging high-salinity soils, addressing specific issues such as hydrophobia and aeration reduction. KMI Zeolite Inc.'s Zeolite 12 x 30 (14 x 40) Mesh is versatile and used in artificial turf, soil amendment, and environmental remediation due to its ability to remove toxic pollutants. Ida-Ore Zeolite, LLC’s Enviro-Guard in the USA excels in poisonous contaminants by absorbing liquids, preventing the release of harmful chemicals into water sources. Finally, Zeolite Australia Pty Ltd. introduces zeolite-infused potting mixes and composts, enhancing nutrient retention and preventing leaching, thus promoting efficient plant growth.

These nano-enabled solutions showcase diverse applications, from water conservation to nutrient management, emphasizing their potential to revolutionize soil remediation practices globally.

3.2 Polluted Wastewater Treatment

Using different nanomaterials, NT has been extensively investigated to find more effective techniques for treating wastewater (“Home | Nanotechnology Products Database | NPD,” 2024.). NPs promise to improve water purification and wastewater treatment methods (Bala et al., 2019). Various nanoparticles, including carbon-based, semiconductor, ceramic, polymeric, metal, and magnetic nanoparticles, are extensively researched for their potential application in treating contaminated and wastewater environments (Punia et al., 2021). The maximum adsorption capacity of CuO nanoparticles for fluoride is reported to be 3152 mg/g, highlighting their ability to remove more than three times the weight of fluoride from water (Ighalo et al., 2021). Large surface area, robust mechanical qualities, increased chemical reactivity, cost-effectiveness, and energy efficiency are just a few of the unique attributes that enable them to effectively remove harmful metal ions, bacteria, viruses, and organic and inorganic solutes from wastewater. Wastewater treatment has shown promise for several nanomaterials, including MNPs, nano-sorbents, bioactive NPs, nanofiltration membranes, CNTs, zeolites, and clay (Usmani et al., 2017). Nano-enabled wastewater treatment technologies exhibit remarkable properties and applications, contributing to the advancement of water purification systems. Lockheed Martin Corporation's Perforin Graphene Membrane from the USA stands out for its chemical resistance (EID, 2009; Ramos-Delgado et al., 2016). Featuring an atomically thin layer of perforated graphene, it pushes the theoretical limits of membrane performance, offering the benefits of standard membranes but with enhanced permeability due to graphene's thinness. Biopure Filtration Pty Ltd. in Australia provides the Nano Ag Activated Carbon Water Filter, a 1-micron filter with antibacterial activity and deodorization capabilities. This filter, designed for whole-house systems, incorporates nano-Ag activated carbon made from natural coconut carbon, effectively reducing taste, odor, chlorine, VOCs, and bacteria resistance. The Vitaloop Defender filter by Vitaloop in Norway is tailored for urban, outdoor, and tropical environments, addressing a broad spectrum of contaminants, including heavy metals and viruses. This versatile water treatment solution emphasizes antibacterial activity and virus removal. India's I3 Nanotec presents Zeolite Membranes available in various tubular formats, offering diverse applications and improving mass transfer in water treatment. These membranes are designed to enhance filtration efficiency and are compatible with different membrane housings. LIG Nanowise Ltd., from the UK, introduces graphene-embedded hollow fiber nanoporous membranes designed for aqueous filtration. These membranes, enhanced with graphene, demonstrate durability, virus removal capability, and reduced energy consumption. With the ability to filter particles as small as 10-20 nm, including viruses and microplastics, they contribute significantly to efficient water purification.

Together, these nano-enabled wastewater treatment solutions showcase a range of advanced technologies addressing diverse water purification needs, from chemical resistance and antibacterial properties to virus removal and energy efficiency.

3.3 Role of Nanoproducts Products in Air remediation

In air remediation, several companies are harnessing NT to develop innovative solutions(Dwevedi and Sharma, 2018). Various types of nanoparticles such as TiO_2-based NPs, dendrimers, Fe-based NPs, silica and carbon nanomaterials, graphene-based NPs, nanotubes, polymers, micelles, and nanomembranes are employed to mitigate environmental hazards (Hussain et al., 2022). This involves utilizing *in-situ* methods such as bioventing, bioslurping, biosparging, phytoremediation, and permeable reactive barriers, as well as *ex-situ* approaches such as biopiles, windrows, bioreactors, and land farming (Hussain et al., 2022). Trane Technologies plc, based in Ireland, offers the Thermo King Air Purification Solution, a graphene-based air purifier primarily used in buses. This solution is known for its antibacterial and antiviral properties. G6 Materials Corp., located in the USA, introduced an air purifier featuring a unique filtration system to eliminate fine particulate matter, volatile organic compounds, and pathogenic microorganisms such as fungal spores, bacteria, and viruses. Graphene in this air purifier contributes to its certified antibacterial, anti-microbial, anti-fungal, anti-pollen, anti-dust, and antiviral activities.

Retapspol. Based in the Czech Republic, Sro has developed the nano-air-cleaner Wood Glazed Air Purifier. This air purification system employs TiO_2 NPs or powder to dispose and decompose harmful substances. The nano-chiller eliminates bacteria, viruses, fungi, microscopic dust, formaldehyde, and toluene. Additionally, the cleaner operates ultra-quietly, has minimal maintenance requirements, and offers various purifier types made of natural materials. Nanolab Instruments SDN BHD, a company from Malaysia, specializes in nanofiber-coated filter media for air purification. Their nanofiber-coated polypropylene filter media enhances the performance of polypropylene filters in removing particulates from air streams. These filters find applications in HVAC systems, vehicles, computer disk drive ventilation, and cabin air filters, contributing to improved user comfort and health. Nano-lab Instruments SDN BHD also offers Nanofiber-Coated Fiberglass Filter Media, particularly suitable for automotive HVAC filters and computer disk drive ventilation, further emphasizing the role of nanofibers in air purification.

4. Nanoproducts Related Safety Risk Assessments and Rules Regulations

Because of their changed behaviours at the nanoscale, nanomaterials pose dangers to human health and the environment and are therefore a source of concern for possible toxicity (Fig. 5). Concerns include environmental effects, cellular interactions, and worker inhalation risks. Concerns regarding regulatory gaps arise from the inability of regulatory frameworks to keep up with changes. To address these issues, we must keep doing multidisciplinary research, working together, and creating customized safety protocols (Iavicoli et al., 2017). Jeevanandam et al. (2018) recommended definition of NPs is a naturally occurring, accidentally occurring, or artificially created material that contains particles in an unbound state, as an aggregation, or as an agglomeration, where one or more of the exterior dimensions of at least 50% of the particles in the number size distribution fall between 1 and 100 nm in size (Peltonen-Sainio et al., 2009). A threshold between one and fifty percent may be used instead of the fifty percent barrier in some situations, as determined by factors such as competitiveness, health, safety, or environmental concerns. Nanomaterials include fullerenes, graphene flakes, and SWCNTs that have one or more exterior dimensions of less than 1 nm. FDA Guidance for Industry (FDA, 2014): The FDA will consider whether a material or final product is designed to have an internal or surface structure, or at least one exterior dimension, in the nanoscale range (about 1 nm–100 nm). Furthermore, even if a material's or finished product's dimensions are outside the nanoscale range up to 1 µm (1000 nm), the FDA will evaluate whether the material or product is created to display phenomena or features, such as physical or chemical attributes or biological impacts, traceable to its dimensions. Chemical substances that are solids at 25 °C and atmospheric pressure that are produced or processed in a way that the primary particles, aggregates, or agglomerates are in size range of 1–100 nm (nm) and exhibit distinctive and novel characteristics or properties due to their size are defined by the US-EPA (Federal Register/Vol. 82, No. 8, 3641, 2017) (Ali et al., 2023). According to ISO/TR 18401:2017, a nanomaterial is defined as A substance that has an internal structure or surface structure at the nanoscale, or any exterior dimension at all, is referred to as a nanomaterial (Trotta et al, 2019).

REACH According to Commission Regulation (EU) 2018/1881, which amends REACH. A nanoform is defined as: According to the Commission's recommendation from October 18, 2011, a nanoform is a natural or artificial material that contains particles, either as an aggregate or in an unbound condition (Allan et al., 2021)The Safe-by-Design (SbD) concept is gaining traction in NT, evident in its integration into numerous EU-funded projects and adoption in the EU Chemical Strategy for Sustainability (Doak et al., 2022; Savolainen et al., 2013). This underscores the increasing acknowledgment and application of SbD as a guiding principle in NT, emphasizing proactive safety measures in developing and implementing nanomaterials. The Advanced Nano GO FAIR Implementation Network 2 (IN) has been established to address the management of nano-safety data. The primary goal of the Advanced Nano IN is to foster data-driven innovation in nanoscience. This objective is closely tied to promoting human health and environmental protection by leveraging machine-enabled reuse of existing safety data. The initiative aims to address the contemporary challenge derived from toxicology in the 21st century, characterized by abundant chemicals and materials (Martens et al., 2021). Several initiatives address bio-concerns in nano-safety, including the EU-funded Nano-Safety Cluster, the OECD's Working Party on Manufactured Nanomaterials (WPMN) (Rasmussen et al., 2016), and the NT Consumer Products Inventory. The Nanomedicine Safety Consortium focuses on the safety of nanomedicines, while the Nano-Safety Research Group contributes to understanding nanomaterial safety.

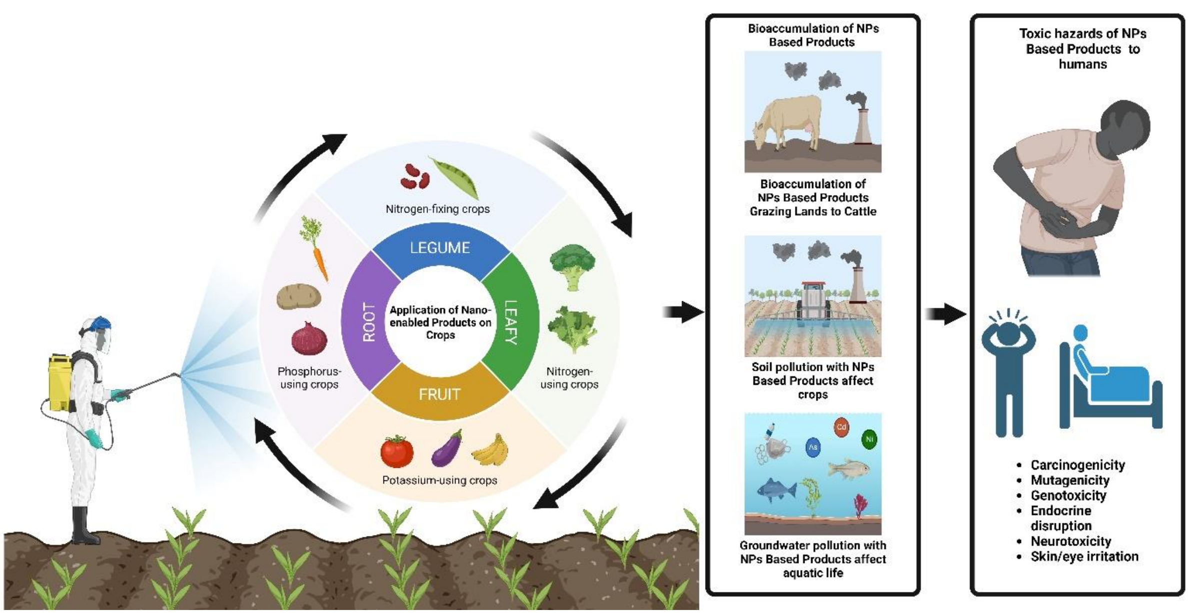

Fig. 5. Application of nano-enabled products can lead to adverse effects such as bioaccumulation and toxicity on human health.

The NanoReg2 project develops testing strategies for regulatory needs (Wang et al., 2017). Additionally, the Woodrow Wilson International Centre's inventory tracks NT in consumer products, and the NT-enabled

Water Treatment Centre addresses water safety concerns (Wang et al., 2017). These efforts collectively aim to ensure the safe development and use of nanomaterials, focusing on bio-related concerns and regulatory requirements.

5. Conclusion

In conclusion, research into nano-enabled products shows they have a wide range of potential uses in agriculture. NT provides numerous options, from creative crop protection strategies to improving soil and encouraging plant development. The field of environmental protection further demonstrates how versatile nanoparticles are in addressing urgent ecological issues. Though the story raises concerns about nanomaterial safety, it also emphasizes the need for continued study and the development of regulatory solid systems. Unleashing NT's full potential in promoting sustainable agriculture and environmental protection involves balancing maintaining safety and fostering innovation.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication

The article contains no such material that may be unlawful, defamatory, or which would, if published in any way whatsoever, violate the terms and conditions as laid down in the agreement.

Availability of data and materials

Not applicable.

Competing interests

The authors declare that they have no conflict of interest in the publication.

Authors' contributions

AS, SR, VDR, TM, SM, ASE, RKS, OS, HER, KG write the original draft and AS, SR, VDR, TM, SM, ASE, RKS, OS, HER, KG edit and finalize the manuscript. All authors read and agree to submit the manuscript to the journal.

Acknowledgment

KG is supported by the Science Committee of the Republic of Armenia, grant number 21AG-4C075 AS is supported by the 23PostDoc-4D007 grant provided by the Science Committee of the Republic of Armenia. VDR acknowledge the financial support of the Ministry of Science and Higher Education of the Russian Federation, agreement no. 075-15-2022-1122).

6. References

Abd-Elsalam, K.A., Al-Dhabaan, F.A., Alghuthaymi, M., Njobeh, P.B., Almoammar, H (2019). Nanobiofungicides: Present concept and future perspectives in fungal control. Nano-Biopesticides Today and Future Perspectives 315–351. https://doi.org/10.1016/B978-0-12-815829-6.00014-0

Afify, R.R., El-Nwehy, S.S., Bakry, A.B. and Abd El-Aziz, M.E., (2019). Response of peanut (*Arachis hypogaea* L.) crop grown on newly reclaimed sandy soil to foliar application of potassium nanofertilizer. Middle East Journal of Applied Sciences, 9(1), 78-85.

Albanese, A., Tang, P.S., Chan, W.C.W., (2012). The Effect of Nanoparticle Size, Shape, and Surface Chemistry on Biological Systems. https://doi.org/10.1146/annurev-bioeng-071811-150124 14, 1–16. https://doi.org/10.1146/ANNUREV-BIOENG-071811-150124

Alengebawy, A., Abdelkhalek, S.T., Qureshi, S.R., Wang, M.Q., (2021). Heavy Metals and Pesticides Toxicity in Agricultural Soil and Plants: Ecological Risks and Human Health Implications. Toxics 2021, Vol. 9, Page 42 9, 42. https://doi.org/10.3390/TOXICS9030042

Allan, J., Belz, S., Hoeveler, A., Hugas, M., Okuda, H., Patri, A., Rauscher, H., Silva, P., Slikker, W., Sokull-Kluettgen, B., Tong, W., Anklam, E., (2021). Regulatory landscape of nanotechnology and nanoplastics from a global perspective. Regulatory Toxicology and Pharmacology 122, 104885. https://doi.org/10.1016/J.YRTPH.2021.104885

Andrić, G.G., Marković, M.M., Adamović, M., Daković, A., Golić, M.P. and Kljajić, P.J., (2012). Insecticidal potential of natural zeolite and diatomaceous earth formulations against rice weevil (*Coleoptera: Curculionidae*) and red flour beetle (*Coleoptera: Tenebrionidae*). Journal of economic entomology, 105(2), pp.670-678.

Arora, S., Sharma, P., Kumar, S., Nayan, R., Khanna, P.K. and Zaidi, M.G.H., (2012). Gold-nanoparticle induced enhancement in growth and seed yield of Brassica juncea. Plant growth regulation, 66, 303-310.

Bala, R., Kalia, A. and Dhaliwal, S.S., (2019). Evaluation of efficacy of ZnO nanoparticles as remedial zinc nanofertilizer for rice. Journal of Soil Science and Plant Nutrition, 19, 379-389.

Bala, R., Kalia, A., Dhaliwal, S.S., (2019). Evaluation of Efficacy of ZnO Nanoparticles as Remedial Zinc Nanofertilizer for Rice. Journal of Soil Science and Plant Nutrition 19, 379–389. https://doi.org/10.1007/S42729-019-00040-Z

Bayda, S., Adeel, M., Tuccinardi, T., Cordani, M., Rizzolio, F., (2020). The History of Nanoscience and Nanotechnology: From Chemical–Physical Applications to Nanomedicine. Molecules 25, 112. https://doi.org/10.3390/MOLECULES25010112

Bhagat, D., Samanta, S.K., Bhattacharya, S., (2013). Efficient Management of Fruit Pests by Pheromone Nanogels. Scientific Reports 3. https://doi.org/10.1038/SREP01294

Bhattacharyya, A., Duraisamy, P., Govindarajan, M., Buhroo, A.A., Prasad, R., (2016). Nano-Biofungicides: Emerging Trend in Insect Pest Control 307–319. https://doi.org/10.1007/978-3-319-42990-8_15

Balaure, P.C., Gudovan, D. and Gudovan, I., (2017). Nanopesticides: a new paradigm in crop protection. In New pesticides and soil sensors (pp. 129-192). Academic Press.

Choudhary, A., Salar, R.K. and Thakur, R., (2024). Synthesis, characterization and insecticidal activity of Mentha spicata essential oil loaded polymeric nanoparticles. Biocatalysis and Agricultural Biotechnology, 55, 102989.

Demirer, G.S., Zhang, H., Goh, N.S., González-Grandío, E., Landry, M.P., (2019). Carbon nanotube–mediated DNA delivery without transgene integration in intact plants. Nature Protocols 2019 14:10 14, 2954–2971. https://doi.org/10.1038/s41596-019-0208-9

Dias, M.C., Santos, C., Pinto, G., Silva, A.M. and Silva, S., (2019). Titanium dioxide nanoparticles impaired both photochemical and non-photochemical phases of photosynthesis in wheat. Protoplasma, 256, pp.69-78.

Dinesh, R., Anandaraj, M., Srinivasan, V., Hamza, S., (2012). Engineered nanoparticles in the soil and their potential implications to microbial activity. Geoderma 173–174, 19–27. https://doi.org/10.1016/J.GEODERMA.2011.12.018

Doak, S.H., Clift, M.J.D., Costa, A., Delmaar, C., Gosens, I., Halappanavar, S., Kelly, S., Pejinenburg, W.J.G.M., Rothen-Rutishauser, B., Schins, R.P.F., Stone, V., Tran, L., Vijver, M.G., Vogel, U., Wohlleben, W., Cassee, F.R., (2022). The Road to Achieving the European Commission's Chemicals Strategy for Nanomaterial Sustainability—A PATROLS Perspective on New Approach Methodologies. Small 18, 2200231. https://doi.org/10.1002/SMLL.202200231

Dwevedi, A., Sharma, J (2018). Production of clean air using combo-technology. Solutions to Environmental Problems Involving Nanotechnology and Enzyme Technology 127–150. https://doi.org/10.1016/B978-0-12-813123-7.00004-9

Eddy, D.R., Ishmah, S.N., Permana, M.D. and Firdaus, M.L (2020). Synthesis of titanium dioxide/silicon dioxide from beach sand as photocatalyst for Cr and Pb remediation. Catalysts, 10(11), 1248.

EID, G.T., (2009). Sizing of a Local Exhaust System in a Furniture Industry, Failure Analysis in a Pressure Vessel (in Portuguese)

El Gamal, A. Y., Atia, M. M., Sayed, T. E., Abou-Zaid, M. I., & Tohamy, M. R., (2022). Antiviral activity of chitosan nanoparticles for controlling plant-infecting viruses. South African Journal of Science, 118(1-2), 1-9.

Elliott, D.W., Zhang, W.X., (2001). Field assessment of nanoscale bimetallic particles for groundwater treatment. Environmental science & technology 35, 4922–4926. https://doi.org/10.1021/ES0108584

El-Temsah, Y.S., Sevcu, A., Bobcikova, K., Cernik, M., Joner, E.J., (2016). DDT degradation efficiency and ecotoxicological effects of two types of nano-sized zero-valent iron (nZVI) in water and soil. Chemosphere 144, 2221–2228. https://doi.org/10.1016/J.CHEMOSPHERE.2015.10.122

Etxeberria, E., Gonzalez, P., Bhattacharya, P., Sharma, P., Ke, P.C (2016). Determining the Size Exclusion for Nanoparticles in Citrus Leaves. HortScience 51, 732–737. https://doi.org/10.21273/HORTSCI.51.6.732

Fan, R., Huang, Y.C., Grusak, M.A., Huang, C.P., Sherrier, D.J (2014). Effects of nano-TiO_2 on the agronomically-relevant Rhizobium–legume symbiosis. Science of The Total Environment 466–467, 503–512. https://doi.org/10.1016/J.SCITOTENV.2013.07.032

Feng, B.H., Peng, L.F. (2012). Synthesis and characterization of carboxymethyl chitosan carrying ricinoleic functions as an emulsifier for azadirachtin. Carbohydrate Polymers 88, 576–582. https://doi.org/10.1016/J.CARBPOL.2012.01.002

Hemathilake, D.M.K.S. and Gunathilake, D.M.C.C (2022). Agricultural productivity and food supply to meet increased demands. In Future foods (pp. 539-553). Academic Press.

Forini, M.M.L., Pontes, M.S., Antunes, D.R., Lima, P.H.C. de, Santos, J.S., Santiago, E.F., Grillo, R (2022). Nano-enabled weed management in agriculture: From strategic design to enhanced herbicidal activity. Plant Nano Biology 1, 100008. https://doi.org/10.1016/J.PLANA.2022.100008

Forján, R., Arias-Estévez, M., Gallego, J.L.R., Santos, E. and Arenas-Lago, D (2024). Biochar-nanoparticle combinations enhance the biogeochemical recovery of a post-mining soil. Science of The Total Environment, 930, 172451.

Gao, Y., Yang, J., Song, X., -, al, Yi Chan, S., Chung Chong, K., Chan Chong, W., Chadha, U., Kumaran Selvaraj, S., Vishak Thanu, S., Cholapadath, V., Mathew Abraham, A., Zaiyan, M.M., Manoharan, M., Paramsivam, V (2022). A review of the function of using carbon nanomaterials in membrane filtration for contaminant removal from wastewater. Materials Research Express 9, 012003. https://doi.org/10.1088/2053-1591/AC48B8

Garg, D., Sridhar, K., Stephen Inbaraj, B., Chawla, P., Tripathi, M., Sharma, M (2023). Nano-Biofertilizer Formulations for Agriculture: A Systematic Review on Recent Advances and Prospective Applications. Bioengineering 10. https://doi.org/10.3390/BIOENGINEERING10091010

Giannousi, K., Avramidis, I., Dendrinou-Samara, C (2013). Synthesis, characterization and evaluation of copper based nanoparticles as agrochemicals against Phytophthorainfestans. RSC Advances 3, 21743–21752. https://doi.org/10.1039/C3RA42118J

Gordillo-Delgado, F., Zuluaga-Acosta, J. and Restrepo-Guerrero, G (2020). Effect of the suspension of Ag-incorporated TiO_2 nanoparticles (Ag-TiO_2 NPs) on certain growth, physiology and phytotoxicity parameters in spinach seedlings. PLoS One, 15(12), p.e0244511.

Gondal, A.H., Bhat, R.A., Gómez, R.L., Areche, F.O., Huaman, J.T (2023). Advances in plastic pollution prevention and their fragile effects on soil, water, and air continuums. International Journal of Environmental Science and Technology 20, 6897–6912. https://doi.org/10.1007/S13762-022-04607-9/METRICS

Gong, Y., Liu, Y., Xiong, Z., Kaback, D., Zhao, D (2012). Immobilization of mercury in field soil and sediment using carboxymethyl cellulose stabilized iron sulfide nanoparticles. Nanotechnology 23. https://doi.org/10.1088/0957-4484/23/29/294007

Gul, I., Manzoor, M., Hashim, N., Yaqoob, K., Kallerhoff, J. and Arshad, M (2019). Comparative effectiveness of organic and inorganic amendments on cadmium bioavailability and uptake by *Pelargonium hortorum*. Journal of soils and sediments, 19, pp.2346-2356.

Hadri, S.H., Afzaal, A., Saeed, L., Arshad, A., Nazeer, S. and Akram, M (2024). Recent Advances in the Development of Nanoparticle Based Fertilizers for Different Kinds of Crops: A Review. Biocatalysis and Agricultural Biotechnology, 103194.

Hu, X., Huang, X., Zhao, H., Liu, F., Wang, L., Zhao, X., Gao, P., Li, X., Ji, P (2021). Possibility of using modified fly ash and organic fertilizers for remediation of heavy-metal-contaminated soils. Journal of Cleaner Production 284, 124713. https://doi.org/10.1016/J.JCLEPRO.2020.124713

Hussain, A., Rehman, F., Rafeeq, H., Waqas, M., Asghar, A., Afsheen, N., Rahdar, A., Bilal, M. and Iqbal, H.M (2022). In-situ, Ex-situ, and nano-remediation strategies to treat polluted soil, water, and air–A review. Chemosphere, 289, p.133252.

Iavicoli, I., Leso, V., Beezhold, D.H., Shvedova, A.A (2017). Nanotechnology in agriculture: Opportunities, toxicological implications, and occupational risks. Toxicol Appl Pharmacol 329, 96–111. https://doi.org/10.1016/J.TAAP.2017.05.025

Ighalo, J.O., Sagboye, P.A., Umenweke, G., Ajala, O.J., Omoarukhe, F.O., Adeyanju, C.A., Ogunniyi, S. and Adeniyi, A.G (2021). CuO nanoparticles (CuO NPs) for water treatment: A review of recent advances. Environmental Nanotechnology, Monitoring & Management, 15,100443.

Jafir, M., Irfan, M., Zia-ur-Rehman, M., Hafeez, F., Ahmad, J.N., Sabir, M.A., Zulfiqar, U., Iqbal, R., Zulfiqar, F., Moosa, A (2023). The global trend of nanomaterial usage to control the important agricultural arthropod pests: A comprehensive review. Plant Stress 10, 100208. https://doi.org/10.1016/J.STRESS.2023.100208

Jeevanandam, J., Barhoum, A., Chan, Y.S., Dufresne, A. and Danquah, M.K (2018). Review on nanoparticles and nanostructured materials: history, sources, toxicity and regulations. Beilstein journal of nanotechnology, 9(1), pp.1050-1074.

Joshua, N.E., Ojha, S.N., Peter, R.M., Gopan, A (2023). Foliar Application of Nano Fertilizer in Agricultural Crops: A Review. Bhartiya Krishi Anusandhan Patrika. https://doi.org/10.18805/BKAP650

Kalidhasan, S., Dror, I., Berkowitz, B (2017). Atrazine degradation through PEI-copper nanoparticles deposited onto montmorillonite and sand. Scientific Reports 2017 7:1 7, 1–13. https://doi.org/10.1038/s41598-017-01429-5

Kang, M.A., Seo, M.J., Hwang, I.C., Jang, C., Park, H.J., Yu, Y.M., Youn, Y.N (2012). Insecticidal activity and feeding behavior of the green peach aphid, Myzuspersicae, after treatment with nano types of pyrifluquinazon. Journal of Asia-Pacific Entomology 15, 533–541. https://doi.org/10.1016/J.ASPEN.2012.05.015

Kannan, G., Sujatha, E.R (2022). A review on the Choice of Nano-Silica as Soil Stabilizer. Silicon 14, 6477–6492. https://doi.org/10.1007/S12633-021-01455-Z

Khanal, U., Wilson, C., Rahman, S., Lee, B.L., Hoang, V.N (2021). Smallholder farmers' adaptation to climate change and its potential contribution to UN's sustainable development goals of zero hunger and no poverty. Journal of Cleaner Production 281, 124999. https://doi.org/10.1016/J.JCLEPRO.2020.124999

Khodakovskaya, M., Dervishi, E., Mahmood, M., Xu, Y., Li, Z., Watanabe, F. and Biris, A.S (2009). Carbon nanotubes are able to penetrate plant seed coat and dramatically affect seed germination and plant growth. ACS nano, 3(10), pp.3221-3227.

Kumar, D., Yadav, M.R., Makarana, G., Rajput, V.D., Biswal, B., Kashyap, S., Kumar, R., Jatav, H.S. and Singh, P (2022). Effects, uptake, translocation and toxicity of Ti-based nanoparticles in plants. In Toxicity of nanoparticles in plants. Academic Press, 211-239.

Kumar, R., Kumar, N., Rajput, V.D., Mandzhieva, S., Minkina, T., Saharan, B.S., Kumar, D., Sadh, P.K., Duhan, J.S (2022). Advances in Biopolymeric Nanopesticides: A New Eco-Friendly/Eco-Protective Perspective in Precision Agriculture. Nanomaterials 12. https://doi.org/10.3390/NANO12223964

Kumar, S., Nehra, M., Dilbaghi, N., Marrazza, G., Hassan, A.A., Kim, K.H (2019). Nano-based smart pesticide formulations: Emerging opportunities for agriculture. Journal of Controlled Release 294, 131–153. https://doi.org/10.1016/J.JCONREL.2018.12.012

Laoufi, I., Saint-Lager, M.C., Lazzari, R., Jupille, J., Robach, O., Garaudée, S., Cabailh, G., Dolle, P., Cruguel, H., Bailly, A (2011). Size and catalytic activity of supported gold nanoparticles: An in operando study during CO oxidation. Journal of Physical Chemistry C 115, 4673–4679. https://doi.org/10.1021/JP1110554/ASSET/IMAGES/MEDIUM/JP-2010-110554_0007.GIF

Dağhan, H., Gülmezoğlu, N., Köleli, N. and Karakaya, B (2020). Impact of titanium dioxide nanoparticles (TiO_2-NPs) on growth and mineral nutrient uptake of wheat (*Triticum vulgare* L.). Biotech Studies, 29(2), pp.69-76.

Lee, C.W., Mahendra, S., Zodrow, K., Li, D., Tsai, Y.C., Braam, J. and Alvarez, P.J (2010). Developmental phytotoxicity of metal oxide nanoparticles to Arabidopsis thaliana. Environmental Toxicology and Chemistry: An International Journal, 29(3), pp.669-675.

Li, Q., Chen, Xijuan, Zhuang, J., Chen, Xin, (2016). Decontaminating soil organic pollutants with manufactured nanoparticles. Environmental science and pollution research international 23, 11533–11548. https://doi.org/10.1007/S11356-016-6255-7

Madhura, L., Singh, S., Kanchi, S., Sabela, M., Bisetty, K., Inamuddin (2018). Nanotechnology-based water quality management for wastewater treatment. Environmental Chemistry Letters 2018 17:1 17, 65–121. https://doi.org/10.1007/S10311-018-0778-8

Malandrakis, A.A., Kavroulakis, N., Chrysikopoulos, C. V (2022). Metal nanoparticles against fungicide resistance: alternatives or partners? Pest Management Science 78, 3953–3956. https://doi.org/10.1002/PS.7014

Mapossa, A.B., Focke, W.W., Tewo, R.K., Androsch, R., Kruger, T (2021). Mosquito-repellent controlled-release formulations for fighting infectious diseases. Malaria Journal 2021 20:1 20, 1–33. https://doi.org/10.1186/S12936-021-03681-7

Martens, M., Stierum, R., Schymanski, E.L., Evelo, C.T., Aalizadeh, R., Aladjov, H., Arturi, K., Audouze, K., Babica, P., Berka, K., Bessems, J., et al. (2021). ELIXIR and Toxicology: a community in development. F1000Research 10. https://doi.org/10.12688/F1000RESEARCH.74502.2/DOI

Merzbacher, C (2020). National Nanotechnology Initiative: A Model for Advancing Revolutionary Technologies 121–133. https://doi.org/10.1007/978-3-030-19951-7_9

Mikhailova, E.O (2020). Silver Nanoparticles: Mechanism of Action and Probable Bio-Application. Journal of Functional Biomaterials 11. https://doi.org/10.3390/JFB11040084

Miola, M., Multari, C., Vernè, E (2022). Iron Oxide-Au Magneto-Plasmonic Heterostructures: Advances in Their Eco-Friendly Synthesis. Materials 15. https://doi.org/10.3390/MA15197036

Mittal, A.K., Chisti, Y., Banerjee, U.C., (2013). Synthesis of metallic nanoparticles using plant extracts. BiotechnolAdv 31, 346–356. https://doi.org/10.1016/J.BIOTECHADV.2013.01.003

Mohamadeen, F.T. and Hassona, N.M (2024). The Activity of Titanium Dioxide Nanoparticles and Its Effect on the Housefly Stages *Musca domastica*. BioNanoScience, 1-9.

Mohamed, I.A.A., Shalby, N., El-Badri, A.M.A., Saleem, M.H., Khan, M.N., Nawaz, M.A., Qin, M., Agami, R.A., Kuai, J., Wang, B., Zhou, G (2020). Stomata and Xylem Vessels Traits Improved by Melatonin Application Contribute to Enhancing Salt Tolerance and Fatty Acid Composition of Brassica napus L. Plants. Agronomy 2020, Vol. 10, Page 1186 10, 1186. https://doi.org/10.3390/AGRONOMY10081186

Mukherjee, A., Peralta-Videa, J.R., Bandyopadhyay, S., Rico, C.M., Zhao, L. and Gardea-Torresdey, J.L (2014). Physiological effects of nanoparticulate ZnO in green peas (*Pisum sativum* L.) cultivated in soil. Metallomics, 6(1), pp.132-138.

Mukhopadhyay, R., Sarkar, B., Khan, E., Alessi, D.S., Biswas, J.K., Manjaiah, K.M., Eguchi, M., Wu, K.C.W., Yamauchi, Y., Ok, Y.S (2022). Nanomaterials for sustainable remediation of chemical contaminants in water and soil. Critical Reviews in Environmental Science and Technology 52, 2611–2660. https://doi.org/10.1080/10643389.2021.1886891

Naderi, M.R., Danesh-Shahraki, A (2013). Nanofertilizers and their roles in sustainable agriculture. International Journal of Agriculture and Crop Sciences (IJACS) 5, 2229–2232.

Nadkarni, MV (2022). Crisis in Indian agriculture: can it be overcome? Journal of Social and Economic Development 24, 228–241. https://doi.org/10.1007/S40847-022-00202-3

Nanotechnology in Agriculture Industry | NPD, (2024). URL https://product.statnano.com/industry/agriculture (accessed 4.5.24).

Nisha Raj, S., Anooj, E.S., Rajendran, K., Vallinayagam, S (2021). A comprehensive review on regulatory invention of nano pesticides in Agricultural nano formulation and food system. J Mol Struct 1239, 130517. https://doi.org/10.1016/J.MOLSTRUC.2021.130517

Noshad, A., Hetherington, C. and Iqbal, M (2019). Impact of AgNPs on seed germination and seedling growth: A focus study on its antibacterial potential against *Clavibacter michiganensis* subsp. michiganensis infection in *Solanum lycopersicum*. Journal of Nanomaterials, 2019(1), p.6316094.

NPD (2024). Nanotechnology Products Database, URL https://product.statnano.com/ (accessed 3.1.24).

Osman, S.A., Salama, D.M., Abd El-Aziz, M.E., Shaaban, E.A. and AbdElwahed, M.S (2020). The influence of MoO3-NPs on agro-morphological criteria, genomic stability of DNA, biochemical assay, and production of common dry bean (*Phaseolusvulgaris* L.). Plant physiology and biochemistry, 151, pp.77-87.

Pan, B., Xing, B., 2012. Applications and implications of manufactured nanoparticles in soils: A review. European Journal of Soil Science 63, 437–456. https://doi.org/10.1111/J.1365-2389.2012.01475.X

Peltonen-Sainio, P., Jauhiainen, L., Laurila, I.P (2009). Cereal yield trends in northern European conditions: Changes in yield potential and its realisation. Field Crops Res 110, 85–90. https://doi.org/https://doi.org/10.1016/j.fcr.2008.07.007

Prasad, R., Bagde, U. S., & Varma, A. (2012). Intellectual property rights and agricultural biotechnology: an overview. Afr J Biotechnol, 11(73), 13746-13752.

Prasad, R., Bhattacharyya, A., Nguyen, Q.D (2017a). Nanotechnology in sustainable agriculture: Recent developments, challenges, and perspectives. Front Microbiol 8, 1014. https://doi.org/10.3389/FMICB.2017.01014/

Prasad, R., Bhattacharyya, A., Nguyen, Q.D., (2017b). Nanotechnology in Sustainable Agriculture: Recent Developments, Challenges, and Perspectives. Frontiers in microbiology 8. https://doi.org/10.3389/FMICB.2017.01014

Punia, P., Bharti, M.K., Chalia, S., Dhar, R., Ravelo, B., Thakur, P. and Thakur, A. (2021). Recent advances in synthesis, characterization, and applications of nanoparticles for contaminated water treatment-A review. Ceramics International, 47(2), 1526-1550.

Rajput, V.D., Singh, A., Minkina, T., Rawat, S., Mandzhieva, S., Sushkova, S., Shuvaeva, V., Nazarenko, O., Rajput, P., Komariah, Verma, K.K., Singh, A.K., Rao, M., Upadhyay, S.K (2021a). Nano-enabled products: Challenges and opportunities for sustainable agriculture. Plants 10. https://doi.org/10.3390/PLANTS10122727

Rajput, V.D., Singh, A., Minkina, T.M., Shende, S.S., Kumar, P., Verma, K.K., Bauer, T., Gorobtsova, O., Deneva, S., Sindireva, A (2021b). Potential Applications of Nanobiotechnology in Plant Nutrition and Protection for Sustainable Agriculture. Nanotechnology in Plant Growth Promotion and Protection 79–92. https://doi.org/10.1002/9781119745884.CH5

Raliya, R. and Tarafdar, J.C (2013). ZnO nanoparticle biosynthesis and its effect on phosphorous-mobilizing enzyme secretion and gum contents in Cluster bean (*Cyamopsis tetragonoloba* L.). Agricultural Research, 2, pp.48-57.

Ramos-Delgado, N.A., Gracia-Pinilla, M., Mangalaraja, R.V., O'Shea, K., Dionysiou, D.D (2016). Industrial synthesis and characterization of nanophotocatalysts materials: titania. Nanotechnology Reviews 5, 467–479. https://doi.org/10.1515/NTREV-2016-0007/ASSET/GRAPHIC/J_NTREV-2016-0007_CV_005.JPG

Regmi, C., Joshi, B., Ray, S.K., Gyawali, G., Pandey, R.P (2018). Understanding Mechanism of Photocatalytic Microbial Decontamination of Environmental Wastewater. Frontiers in Chemistry 6, 331121. https://doi.org/10.3389/FCHEM.2018.00033/BIBTEX

Sadak, M.S (2019). Impact of silver nanoparticles on plant growth, some biochemical aspects, and yield of fenugreek plant (*Trigonellafoenum-graecum*). Bulletin of the National Research Centre, 43(1), pp.1-6.

Saratale, R.G., Saratale, G.D., Shin, H.S., Jacob, J.M., Pugazhendhi, A., Bhaisare, M., Kumar, G (2017). New insights on the green synthesis of metallic nanoparticles using plant and waste biomaterials: current knowledge, their agricultural and environmental applications. Environmental Science and Pollution Research 2017 25:11 25, 10164–10183. https://doi.org/10.1007/S11356-017-9912-6

Savolainen, K., Backman, U., Brouwer, D., Fadeel, B., Fernandes, T., Kuhlbusch, T., Landsiedel, R (2013). Nanosafety in Europe 2015-2025: Towards Safe and Sustainable Nanomaterials and Nanotechnology Innovations. https://www.nanowerk.com/nanotechnology/reports/reportpdf/report159.pdf

Seleiman, M.F., Alotaibi, M.A., Alhammad, B.A., Alharbi, B.M., Refay, Y., Badawy, S.A (2020). Effects of ZnO Nanoparticles and Biochar of Rice Straw and Cow Manure on Characteristics of Contaminated Soil and Sunflower Productivity, Oil Quality, and Heavy Metals Uptake. Agronomy 2020, Vol. 10, Page 790 10, 790. https://doi.org/10.3390/AGRONOMY10060790

Sharma, D., Afzal, S., Singh, N.K (2021). Nanopriming with phytosynthesized zinc oxide nanoparticles for promoting germination and starch metabolism in rice seeds. J Biotechnol 336, 64–75. https://doi.org/10.1016/J.JBIOTEC.2021.06.014

Sharma, P., Sharma, A., Sharma, M., Bhalla, N., Estrela, P., Jain, A., Thakur, P., Thakur, A (2017). Nanomaterial Fungicides: In Vitro and In Vivo Antimycotic Activity of Cobalt and Nickel Nanoferrites on Phytopathogenic Fungi. Global Challenges 1, 1700041. https://doi.org/10.1002/GCH2.201700041

Shelar, G.B. and Chavan, A.M., 2015. Myco-synthesis of silver nanoparticles from Trichodermaharzianum and its impact on germination status of oil seed. Biolife, 3(1), 109-113.

Siddiqi, K.S., Husen, A (2017). Plant Response to Engineered Metal Oxide Nanoparticles. Nanoscale Research Letters 2017 12:1 12, 1–18. https://doi.org/10.1186/S11671-017-1861-Y

Siddiqui, M.H. and Al-Whaibi, M.H (2014). Role of nano-SiO_2 in germination of tomato (*Lycopersicumesculentum* seeds Mill.). Saudi journal of biological sciences, 21(1), pp.13-17.

Singh, A., Agrawal, S., Rajput, V.D., Ghazaryan, K., Movsesyan, H.S., Minkina, T., Al Tawaha, A.R.M., Alexiou, A., Singh, B., Gupta, S.K., (2023a). Seed Nano-priming: An Innovative Approach for Upregulating Seed Germination and Plant Growth Under Salinity Stress. 290–313. https://doi.org/10.4018/978-1-6684-7232-3.CH013

Singh, A., Margaryan, G., Harutyunyan, A., S. Movsesyan, H., Khachatryan, H., Rajput, V.D., Minkina, T., Alexiou, A., Petropoulos, D., Kriemadis, A., El-Ramady, H., Ghazaryan, K (2024a). Advancing Agricultural Resilience in Ararat Plain, Armenia: Utilizing Biogenic Nanoparticles and Biochar under Saline Environments to Optimize Food Security and Foster European Trade. Egyptian Journal of Soil Science 64, 459–483. https://doi.org/10.21608/EJSS.2024.257000.1703

Singh, A., Rajput, V.D., Varshney, A., Ghazaryan, K., Minkina, T (2023b). Small Tech, Big Impact: Agri-nanotechnology Journey to Optimize Crop Protection and Production for Sustainable Agriculture. Plant Stress 10, 100253. https://doi.org/10.1016/J.STRESS.2023.100253

Singh, A., Rajput, V.D., Varshney, A., Sharma, R., Ghazaryan, K., Minkina, T., Alexiou, A., El-Ramady, H., (2024b). Revolutionizing Crop Production: Nanoscale Wonders - Current Applications, Advances, and Future Frontiers. Egyptian Journal of Soil Science 64, 0–0. https://doi.org/10.21608/EJSS.2023.246354.1684

Singh, A., Sengar, R.S., Rajput, V.D., Al-Ghzawi, A.L., Shahi, U.P., Ghazaryan, K., Minkina, T., Al Tawaha, A.R.M., Al Zoubi, O.M., Habeeb, T., (2024c). Impact of Salinity Stress and Zinc Oxide Nanoparticles on Macro and Micronutrient Assimilation: Unraveling the Link between Environmental Factors and Nutrient Uptake. Journal of Ecological Engineering 25, 1–9. https://doi.org/10.12911/22998993/172947

Sivarethinamohan, R., Sujatha, S., (2021). Unlocking the potentials of using nanotechnology to stabilize agriculture and food production. AIP Conf Proc 2327, 020022. https://doi.org/10.1063/5.0039418

Snehal, S., Sc, M.A., Lohani, P., Correspondence, S., Snehal, M., Sc, A., (2018). Silica nanoparticles: Its green synthesis and importance in agriculture. ~ 3383 ~ Journal of Pharmacognosy and Phytochemistry 7, 3383–3393.

Solorzano Toala, R., Gutierrez-Miceli, F., Valdez-Salas, B., Beltran-Partida, E., Gonzalez-Mendoza, D., Tzintzun-Camacho, O., Grimaldo-Juarez, O. and Basilio-Cortes, A., (2024). Biosynthesis of Copper Nanoparticles from Acacia cornigera and Annona purpurea and Their Insecticidal Effect against Triboliumcastaneum. Reactions, 5(2), 274-284.

Steenwerth, K.L., Hodson, A.K., Bloom, A.J., Carter, M.R., Cattaneo, A., Chartres, C.J., Hatfield, J.L., Henry, K., Hopmans, J.W., Horwath, W.R., Jenkins, B.M., Kebreab, E., Leemans, R., Lipper, L., Lubell, M.N., Msangi, S., Prabhu, R., Reynolds, M.P., Sandoval Solis, S., Sischo, W.M., Springborn, M., Tittonell, P., Wheeler, S.M., Vermeulen, S.J., Wollenberg, E.K., Jarvis, L.S., Jackson, L.E., (2014). Climate-smart agriculture global research agenda: Scientific basis for action. Agriculture and Food Security 3, 1–39. https://doi.org/10.1186/2048-7010-3-11/FIGURES/12

Suriyaprabha, R., Karunakaran, G., Yuvakkumar, R., Prabu, P., Rajendran, V. and Kannan, N., (2012). Growth and physiological responses of maize (*Zea mays* L.) to porous silica nanoparticles in soil. Journal of Nanoparticle Research, 14, 1-14.

Tadele, Z., 2017. Raising Crop Productivity in Africa through Intensification. Agronomy 2017, Vol. 7, Page 22 7, 22. https://doi.org/10.3390/AGRONOMY7010022

Talebian, H., Herrera, O.E., Mérida, W., (2021). Policy effectiveness on emissions and cost reduction for hydrogen supply chains: The case for British Columbia. International Journal of Hydrogen Energy 46, 998–1011. https://doi.org/10.1016/J.IJHYDENE.2020.09.190

Usman, M., Farooq, M., Wakeel, A., Nawaz, A., Cheema, S.A., Rehman, H. ur, Ashraf, I., Sanaullah, M., (2020). Nanotechnology in agriculture: Current status, challenges and future opportunities. The Science of the total environment 721. https://doi.org/10.1016/J.SCITOTENV.2020.137778

Usmani, M., Khan, I., Bhat, A., Pillai, R., Ahmad, N., Haafiz, M., Oves, M., (2017). Current Trend in the Application of Nanoparticles for Waste Water Treatment and Purification: A Review. Current Organic Synthesis 14, 206–226. https://doi.org/10.2174/1570179413666160928125328

Vats, S., (2015). Herbicides: History, Classification and Genetic Manipulation of Plants for Herbicide Resistance 153–192. https://doi.org/10.1007/978-3-319-09132-7_3

Venugopal, E., Krishna, S.B.N., Golla, N. and Patil, S.J., (2024). Nanofungicides: A Promising Solution for Climate-Resilient Plant Disease Management. In Plant Quarantine Challenges under Climate Change Anxiety. Cham: Springer Nature Switzerland, 513-532.

Verma, K.K., Song, X.-P., Joshi, A., Rajput, V.D., Singh, M., Sharma, A., Singh, R.K., Li, D.-M., Arora, J., Minkina, T., Li, Y.-R., (2022). Nanofertilizer Possibilities for Healthy Soil, Water, and Food in Future: An Overview. Front Plant Sci 13. https://doi.org/10.3389/FPLS.2022.865048

Vishwakarma, K., Upadhyay, N., Kumar, N., Tripathi, D.K., Chauhan, D.K., Sharma, S., Sahi, S., (2018). Potential Applications and Avenues of Nanotechnology in Sustainable Agriculture. Nanomaterials in Plants, Algae, and Microorganisms 1, 473–500. https://doi.org/10.1016/B978-0-12-811487-2.00021-9

Wang, X., Han, H., Liu, X., Gu, X., Chen, K. and Lu, D., (2012). Multi-walled carbon nanotubes can enhance root elongation of wheat (*Triticum aestivum*) plants. Journal of Nanoparticle Research, 14, 1-10.

Wang, Z., Cheng, J., Qi, B., -, al, Nemet, G.F., Callaghan, M.W., Micheletti, C., Roman, M., Tedesco, E., Olivato, I., Benetti, F., (2017). Implementation of the NANoREG Safe-by-Design approach for different nanomaterial applications. Journal of Physics: Conference Series 838, 012019. https://doi.org/10.1088/1742-6596/838/1/012019

Yassen, A., Abdallah, E., Gaballah, M. and Zaghloul, S., (2017). Role of silicon dioxide nano fertilizer in mitigating salt stress on growth, yield and chemical composition of cucumber (*Cucumis sativus* L.). Int. J. Agric. Res, 22, 130-135.

Yoon, S.J., Kwak, J.I., Lee, W.M., Holden, P.A. and An, Y.J., (2014). Zinc oxide nanoparticles delay soybean development: a standard soil microcosm study. Ecotoxicology and environmental safety, 100, 131-137.

Yu, B., Zeng, J., Gong, L., Zhang, M., Zhang, L., Chen, X., (2007). Investigation of the photocatalytic degradation of organochlorine pesticides on a nano-TiO2 coated film. Talanta 72, 1667–1674. https://doi.org/10.1016/J.TALANTA.2007.03.013

Zafar, S., Akhtar, M., Perveen, S., Hasnain, Z., Khalil, A., (2020). Attenuating the adverse aspects of water stress on wheat genotypes by foliar spray of melatonin and indole-3-acetic acid. Physiology and molecular biology of plants : an international journal of functional plant biology 26, 1751–1762. https://doi.org/10.1007/S12298-020-00855-6

Zhang, W.X., (2003). Nanoscale iron particles for environmental remediation: An overview. Journal of Nanoparticle Research 5, 323–332. https://doi.org/10.1023/A:1025520116015/METRICS

Zhao, F., Xin, X., Cao, Y., Su, D., Ji, P., Zhu, Z. and He, Z., (2021). Use of carbon nanoparticles to improve soil fertility, crop growth and nutrient uptake by corn (*Zea mays* L.). Nanomaterials, 11(10), 2717.

Zheng, M., Huang, Z., Ji, H., Qiu, F., Zhao, D., Bredar, A.R.C., Farnum, B.H., (2020). Simultaneous control of soil erosion and arsenic leaching at disturbed land using polyacrylamide modified magnetite nanoparticles. The Science of the total environment 702. https://doi.org/10.1016/J.SCITOTENV.2019.134997

Ziaee, M., SheikhzadehTakabi, A., Ebadollahi, A., (2023). Fabrication of Carumcopticum essential oil–loaded chitosan nanoparticles and evaluation its insecticidal activity for controlling Rhyzoperthadominica and Triboliumconfusum. Frontiers in Plant Science 14. https://doi.org/10.3389/FPLS.2023.1187616