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Organic and Biogenic Nano-Agri-Inputs in Sustainable Crop Production

A Path to Food Safety and Security

Vishnu D. Rajput • Deepak Kumar
J.C. Tarafdar • Tatiana Minkina
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Chapter 6

Recent Advances in Organic and Nano-Agri-Input Applications for Climate-Resilient Agriculture

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Abstract

The agricultural sector provides food and raw resources to the energy, fabric, medicine, and construction sectors. Recent issues affecting agriculture include changing climates, soil deterioration, shrinking land holdings, growing urbanisation, unsustainable resource use, excessive pesticide usage, declining biodiversity, contaminants in the air, and other grave problems. These problems call for immediate action. As they are complicated, labour-intensive, slow, inefficient, demand a lot of crop nutrients, and are not targeted, conventional agriculture practices are unable to meet these difficulties. A severe threat to the ecology is also posed by the ineffective use of agrochemicals. Therefore, researchers,

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farmers, and decision-makers are always looking for novel ways to address current problems. The future saviour of sustainable agriculture is nanotechnology. Nanosensors have been used in agriculture fields for the detection of chemically hazardous analytes and crop diseases, in addition to precision farming. Additionally, nanotechnology in robotics and barcodes has had a significant impact on agricultural practices to increase agricultural productivity. Furthermore, bioimaging, sensing, photocatalysis, and pesticide distribution are all huge applications of nanotools in agriculture. This chapter carefully examines the various astonishing ways that nanotechnology has been used to get over the constraints of traditional agronomic practices as well as the future applications of nanotechnology in agriculture.

Keywords: organic and nanoagricultural inputs, resilient agriculture, biological control, nanofertilizers and nanopesticides

1. Introduction

By sustainably utilising the natural resources currently at hand through agricultural and animal husbandry processes, climate-resilient farming seeks to boost revenue from farming and productivity over a long period of time. For the food industry to thrive and flourish sustainably, the agriculture industry has consistently been the most reliable and capable sector to serve as the principal supply of raw materials (Khan et al., 2022). The textile, building, pharmaceutical, and energy industries all rely on agriculture for their raw materials and food supplies. Recent years have seen a number of issues that have an impact on agriculture, some of which are alarming and call for immediate action (Yadav et al., 2023). These concerns include things like air pollution, falling land ownership, growing cities, erosion of soil, inappropriate resource use, excessive pesticide usage, and global warming. One of the most challenging problems of the 21st century is how to feed an expanding population while protecting a fragile ecology that is already endangered by climate change. By the time the world population reaches 9 billion people in 2050, predictions indicate that the demand for food will increase from 59 to 98% (Duro et al., 2020). According to the Food and Agriculture Organisation (FAO), by the year 2050, there will be 10 billion people on the planet, which would result in a 50% rise in worldwide hunger, predominantly in developing countries (Usman et al., 2020). Agriculture is greatly influenced by the climate. Temperature, greenhouse gases (CO_2), humidity, accessibility to water, and other elements all have an indirect or direct impact on agricultural development and output. The agricultural ecology is altering due to increased atmospheric CO_2 levels, which also contribute to global warming (Panneerselvam et al., 2019). Climate change-related biotic and abiotic stressors may upset the delicate environmental balance required for food production and potentially result in crop failure (Hussein and Abou-Baker., 2018, Robroek et al., 2017). Innovative and cutting-edge agritechnologies must be deployed to boost plant productivity and ensure the security of the global food supply (Mandal, 2021., Verma et al., 2022). Natural resources are being rapidly depleted by the rapidly growing human population and their consumerist lifestyles, which makes sustainable development challenging. The over-reliance on supplemental irrigation, the level of groundwater depletion, soil degradation, contamination from pesticides and fertilizers, lack of youth interest in agriculture, ineffective current agricultural techniques, etc. are just a few of the issues with modern agriculture (Yadav et al., 2023., Gleick, 2014., Rodell et al., 2009). Researchers are attempting to identify other technologies that can enhance the food supply chain and lessen current food consumption. One of the many promising technologies nowadays is nanotechnology, which can increase crop yields along with effective herbicides, pesticides, nanofertilizers, pesticides, managing soil nutrition, and wastewater remediation (Elsakhawy et al., 2018., Okey-Onyesolu et al., 2021., Yadu et al., 2021, Khan et al., 2022). However, the likelihood of eutrophication of groundwater and surface water bodies has grown due to overuse of pesticides and fertilizers. In the end, the ecosystem’s fundamental integrity has been damaged. In addition, interrupted ecosystem cycles also affect the longevity of living organisms. Serious difficulties with human health have recently arisen because of environmental degradation (Mesnage and Séralini, 2018).

The likelihood of eutrophication of groundwater and surface water bodies has grown due to overuse of pesticides and fertilisers. In the end, the ecosystem’s fundamental integrity has been damaged. In addition, interrupted ecosystem cycles have an impact on how long living things live. Serious difficulties with human health have recently arisen because of environmental degradation (Mesnage and Séralini, 2018). Nanomaterials are employed in agriculture for a variety of purposes, including the creation of biosensors and the nanoformulation of pesticides and fertilisers, the genetic modification of plants and animals to produce desired traits, and the creation of nano plant growth regulators (Singh and Gurjar, 2022). Precision farming and agricultural development are being significantly impacted by new developments in nanotechnology research. With the use of nano-enabled products, agricultural production (i.e., yield) is increased while agrochemical input (herbicides, insecticides, and fertilisers) is reduced (Figure 1).

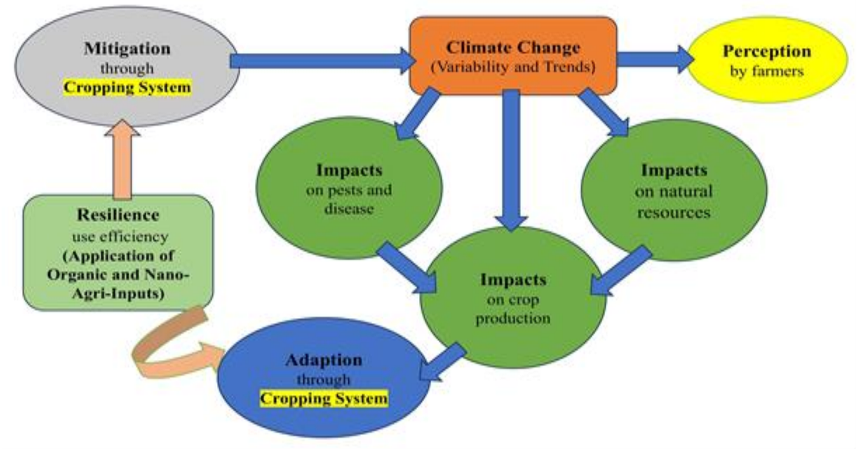

Figure 1. An illustration of how cropping systems affect both adaptation and mitigation of climate change challenges for achieving resilient agriculture by incorporating the application of organic and nano-agricultural inputs (adapted from Debaeke et al., 2017).

2. Farming Methods and Crop Production Practices

2.1. Conventional Methods

Conventional farming practices, the use of synthetic fertilisers and pesticides, excessive consumption of water, the burning of fossil fuels, and the regular cultivation of only a few crops are all short-term fixes. In order for farmers to provide for their families and for the harvest to be available to everyone, food is often produced as inexpensively as possible. On the other hand, traditional farming practices cannot be maintained over time. The nitrogen and chemical content of the fertilised soil deteriorate. There are financial repercussions, a decline in the amount of usable land, an increase in the need for water and energy, and it is not ecologically sound (Gomiero, 2016). These approaches provide the social, environmental, and economic components that are essential for resilient agricultural systems, acting as a solid background for specific NUE strategies (Panhwar et al., 2019).

2.2. Organic Farming for Climate Resilient Agriculture

By definition, organic farming is "*a system that avoids and largely excludes the use of artificial inputs*" (such as chemicals, fertilisers, hormonal substances, additives to livestock feed, etc.), as defined by the United States Department of Agriculture (USDA). By increasing the resilience of agricultural ecosystems, organic farming increases resilience to the negative effects of global warming. It creates farming methods that are efficient, environmentally friendly, and able to cope with drought, temperature changes, and soil erosion. Additionally, it promotes environmentally friendly and environmentally sound administration, restoration efforts, and conservation techniques. Compared to modern agricultural methods, organic farming has a far lower financial requirement (Murmu et al., 2022; Gamage et al., 2023).

2.2.1. Organic Soil Management Practices

The Organic Fertilizer (Compost, Vermicompost etc.) application has long been acknowledged for its substantial influence on soil quality, which includes physical, chemical, and biological factors and ultimately results in increased crop yields (Handreck, 1986). Vermicomposting has become a useful technique in the field of organic farming, where synthetic mineral fertilizers are prohibited (Tomati et al., 1990). It turns waste products into a strong organic fertilizer. Depending on the source, vermicompost has different chemical compositions (Handreck 1986). The fact that VCs from the same waste source may be reliably replicated is important (Tomati et al., 1990). As a nutrient-dense "organic fertilizer," VC boasts high concentrations of micronutrients, helpful rhizospheric microbes, including "nitrogen-fixing bacteria" and "mycorrhizal fungi," as well as plant growth hormones. Importantly, it contains the following critical elements: phosphorus (P) at 1.55-2.25%, potassium (K) at 1.85-2.25%, and nitrogen (N) at 2-3%. Surprisingly, Kale and Bano's (1986) investigation discovered that vermicast from worms can include up to 7.37% N and 19.58% P as P2O5. Furthermore, Atiyeh et al. (2000) discovered that while traditional composts are richer in "ammonium," VC tends to have larger levels of "nitrates," a more easily accessible form of nitrogen essential for robust plant development and output. When added to the soil, VC considerably improves the availability of numerous additional vital growth nutrients, such as phosphorus (P), potassium (K), sulfur (S), and magnesium (Mg), outperforming the benefits of conventional compost (Atiyeh et al., 2000). On a weight basis, VC also shows better nitrogen (N) availability than conventional compost (Atiyeh et al., 2000). The capacity of VC to hold onto nutrients for an extended period of time is another notable characteristic (Subler et al., 1998). This capability ensures a persistent supply of nutrients (macro and micro), such as the essential NKP element, to plants. In conclusion, VCs provide agriculture with a wealth of advantages. They are regarded as valuable alternatives to conventional composts due to a variety of factors, like serving as an abundant resource of organic matter, improving soil moisture retention, facilitating superior nutrient uptake, and exerting effects akin to plant hormones (Tomati et al., 1988, Galli et al., 1990, Suthar, 2010, Table 1).

2.2.2. Crop Rotation Practices

In subsequent growth and seeding cycles, different crops are grown on the same plot of land in a practice known as crop rotation (Arriaga et al., 2017). Both traditional and organic approaches include cropping practices such as intercropping, crop switching, and cover crops, all of which seem to promote the development and activity of microbes. Intercropping, also referred to as polyculture, is the practice of growing two or more crops concurrently on the same piece of land (Lithourgidis et al., 2011). Legumes are often grown in combining arrangements to promote the symbiotic connections between Rhizobia and legumes that lead to the fixation of biological nitrogen (FAO, 2001). Groundnut (Arachis hypogea) and pigeon pea (*Cajanus cajan)* are interplanted in a way that promotes nitrogen fixation (Njira, 2012).

2.2.3. Mulching

The word mulch comes from the German word molsch, which means "*easy to decay,*" and mulches have traditionally been used to boost horticultural crop yields (especially vegetables) (Lightfoot, 1994). Mulching is a method of applying different coverings to the soil's top in order to boost crop production and decrease moisture loss and weed growth (Nalayini, 2007, Kader et al., 2019). According to Rathore et al. (1998), mulches have the power to decrease water runoff, improve soil infiltration, minimise weed development by providing shade, and hinder the transpiration of water. Mulching also improves soil overall health, controls soil and plant root temperature, minimises nutrient losses, prevents soil erosion and compaction, and reduces nutrient losses (Ngouajio and McGiffen, 2004, Lamont, 2005). There are following benefits of the mulching:

Table 1. Mode of action of selected bioinputs that are recommended for resilient agriculture

Name and source of Bioinput	Category	Mode of action	Reference
Plant extracts based biopesticides			
Azadirachta indica extracts	Plant based biopesticide	-antifeedant -growth redressal -target the neurological system of insects through binding with acetylcholine receptors.	Kilani-Morakchi et al., 2021, Michel et al., 2023
Allium sativum extracts	Plant based biopesticide	-non-toxic repellent -obstructs protein and DNA synthesis -caused *repellency* and mortality in different stages of insects -antibacterial and antifungal	Plata-Rueda et al., 2017, Perelló et al., 2013
Tagetes minuta/patula extracts	Plant based biopesticide	-insecticidal activity -effective against hemipteran *pests*	Fabrick et al., 2020, Dunkel et al., 2010
Nepeta nuda subsp. *nuda extract*	Plant based viricide	-prevents virus replication -restricts the release of nucleic acids - avoid virus adsorption	Tondorov et al., 2015
Aloe vera L. extracts	Plant based biopesticides	-antibacterial and antifungal -acarcidal and insecticidal -contact toxicity and ovicidal activity	Karpagam and Devaraj, 2011, Zhang et al., 2013
Microbial biopesticides			
Trichoderma sp.	biofungicide, biofertilizer, biopesticide	-mycoparasitism -antibiosis -synthesis of secondary metabolites -promoting plant defensive mechanism and plant growth -mineral solubilization	Benítez et al., 2004, Asad et al., 2022
Beauveria bassiana	-bioinsecticide	-entomopathogenic -target insect integument through spore penetration -having extracellular hydrolytic enzymes for dissolving the insect cuticle -disables host immune system	Singh et al., 2015, Mannino et al., 2019

Table 1. (Continued)

Name and source of Bioinput	Category	Mode of action	Reference
Metarhizium anisopliae	-bioinsecticide	-entomopathogenic -host body adhesion and spore germination -epicuticle degradation through secreting extracellular hydrolytic enzymes -affect the host immune system	Aw and Hue, 2017, Kim et al., 2020,
Paecilomyces lilacinus	-nematicide	-nematophagous Fungi -antibiosis and parasitism *-parasitizes nematodes' eggs* *-release extracellular hydrolytic enzyme*	Moreno-Gavíra et al., 2020, Lopez-Llorca et al., 2008
Lecanicillium lecanii	-bioinsecticide	-entomopathogenic -target nymphs and adults -adhesion and disruption of epicuticle of host	Abdulle et al., 2021, Xie et al., 2019
Bacillus thuringiensis	-bioinsecticide	-produce parasporal crystals (Cry/cyt crystals) -Lepidoptera insect -binding with host midgut receptors, pore formation and cell lysis	Schünemann et al., 2014, Bravo et al., 2007
Microbial fertilizers (=Biofertilizers)			
Azotobacter sp.	-biofertilizer	-development and growth of plants -atmospheric nitrogen assimilation to ammonia - impede the development of pathogenic fungi	Sumbul et al., 2020, Aasfar et al., 2021
Rhizobium sp.	-biofertilizer	-overall plant growth -induce nodulation in leguminous plant -nodules fix the atmospheric nitrogen to ammonia	Jaiswal et al., 2021, Purwaningsih et al., 2021
Azospirilium sp.	-biofertilizer	-nitrogen fixation -produce plant growth hormones like IAA, GA3, and polyamine and trehalose production	Cruz-Hernández et al., 2022, Fukami et al., 2018

Name and source of Bioinput	Category	Mode of action	Reference
Bacillus sp.	-biofertilizer	-mineral solubilization (P, K, Zn, Fe) -produce phytohormones (IAA, GA3, ammonia) -overall plant growth	Hashem et al., 2019, Gohil et al., 2022
Vesicular-arbuscular mycorrhizae	-biofertilizer	-mineral solubilization and *increased intake of nutrients* *-resistance to disease* *-resilience to stress*	Begum et al., 2019 Sharma et al., 1992

- Mulching Improves Soil Fertility: In order to define and/or improve soil quality and achieve optimal yields for each soil and climate condition, having an understanding of the physical attributes of soil is crucial. This assumes that the soil must be kept in an ecological state that allows for adequate crop growth in order to increase agricultural production. Even when every other prerequisite is met, a crop's genetic yield potential cannot be realised unless the soil's physical environment is kept at its optimal level. Without a doubt, if these soils are adequately managed for physical health, the yield potential of many crops can be greatly boosted.
- Soil Temperature: The hue of the plastic mulch affects the ambient temperature of the soil underneath it, which is frequently high. The black plastic-film mulched plots' soil temperatures were significantly lower (1 to 2.8 °C) than those of the transparent plastic-film mulched plots. In contrast to plots with plastic film mulch, a significant amount of the direct sunlight that black plastic film mulch captures into the atmosphere is lost to irradiation and generated convection (Schales et al., 1990). According to Anikwe et al. (2007), and without mulched plots showed the coolest soil temperatures (about 1-3.8 °C lower) at different times after planting. By altering the heat balance, plastic film mulching, among several mulching techniques, elevates the soil's surface temperature, which in turn elevates the temperature of the soil and favourably influences crop emergence (Anikwe et al., 2004).
- Nutrient Availability: The decomposition of organic remnants under plastic mulch causes the release of organic acids into the soil, which reduces soil pH and may improve the accessibility of minerals including Zn, Mn, Cu, and Fe. The increased levels of Fe and Zn in the soil underneath the plastic mulch provided additional support for this (Tisdale et al., 1990). The soil has a high mineral N content (NO_3 and NH^{4+}) because organic nitrogen gradually mineralizes over time, increasing the soil's availability of nitrogen. Fulvic acid, NH^{4+}, NO^{3+}, Ca^{2+}, and Mg^{2+} are among the soluble minerals that are made more readily available to the soil under plastic mulch by the decomposition of organic material.

2.3. Biological Control of Insect Pest and Diseases

The use of living organisms to minimise the effects of insect populations and the damage that they might be causing is referred to as "biological control." This method is flexible and effective for eradicating a range of pests, including insects, weeds, diseases, and animals. Nevertheless, depending on the kind of pest at hand, different methods and substances are used. Our main area of interest in this article is biological management of insects and related species. Predators, parasitoids, and diseases are the three main groups of natural enemies that target insect pests (Stoner, 1998).

- Predators: In their search for food, a wide variety of predators feed on insects. There are several vertebrates among the ranks of these insect-hungry species, such as birds, reptiles, amphibians, fish, and mammals. In general, insectivorous vertebrates have a wide range of diets and hardly ever focus on pest species unless they are extremely prevalent. Because they have a more limited range of food and shorter life cycles than other arthropod predators, which allow them to adapt to changes in prey density, insect and other arthropod predators take centre stage when discussing biological control. These include ground beetles (Pterostichus nigra), lady beetles (Coccinella septempunctata), rove beetles (Staphylinidae), flower bugs (Orius insidiosus), various predatory true bugs, lacewings, and hoverflies, among other important insect predators.
- Parasitoids: A particular type of insects called parasitoids, they have a life cycle that starts with an embryonic stage that dwells inside or on a single insect host and concludes with the host's mortality. Adults in this group generally live autonomous lives and may even act as predators. They may also consume food from unorthodox sources such as pollen, honeydew, or plant nectar. Because they can only live on a small number of different types of hosts, parasitoids are only as specialized as their ability to adapt to their physiology, life cycle, and defence mechanisms. Therefore, when using parasitoids strategically for biological control, precise identification of both host and parasitoid species is crucial.
- Pathogens: Similar to other members of the animal and plant kingdoms, insects are vulnerable to a variety of microorganisms that can cause disease, including bacteria, fungi, protozoans, and viruses.

These conditions may present in a variety of ways, like a reduction in feeding and growth rates of insect pests, a loss in the ability to reproduce, or outright death. In addition, insects must struggle with nematode species, which frequently have bacterial symbionts and cause illnesses or even death in their hosts. These illnesses can spread naturally through an insect population under specific environmental circumstances, especially when insect populations rise.

2.4. Organic Management of Insect Pests and Diseases

The alternatives for controlling pests and diseases in organic farming mainly rely on preventive measures as opposed to curative treatments, which are based on management techniques that are more environmentally friendly. Maintaining the ecosystem's health has been prioritized in order to help plants develop resistance to pests and illnesses. The wide oversight of the ecosystem by minor alterations in cultural practices, such as rotation of crops and the management of the soil's quality through the introduction of organic amendments, serves as the initial line of defence against insect pests and diseases. Using curative strategies such as parasitoids, predators, herbal remedies, and environmentally friendly pesticides is the next line of defence against insect pests and diseases (Haldhar et al., 2017).

2.4.1. Plant Extract-Based Pesticides

Botanical insecticides are plant-derived substances that deter, prevent the growth of, or eliminate pests. Some plant-based insecticides are covered under the plant-based pesticide (Hikal et al., 2017). The extracts from *T. minuta* and *Carica papaya L.* were the most effective at reducing the number of aphids and they damaged the foliage in some way. This might be due to the numerous insecticidal elements included in these plant products (Murovhi et al., 2020). Aphids, whiteflies, and spotted bollworms are a few of the nuisance insects that feed on plants and are harmed by the cysteine protease enzymes in the *C. papaya* leaf extract, which also contain papain, terpenoids, flavonoids, alkaloids, and non-protein amino acids (Ahmed, 2018). Insect pests can be controlled by using *T. minuta* leaf extracts, which include a number of insecticidal compounds like phenylpropanoids, phototoxin alphaterthieenyl, carotenoids, thiophenes, and flavonoids. According to Dunkel (2010), azadirachtin has a number of diverse modes of action, including those that suppress fertility, have detrimental effects on morphology, alter biological fitness, suppress fecundidad, limit growth, deter the oviposition process, and even disinfect (Zhang and Boulahbel, 2015). Azadirachtin had negative metamorphosis effects on *S. frugiperda*, *D. melanogaster*, and *Callosobruchus maculatus*, including slowing down the stage of pupation time and impairing progression from larva to pupa (Lai et al., 2014, Asaduzzaman et al., 2016).

2.4.2. Integrated Pest Management

An efficient and responsible method of managing pests is integrated pest management (IPM) (Kabir and Rainis, 2015). Beneficial insects are protected, and subsequent pest outbreaks, pest comeback, and disease transmission are also prevented. IPM techniques seek to achieve certain production goals while preserving air, water, and soil resources (Mangan and Mangan, 1998, National Pesticides Information Center in the USA, 2015). IPM integrates the use of several pest-management techniques into an approach that promotes the biological suppression of pests in crops with the goal of enhancing financial, public-health, and ecological outcomes. Successful IPM techniques must include the monitoring of populations of pests, the identification of pest-resistant plant varieties, and the modification of mechanical, cultural, chemical, and biological measures as required to meet production goals (Adams, 1996). IPM strategies must take into consideration farmers' present agricultural practices, their previous involvement in a certain agro-ecosystem, and their longstanding agricultural experience with life cycles and insect behaviour (Petit et al., 2003, Roitberg, 2007, Vinatier et al., 2012).

3. Nano Agri Inputs for Climate-Resilient Agriculture

By encapsulating plant nutrients in nanoparticles, applying a thin layer of nanomaterials to the nutrients for plants, and dispersing them as nano-sized emulsions, nanofertilizers are created. Higher nutrient utilization efficiency (NUE) is made possible by the penetration of nanomaterials deep inside plant leaves through nanopores and stomatal apertures. The delivery of nutrients from nanofertilizers to cells is facilitated by plasmodesmata, which are 50–60 nm-wide nanoscale channels between cells. Field crops had higher yield (6-17%) and better nutritional quality thanks to nanofertilizers' higher NUE and noticeably lower nutrient losses. However, the main problems preventing their widespread use as plant nutrient sources are their manufacture and availability, their adequate effectiveness in law, and associated risk management. There have been reports of various fertilizer inputs being downsized into smaller parts. In a separate formulation, ground urea was combined with several biofertilizers to create a potent nanofertilizer that delivers nutrients progressively over time (Wang et al., 2013). Ammonium humate, peat, and other synthetic components were combined in a similar manner to create nanosized fertilizers. In order to produce these nanofertilizers, a mechanical and biochemical process is required. First, materials are crushed mechanically into nanosized particles, and then biochemical techniques are applied to produce effective nanoformulations (Table 2). Additionally, nanosized colloids are being added to emulsions in order to create nano-emulsions (Taiz and Zeiger, 2010). In conclusion, encapsulating fertilisers with nanoparticles creates a range of opportunities for producing crop nutrients with improved absorption and nutrient usage efficiency. Plant nutrients can be enclosed within nanoparticles of various natures and chemical compositions in one of three ways, i.e., (i) the use of nanoparticles to encapsulate nutrients. (ii) It's possible for nutrient particles to have a fine coating of nanoparticles, such as polymer films. (iii) The delivery of nutrients can also take place through the use of emulsions and nanoparticle-sized particles.

3.1. Role of Nanotechnology in Agriculture

Nanotechnology is one of the potential fields for boosting food production and developing new goods for usage in farming, nutrition, water supply, surroundings, health care, fuel, and electronics. In terms of agriculture and food research, it is a burgeoning and constantly expanding territory with novel and distinctive applications (Sadeghi et al., 2017). The greatest solution may be to increase productivity and decrease postharvest costs through better results supported by more recent technological studies using nanotechnology and biotechnology in food products (Yadollahi et al., 2010). In a few crucial areas, such as the decrease of chemical spread, the lowering of nutrient losses during fertilisation, and the improvement of yield through pest and nutrient management, nanomaterials are being used more frequently in agriculture (Prasad et al., 2017a). Some of the recent advances in food-related nanotechnology can be greatly enhanced in the areas of intelligent nutrient delivery, quick sampling of pollutants, nanoencapsulation of dietary supplements, emulsification, and delivery (Ravichandran, 2010, Sozer and Kokini, 2009).

Table 2. Some of the commercial nano-agricultural input products available in the global market

Trade name	Nutrient / Pesticidal active ingredient/ Mode of action	Formulation composition related information	Industry	Country
Nanofertilizers				
TAG Nano Phos	P	Proteino-lacto-gluconate chelated	Tropical Agrosystem India (P). Ltd	India
TAG Nano Zinc	Zn			
TAG Nano Potash	K			
TAG Nano NPK	N, P, K			
IFFCO NanoDAP	P	Biogenic synthesized nanoformulations	IFFCO	India
IFFCO Nano Ura	N			
Nano-Ag Answer®	NPK	Blends of sea kelp, microorganisms, and mineral electrolytes	Urth Agriculture	USA
Nano Calcium	Ca	-	AC International Network Co. Ltd.	Germany
Nanopesticides				
NANO TRACER	Inhibition of synthesis as well as release of moulting hormones from prothoracic glands	Combination of herbal and organic extracts	Annadata Organic	India
Nanofungicides				
Knockout Nano	Nano copper	-	Zeal Biologicals	India
NANOCU	Nano copper	-	Bio Nano Technology	Egypt

Food nanotechnology involves the use of nanocarrier techniques to improve bioactive substances and change their biological accessibility and barriers against various chemical or environmental variations (Mozafari et al., 2008). It improves food consistency and induces better sensory qualities such as colour, flavour, and texture (Kalita and Baruah, 2019). Additionally, it enhanced the biological comfort and enticement of both medication delivery methods (Safari and Zarnegar, 2014) and nutraceuticals (Jafari and McClements, 2017). Nanotechnology benefits the food sector by creating novel food packaging materials with improved fencing, mechanical, and antibacterial qualities (Mustafa and Andreescu, 2020, Rossi et al., 2017, Duncan, 2011). The capacity to encapsulate food additives or modifiers, monitor the state of the diet throughout transportation and storage, and apply sensors for detecting traces using nanotechnology were some additional advantages of the technique (Chaudhry et al., 2008).

3.1.1. Nano Fertilizer

Nanofertilisers are divided into three subcategories: nanoscale coatings, nanoscale additives, and nanoscale fertilisers (Mikkelsen, 2018). The interaction of three different elements causes nutrients that are physiologically, biologically, and chemically enclosed inside a specific nanocarrier to release. The coating, which is made of a biodegradable or artificial polymeric substance, is biodegraded by fungi, bacteria, and other microorganisms, liberating and absorbing minerals in the soil. Moisture, pH variation, solubilization, type of soil, and ionic exchange reactions are a few of the chemically driven processes (Ramzan et al., 2020, Ribeiro and Carmo, 2019, Weeks and Hettiarachchi, 2019). The physical components are magnetic, ultrasonic, field, heat, and diffusion-controlled release. Since nanostructured 2D clays are ionic systems containing anions and cations that balance each other out to create neutrality, they can be seen as strong options for carrying nutrients (Lazaratou et al., 2020). Clays have high ion exchange rates, an ionic composition, and the capacity to host a wide variety of both inorganic and organic ions (Mikkelsen 2018, Ribeiro and Carmo, 2019).

3.1.2. Pest Control through Nanopesticides

In order to boost agricultural productivity, nanotechnology reduces chemical doses and offers novel agrochemicals and distribution techniques. The agrochemicals on hand efficiently increase crop productivity and control pests and illnesses. However, a sizeable level of affectivity and haphazard application are required (Khan et al., 2017). By encapsulating, coating, etc., the use of nanotechnology aims to reduce the dose of agrochemicals (Ayyaril et al., 2023). Insect pest prevention and control are possible with the use of engineered nanomaterials (ENM). A different application of nanotechnology is nano-encapsulation, which has a number of appealing qualities, such as controlled release, increased efficacy, prolonged residual amounts, and the absence of organic carriers (Hack et al., 2012). Encapsulation formulations, which use lower doses than traditional pesticides to accomplish full effect and more intense pesticide activity, have transformed the way pesticides are applied as a result of the advent of nanoscience in the control of insect pests. The main component (pesticide) is encapsulated and wrapped in a capsulation substance or casing during this procedure, which causes the pesticide to shrink in size to a nanosize. Nanogenic preparations with ENM can improve the active ingredient's penetrability, stability, ability to dissolve, and precisely controlled release properties for target species in traditional herbicides and insecticides by utilising nano-emulsification and nanoencapsulation (Adisa et al., 2019). Limiting adverse effects on non-target creatures and the surrounding environment is possible by minimising the amount of material discharged into the system (Yin et al., 2018). By improving the accuracy and precision of the delivery of active ingredients, such as nanofertilizers and antimicrobials, this can be accomplished. In order to react to the targeted tissues, nanoparticles' size, shape, and orientation are controlled by the atomic structure (Baig et al., 2021). Exceptional strength, great chemical reactivity, and high conductivity are only a few of the unique characteristics of nanoparticles (Baig et al., 2021). Biopesticides made from controlled-release formulations of various nanoparticles, including nanospheres, nanocapsules, nanogels, and mcielles, are employed (Ragaei and Sabry 2014, Harish et al., 2022).

In order to increase crop output, nano-sized particles with certain qualities are used in farming. Nano-encapsulation is a different use of nanotechnology that offers a variety of enticing properties, including controlled release, greater efficiency, prolonged residual levels, and the elimination of organic solvents (Hack et al., 2012). The application of pesticides has been transformed by encapsulation formulations, which require lower dosages than traditional pesticides to have a full effect and more targeted pesticide activity. This process involves shrinking the pesticide to a nanosize and encasing the active ingredient (the pesticide) in a coating or shell (Batsmanova et al., 2013; Scott and Chen, 2013).

Scott and Chen (2013) and Batsmanova et al. (2013) both claim that nano-agriculture uses microscopic particles to boost crop productivity. Nano-encapsulation, a branch of nanotechnology, has advantages including controlled release, greater efficacy, longer residual concentrations, and reduced human exposure to active chemicals (Hack et al., 2012). As its pesticide activity is tailored, this method aids in dose reduction. Nanotechnology helps the agricultural industry with product production, storage, packaging, and delivery. Effective slow-release herbicides built on nanotechnology are required for precision farming (Harish et al., 2022). By ensuring the right number of agrochemicals is utilised, controlled delivery systems throughout time reduce losses and environmental harm (Shojaei et al., 2019). Nano-based systems increase solubility, reduce pesticide use, extend validity, boost bio-efficacy, and safeguard non-target species (John et al., 2017; Anjali et al., 2012). Carbon nanotubes can enhance crop yields and seed efficiency, as well as regulate plant growth (Zheng et al., 2005; Khodakovskaya et al., 2013). Nano-agriculture offers prospective opportunities across the board.

Conclusion

Sustainable agriculture is based on organic farming practices, which eliminate synthetic chemicals and place an emphasis on natural processes. The benefits of organic inputs in terms of soil health, biodiversity preservation, and less environmental impact in comparison to conventional farming practices may be highlighted in the conclusion. By providing tailored delivery systems for nutrients, insecticides, and other agricultural inputs, nanotechnology has demonstrated promise in the agriculture industry. The discussion of how nanomaterials can improve nutrient use efficiency, lessen environmental contamination, and increase crop yields under difficult environmental circumstances may be included in the conclusion. The significance of these cutting-edge agri-inputs in enhancing climate resilience in agricultural systems may be emphasised in the study. This could include methods for coping with weather extremes, water shortages, and the shifting dynamics of diseases and pests. The research findings may shed information on the potential of organic and nano-agricultural inputs to lessen agriculture's environmental impact. This may entail cutting back on greenhouse gas emissions, reducing chemical runoff, and protecting natural habitats. The economic feasibility of implementing these technologies may also be covered in the conclusions. This can entail analyses of the costs and advantages of switching to organic farming methods or integrating nano-agri-inputs into current systems. Scientific articles frequently identify topics that require more investigation. The conclusion could indicate unresolved issues or locations where further research could yield insightful data. The conclusion could have potential policy implications, depending on the research's primary topic. This can include suggestions for decision-makers on how to encourage the use of agricultural practices that are climate-resilient.

References

Aasfar, A., Bargaz, A., Yaakoubi, K., Hilali, A., Bennis, I., Zeroual, Y., Meftah Kadmiri, I. (2021). Nitrogen fixing Azotobacter species as potential soil biological enhancers for crop nutrition and yield stability. *Front. Microbiol*. 12: 628379. https://doi.org/10.3389/fmicb.2021.628379.

Abdulle, Y. A., Nazir, T., Sayed, S., Mahmoud, S. F., Majeed, M. Z., Aslam, H. M. U., Iqbal, Z., Nisar, M. S., Keerio, A. U., Ali, H., Qiu., D. (2021). Sub-lethal effects of *Lecanicillium lecanii* (Zimmermann)-derived partially purified protein and its potential implication in cotton (*Gossypium hirsutum* L.) defence against *Bemisia tabaci* Gennadius (Aleyrodidae: Hemiptera). *Agriculture.*, 11: 778. https://doi.org/10.3390/agriculture11080778.

Adams, R. G. (1996). Introduction to integrated pest management. In: Adams, R. G. and Clark, J. C. (eds)., Northeast sweet corn production and integrated pest management manual. *University of Connecticut Cooperative Extension.*, pp: 120.

Anikwe M. A. N., Mbah C. N., Ezeaku P. I. and Onyia V. N. (2007). Tillage and plastic mulch effects on soil properties and growth and yield of cocoyam (*Colocasia esculenta*) on an ultisol in southeastern Nigeria. *Soil and Tillage Research*., 93: 264–272.

Anikwe, N. L., Okereke, O. U. and Anikwe, M. A. N. (2004). Modulating effect of black plastic mulch on the environment, growth and yield of cassava in a derived savannah belt of Nigeria. *Tropicultura*., 22: 185-190.

Arriaga, F. J., Guzman, J., Lowery, B. (2017). Conventional agricultural production systems and soil functions. *Soil Health Intensif. Agroecosytems*. 1: 109–125.

Asad, S. A. (2022). Mechanisms of action and biocontrol potential of *Trichoderma* against fungal plant diseases - A review. *Ecological Complexity*. 49: 100978. https://doi.org/10.1016/j.ecocom.2021.100978.

Asaduzzaman, M., Shim, J. K., Lee, S., Lee, K. Y. (2016). Azadirachtin ingestion is lethal and inhibits expression of ferritin and thioredoxin peroxidase genes of the sweet potato whitefly. *Bemisiatabaci*. *J. Asia-Pac. Entomol.*, 19: 1–4.

Atiyeh, R. M., Arancon, N. Q., Edwards, C. A, and Metzger, J. D. (2000). Influence of earthworm-processed pig manure on the growth and yield of greenhouse tomatoes. *Bioresource Technology*., 75: 175-180.

Aw, K. M. S., Hue, S. M. (2017). Mode of infection of Metarhizium spp. fungus and their potential as biological control agents. *J Fungi* (Basel). 3(2): 30. https://doi.org/10.3390/jof3020030.

Begum, N., Qin, C., Ahanger, M. A., Raza, S., Khan, M. I., Ashraf, M., Ahmed, N., Zhang. L. (2019). Role of arbuscular mycorrhizal fungi in plant growth regulation: Implications in abiotic stress tolerance. *Front. Plant Sci*., 10: 1068. https://doi.org/10.3389/fpls.2019.01068.

Benítez, T., Rincón, A. M., Limón, M. C., Codón, A. C. (2004). Biocontrol mechanisms of Trichoderma strains. Int Microbiol., 4: 249-260.

Boulahbel, B., Aribi, N., Kilani-Morakchi, S., Soltani, N. (2015). Insecticidal activity of azadirachtin on *Drosophila melanogaster* and recovery of normal status by exogenous 20-hydroxyecdysone. *Af*rican *Entomol*ogy., 23(1): 224–233. https://doi.org/10.4001/003.023.0104.

Bravo, A., Gill, S. S., Soberón, M. (2007). Mode of action of Bacillus thuringiensis Cry and Cyt toxins and their potential for insect control. Toxicon., 49(4): 423-35.

Chaudhry, Q., Scotter, M., Blackburn, J., Ross, B., Boxall., A., Castle, L., Aitken, R., Watkins, R. Applications and implications of nanotechnologies for the food sector. Food Addit Contam Part A Chem Anal Control Expo Risk Assess., 25(3): 241-258.

Craig, T. (2015). The rise and demise of integrated pest management in rice in Indonesia. *Insects*., 6(2): 381–408. https://doi.org/10.3390/insects6020381.

Cruz-Hernández, M. A., Mendoza-Herrera, A., Bocanegra-García, V., Rivera, G. (2022). *Azospirillum* spp. from Plant Growth-Promoting Bacteria to Their Use in Bioremediation. *Microorganisms*. 10(5): 1057. https://doi.org/10.3390/microorganisms10051057.

Debaeke, P., Pellerin, S., Scopel, E. (2017). Climate-smart cropping systems for temperate and tropical agriculture: mitigation, adaptation and trade-offs. *Cah. Agric.*, 26: 34002. https://doi.org/10.1051/cagri/2017028.

Duncan, T. V. (2011). Applications of nanotechnology in food packaging and food safety barrier materials, antimicrobials and sensors. *Journal of Colloid and Interference Science*., 363(1): 1-24. https://doi.org/10.1016/j.jcis.2011.07.017.

Dunkel, F. V., Jaronski, S. T., Sedlak, C. W., Meiler, S. U., Veo, K. D. (2010). Effects of steam-distilled shoot extract of *Tagetes minuta* L. (Asterales: Asteraceae) and entomopathogenic fungi on larval *Tetanops myopaeformis*. *Environmental Entomology*., 39(3): 979–988. https://doi.org/10.1603/EN09259.

Duro, J. A., Lauk, C., Kastner, T., Erb, K. H., Haberl, H. (2020). Global inequalities in food consumption, cropland demand and land-use efficiency: a decomposition analysis. *Global Environmental Change*., 64: 102124. https://doi.org/10.1016/j.gloenvcha.2020.102124.

Elsakhawy, T., Omara, A. E. D., Alshaal, T., El-Ramady, H. (2018). Nanomaterials and plant abiotic stress in agroecosystems. *Environment, Biodiversity and Soil Secur*ity., 2: 73–94.

Fabrick, J. A., Yool, A. J., Spurgeon, D. W. (2020). Insecticidal activity of marigold Tagetes patula plants and foliar extracts against the hemipteran pests, Lygus hesperus and Bemisia tabaci. *PLoS One*., 15(5): e0233511. https://doi.org/10.1371/journal.pone.0233511.

Feyisa, B., Lencho, A., Selvaraj, T., Getaneh, G. (2015). Evaluation of some botanicals and *Trichoderma harzianum* for the management of tomato root-knot nematode (*Meloidogyne incognita* (Kofoid and White) Chit Wood). *Adv. Crop Sci. Technol*., 4(1): 201.

Food and Agricultural Organization of the United Nations (FAO) (2001). The economics of conservation agriculture. *FAO corporate documents repository*. Retrieved on August 17, 2023. https://www.fao.org/3/Y2781E/y2781e06.htm.

Fukami, J., Cerezini, P., Hungria, M. (2018). *Azospirillum*: benefits that go far beyond biological nitrogen fixation. *AMB Expr*, 8: 73. https://doi.org/10.1186/s13568-018-0608-1.

Galli, E., Tomati, U., Grappelli, A., Di Lena, G. (1990). Effect of earthworm casts on protein synthesis in *Agaricus bisporus*. *Biology and Fertility of Soils*. 9: 290-291. https://doi.org/10.1007/BF00634103.

Gamage, A., Gangahagedara, R., Gamage, J., Jayasinghe, N., Kodikara, N., Suraweera, P., Merah, O. (2023). Role of organic farming for achieving sustainability in agriculture. *Farming System*., 1(1): 100005. https://doi.org/10.1016/j.farsys.2023.100005.

Gohil, R. B., Raval, V. H., Panchal, R. R. and Rajput, K. N. (2022). Plant growth-promoting activity of Bacillus sp. PG-8 isolated from fermented Panchagavya and its effect on the growth of Arachis hypogea. *Front. Agron.* 4: 805454. https://doi.org/10.3389/fagro.2022.805454.

Gomiero, T. (2016). Soil Degradation, Land Scarcity and Food Security: Reviewing a Complex Challenge. *Sustainability*., *8*(3): 281. https://doi.org/10.3390/su8030281.

Grdiša, M. and Gršić, K. (2013). Botanical insecticides in plant protection. *Agric. Conspect. Sci*., 2: 85-93.

Hack, B., Egger, H., Uhlemann, J., Henriet, M., Wirth, W., Vermeer, A. W. P., and Duff, D. G. (2012) Advanced agrochemical formulations through encapsulation strategies. *Chem Ing Tech*. 84: 223–234.

Haldhar, S. M., Jat, G. C., Deshwal, H. L., Gora, J. S. and Singh, D. (2017). Insect pest and disease management in organic farming., In: Gangwar, B., Jat, N. K. (Eds.)., *Towards Organic Agriculture*., 359-390.

Harish, V., Tewari, D., Gaur, M., Yadav, A. B., Swaroop, S., Bechelany, M., Barhoum, A. (2022). Review on nanoparticles and nanostructured materials: Bioimaging, biosensing, drug delivery, tissue engineering, antimicrobial, and agro-Food applications. *Nanomaterials*., 12(3): 457. https://doi.org/10.3390/nano12030457.

Hashem, A., Tabassum, B., Abd-Allah, E. F. (2019). Bacillus subtilis: A plant-growth promoting rhizobacterium that also impacts biotic stress. *Saudi J Biol Sci*. 26(6):1291-1297. https://doi.org/10.1016/j.sjbs.2019.05.004.

Hussein, M. M., Abou-Baker, N. H. (2018). The contribution of nano-zinc to alleviate salinity stress on cotton plants. *R. Soc. Open Sci*., 5(8): 171809. https://doi.org/10.1098/rsos.171809.

Jafari, S. M., McClements, D. J. (2017). Nanotechnology approaches for increasing nutrient bioavailability *Adv. Food Nutr. Res*., 81: 1-30. https://doi.org/10.1016/bs.afnr.2016.12.008.

Jaiswal, S. K., Mohammed, M., Ibny, F. Y. I., Dakora, F. D. (2021). Rhizobia as a source of plant growth-promoting molecules: Potential applications and possible operational mechanisms. *Front. Sustain. Food Syst*. 4: 619676. https://doi.org/10.3389/fsufs.2020.619676.

Kabir, M. H., and Rainis, R. (2015). Do farmers not widely adopt environmentally friendly technologies? Lesson from Integrated Pest Management (IPM). *Modern Appl. Sci*., 9(3): 208–215.

Kader, M. A., Singha, A., Begum, M. A., Jewel, A., Khan, F. H. and Khan, N. I. (2019). Mulching as water-saving technique in dry land agriculture. *Bulletin of the National Research Centre*., 43:1–6.

Kale, R. D. and Bano, K. (1986). Field trials with vermicompost: An organic fertilizer. In: *Proceedings of National Seminar on 'Organic Waste Utilization by Vermicomposting*,' GKVK, Bangalore, India, pp 151-160.

Kalita, D. and Baruah, S. (2019). The impact of nanotechnology on food. In: Nascimento, R. F., Ferreira, O. P., De Paula, A. J., Neto, V. O. S. (Eds.), Nanomaterials Applications for Environmental Matrices: Water, Soil and Air, *Advanced Nanomaterials*., 369-379. https://doi.org/10.1016/B978-0-12-814829-7.00011-2.

Karpagam, T., Devaraj, A. (2011). Studies on the efficacy of *Aloe vera* on antimicrobial activity. *Int. J. Res. Ayurveda and Pharm*., 2(4): 1286-1289.

Kilani-Morakchi, S., Morakchi-Goudjil, H., and Sifi, K. (2021). Azadirachtin-based insecticide: Overview, risk assessments, and future directions. *Front. Agron*. 3: 676208. https://doi.org/10.3389/fagro.2021.676208.

Kim, H. M., Jeong, S., Choi, I. S., yang, J. E., Lee, K. H., Kim, J., Kim, J. C., Kim, J. S., Park, H. W. (2020). Mechanisms of insecticidal action of *Metarhizium anisopliae* on adult Japanese pine sawyer beetles (*Monochamus alternatus*). *ACS Omega*., 5(39): 25312–25318. https://doi.org/10.1021/acsomega.0c03585.

Lai, D., Jin, X., Wang, H., Yuan, M., Xu, H. (2014). Gene expression profile change and growth inhibition in Drosophila larvae treated with azadirachtin. *J. Biotechnol.* 185: 51–56.

Lamont, W. J. (2005). Plastics: modifying the microclimate for the production of vegetable crops. *Hortic. Technol.*, 15:477–48.

Lazaratou, C. V., Vayenas, D. V., and Papoulis, D. (2020). The role of clays, clay minerals and clay-based materials for nitrate removal from water systems: a review. *Appl. Clay Sci.*, 185: 105377. https://doi.org/10.1016/j.clay.2019.105377.

Lightfoot, D. R. (1994). Morphology and ecology of lithic-mulch agriculture. *Geo. Rev.*, 25:172–185.

Lithourgidis, A. S., Dordas, C. A., Damalas, C. A. and Vlachostergios. D. N. (2011). Annual Intercrops: an alternative pathway for sustainable agriculture. *Australian Journal of Crop Science*, 5(4): 396-410.

Lopez-Llorca, L. V., Maciá-Vicente, J. G., Jansson, H. B. (2008). Mode of action and interactions of nematophagous fungi. In: Ciancio, A., Mukerji, K. G. (eds), Integrated management and biocontrol of vegetable and grain crops nematodes. *Integrated Management of Plant Pests and Diseases*, Springer, Dordrecht, 51-78. https://doi.org/10.1007/978-1-4020-6063-2_3.

Mandal, D. (2021). Nanofertilizer and its application in horticulture. *J. Appl. Hortic*. 23: 70–77.

Mangan, M., and Mangan, M. S. (1998). A comparison of two IPM training strategies in China: the importance of concept of the rice ecosystem for sustainable insect pest management. *Agril. Hum.*, 15: 209–221.

Mannino, M. C., Huarte-Bonnet, C., Davyt-Colo, B., Pedrini, N. (2019). Is the insect cuticle the only entry gate for fungal infection? Insights into alternative modes of action of entomopathogenic fungi. *J. Fungi.*, 5(2): 33. https://doi.org/10.3390/jof5020033.

Mesnage, R. and Séralini, G. E., (2018). Editorial: toxicity of pesticides on health and environment. *Front. Public Heal.*, 6: 268. https://doi.org/10.3389/fpubh.2018.00268.

Michel, M. R., Aguilar-Zárate, M., Rojas, R., Martínez-Ávila, G. C. G., Aguilar-Zárate, P. (2023). The insecticidal activity of Azadirachta indica leaf extract: Optimization of the microencapsulation process by complex coacervation. *Plants* (Basel)., 12(6): 1318. https://doi.org/10.3390/plants12061318.

Mikkelsen, R. (2018). Nanofertilizer and Nanotechnology: a quick look. *Better Crops*., 102: 18–19. https://doi.org/10.24047/BC102318.

Mittal, D., Kaur, G., Singh, P., Yadav, K., Ali, S. A. (2020). Nanoparticle-based sustainable agriculture and food science: Recent advances and future outlook. *Front. Nanotechnol*. 2: 579954. https://doi.org/10.3389/fnano.2020.579954.

Moreno-Gavíra, A., Huertas, V., Diánez, F., Sánchez-Montesinos, B., Santos, M. (2020). Paecilomyces and Its Importance in the biological control of agricultural pests and diseases. *Plants*., 9(12): 1746. https://doi.org/10.3390/plants9121746.

Mozafari, M. R., Johnson, C., Hatziantoniou, S., Demetzos, C. (2008). Nanoliposomes and their applications in food nanotechnology J. *Liposome Res*., 18: 309-327.

Munroe, G. (2007). *Manual of on-farm vermicomposting and vermiculture, organic agriculture centre of Canada*., 1-40.

Murmu, K., Das, P., Sarkar, A., Bandopadhyay, P. (2022). Organic agriculture: as a climate change adaptation and mitigation strategy. *Zeichen J*., 8(3): 171–187.

Murovhi, J., Phophi, M. M., Mafongoya, P. (2020). Efficacy of plant materials in controlling aphids on okra (*Abelmoschus esculentus* L. Moench) in Limpopo Province of South Africa. *Agronomy*., 10(12): 1968. https://doi.org/10.3390/agronomy 10121968.

Mustafa, F. and Andreescu, S. (2020). Nanotechnology-based approaches for food sensing and packaging applications, *RSC Adv*., 10 (33): 19309-19336.

Nalayini P. (2007). Poly-mulching a case study to increase cotton productivity, *Central Institute for Cotton Research,* Regional Station, Coimbatore.

Ngouajio, M. and McGiffen, M. E (2004). Sustainable vegetable production: effects of cropping systems on weed and insect population dynamics. *Acta. Hortic*. 638: 77–83.

Njira, K. O. W. (2012). *Biological nitrogen fixation and crop yields under sole cropped and doubled-up legume technologies. MSc Thesis*. University of Malawi., Malawi., 1-96.

Okey-Onyesolu, C. F., Hassanisaadi, M., Bilal, M., Barani, M., Rahdar, A., Iqbal, J., Kyzas, G. Z. (2021). Nanomaterials as nanofertilizers and nanopesticides: An overview. *Chemistry Select*., 6: 8645–8663.

Panhwar, Q. A., Ali, A., Naher, U. A., Memon M. Y. (2019). Fertilizer management strategies for enhancing nutrient use efficiency and sustainable wheat production. In: Chandran, S., Unni, M. R., Thomas, S. (Eds.), *Organic Farming Global Perspectives and Methods Woodhead Publishing Series in Food Science, Technology and Nutrition.,* 17-39.

Panneerselvam, P., Kumar U., Senapati, A., Parameswaran, C., Anandan, A., Kumar, A., Jahan, A., Padhy, S. R., Nayak, A. K. (2019). Influence of elevated CO_2 on arbuscular mycorrhizal fungal community elucidated using IlluminaMiSeq platform in sub-humid tropical paddy soil. *Applied Soil Ecology*., 145: 103344. https://doi.org/10.1016/j.apsoil.2019.08.006.

Perelló, A., Noll, U., Slusarenko, A. J. (2013). *In vitro* efficacy of garlic extracts to control fungal pathogens of wheat. *Journal of Med. Plants Res*., 7(24): 1809-1817. https://doi.org/10.5897/JMPR12.511.

Petit, S., Haysom, K., Pywell, R., Warman, L., Allen, D., Booth, R. (2003). Habitat-based models for predicting the occurrence of ground-beetles in arable landscapes: two alternative approaches. *Agrl. Ecosyst. Environ*., 95(1): 19–28. https://doi.org/10.1016/S0167-8809(02)00173-1.

Plata-Rueda, A., Martínez, L. C., Santos, M. H. D., Fernandes, F. L., Wilcken, C. F., Soares, M. A., Serrão, J. E., Zanuncio, J. C. (2017). Insecticidal activity of garlic essential oil and their constituents against the mealworm beetle, Tenebrio molitor Linnaeus (Coleoptera: Tenebrionidae)., *Sci Rep*., 7: 46406. https://doi.org/10.1038/srep46406.

Pramanik, P., Krishnan, P., Maity, A., Mridha, N., Mukherjee, A., Rai, V. (2020). Application of nanotechnology in agriculture. *Environ. Nanotechnol.* 4: 317348.

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

Purwaningsih, S., Agustiyani, D., Antonius, S. (2021). Diversity, activity, and effectiveness of Rhizobium bacteria as plant growth promoting rhizobacteria (PGPR) isolated from Dieng, central Java., *Iran J Microbiol*. 13(1): 130-136.

Rahman, M. M. (2012). Problems and suggestions for farmers' adoption of IPM practices in rice (*Oryza sativa*) cultivation. *Bangladesh J. Agril. Res*. 37: 121–128.

Rathore, A. L., Pal, A. R. and Sahu, K. K. (1998). Tillage and mulching effects on water use, root growth, and yield of rain-fed mustard and chickpea grown after lowland rice. *J. Sci. Food. Agric*., 78:149–161.

Ravichandran, R. (2010). Nanotechnology applications in food and food processing: innovative green approaches, opportunities and uncertainties for global market. *Int. J. Green Nanotechnol: Phys. Chem*., 1(2): P72-P96. https://doi.org/10.1080/19430871003684440.

Ribeiro, C., and Carmo, M. (2019). Why nonconventional materials are answers for sustainable agriculture. *MRS Energy Sustain*., 6: 7. https://doi.org/10.1557/mre.2019.7.

Robroek, B. J. M., Jassey, V. E. J., Beltman, B., Hefting, M. (2017). Diverse fen plant communities enhance carbon-related multifunctionality, but do not mitigate negative effects of drought. *R. Soc. Open Sci*., 4(10): 170449. https://doi.org/10.1098/rsos.170449.

Roitberg, B. D. (2007). Why pest management needs behavioural ecology and vice versa. *Entomol. Res.* 37: 14–18.

Rossi, M., Passeri, D., Sinibaldi, A., Angjellari, M., Tamburri, E., Sorbo, A., Carata, E., Dini, L. (2017). Nanotechnology for Food Packaging and Food Quality Assessment. *Adv Food Nutr Res.*, 82: 149-204.

Sadeghi, R., Rodriguez, R. J., Yao, Y., Kokini, J. L. (2017). Advances in nanotechnology as they pertain to food and agriculture: benefits and risks. *Annu. Rev. Food Sci. Technol*., 8: 467-492.

Safari, J., Zarnegar, Z. (2014). Advanced drug delivery systems: nanotechnology of health design A review. *Journal of Saudi Chem. Soc.*, 18(2): 85-99. https://doi.org/10.1016/j.jscs.2012.12.009.

Schales, F. (1990). Agricultural plastics use in the United States. *Proceedings of the 11th International Congress of Plastics in Agriculture.*, 54-56.

Schünemann, R., Knaak, N., Fiuza, L. M. (2014). Mode of action and specificity of Bacillus thuringiensis toxins in the control of caterpillars and stink bugs in soybean culture. *ISRN Microbiol*., 2014: 135675. https://doi.org/10.1155/2014/135675.

Scott, N., Chen, H. (2013). Nanoscale science and engineering for agriculture and food systems. *Industrial Biotechnol.*, 9(1): 17–18. https://doi.org/10.1089/ind.2012.1549.

Sharma, A. K., Johri, B. N. & Gianinazzi, S. (1992). Vesicular-arbuscular mycorrhizae in relation to plant disease. *World J Microbiol Biotechnol*., 8: 559–563. https://doi.org/10.1007/BF01238788.

Singh, D., Gurjar, B. R., (2022). Nanotechnology for agricultural applications: facts, issues, knowledge gaps, and challenges in environmental risk assessment. *J. Environ. Manag*., 322: 116033. https://doi.org/10.1016/j.jenvman.2022.116033.

Singh, H. B., Keswani, C., Ray, S., Yadav, S. K., Singh, S. P., Singh, S., Sarma, B. K. (2015). Beauveria bassiana: Biocontrol Beyond Lepidopteran Pests. *Biocontrol of Lepidopteran Pests*., 43: 219–235.

Sinha, R. K. (2008). Organic farming: An economic solution for food safety and environmental security. *Green Farming*., 1: 42-49.

Sinha, R. K., Bharambe, G. (2007). *Studies on agronomic impacts of vermicompost vis-à-vis conventional compost and chemical fertilizers on corn crops. CESR Sponsored Project*; Griffith University, Brisbane, Australia.

Sinha, R. K., Herat, S., Bharambe, G., Patil, S., Bapat, P. D., Chauhan, K., Valani, D. (2009). Vermiculture biotechnology: The emerging cost-effective and sustainable technology of the 21st century for multiple uses from waste and land management to safe and sustained food production. *Environmental Research Journal*., 3: 2-3.

Sozer, N., and Kokini, J. L. (2009). Nanotechnology and its applications in the food sector. *Trends*. *Biotechnol.,* 27(2): 82-89. https://doi.org/10.1016/j.tibtech.2008.10.010.

Stoner, K. (1998). Approaches to the biological control of insects, Sustainable agriculture fact sheet, Maine Cooperative Extension Service, *UMCE Bulletin #7144*, Accessed on August 20, 2023. https://portal.ct.gov/CAES/Fact-Sheets/Entomology/Approaches-to-the-Biological-Control-of-Insect-Pests.

Subler, S., Edwards, C., Metzger, J. (1998). Comparing vermicomposts and composts. *Biocycle*., 39: 63-66.

Suhane, R. K. (2007). *Vermicompost*, Rajendra Agriculture University, Pusa, Bihar, India, 88 pp (in Hindi).

Sumbul, A., Ansari, R. A., Rizvi, R., Mahmood, I. (2020). Azotobacter: A potential bio-fertilizer for soil and plant health management. *Saudi J Biol Sci*. 27(12): 3634-3640.

Suthar, S. (2010). Evidence of plant hormone like substances in vermiwash: An ecologically safe option of synthetic chemicals for sustainable farming. *Ecological Engineering*., 36: 1089-1092.

Taiz, L., Zeiger, E. (2010). *Plant Physiology. 5th ed*. Sunderland, MA, USA: Sinauer Associates Inc; pp: 67-86.

Tisdale, S. L., Nelson, W. L. and Beaton, J. D. (1985). *Soil Fertility and Fertilizers. 4th Edition*, Macmillan Publishing Company, New York.

Tomati, V., Grappelli, A., Galli, E. (1987). The presence of growth regulators in earthworm-worked wastes. In: *Proceeding of an International Symposium on 'Earthworms,'* 31 March-5 April, 1985, Italy, 423-435.

Tondorov, D., Shishkova, K., Dragolova, D., Hinkov, A., Kapchina-Toteva, V., Shishkov, S. (2015). Antiviral activity of medicinal plant *Nepeta nuda*. *Biotechnology & Biotechnological Equipment*., 29(1): S39-S43. https://doi.org/10.1080/13102818.2015.1047215.

Usman, M., Farooq, M., Wakeel, A., Nawaz, A., Cheema, S. A., Rehman, H., Ashraf, I. and Sanaullah, M. (2020). Nanotechnology in agriculture: current status, challenges and future opportunities. *Sci. Total Environ.*, 721: 137778. https://doi.org/10.1016/j.scitotenv.2020.137778.

Vinatier, F., Lescourret, F., Duyck, P. F., Tixier, P. (2012). From IBM to IPM: Using individual-based models to design the spatial arrangement of traps and crops in integrated pest management strategies. *Agril. Ecosyst. Environ*., 146(1): 52– 59. https://doi.org/10.1016/j.agee.2011.10.005.

Wan, A., Gao, Q., Li, H. (2010). Effects of molecular weight and degree of acetylation on the release of nitric oxide from chitosan–nitric oxide adducts. *Journal of Applied Polymer Science*., 117: 2183-2188.

Wang, J., Koo, Y., Alexander, A., Yang, Y., Westerhof, S., Zhang, Q. (2013). Phytostimulation of poplars and Arabidopsis exposed to silver nanoparticles and Ag+ at sublethal concentrations. *Environmental Science and Technology*., 47: 5442-5449.

Weeks, J. J. and Hettiarachchi, G. M. (2019). A review of the latest in phosphorus fertilizer technology: possibilities and pragmatism. *J. Environ. Qual*., 48: 1300–1313.

Xie, T., Jiang, L., Li, J., Hong, B., Wang, X., Jia, Y. (2019). Effects of Lecanicillium lecanii strain JMC-01 on the physiology, biochemistry, and mortality of Bemisia tabaci Q-biotype nymphs. *Peer J.*, 7: e7690. https://doi.org/10.7717/peerj.7690.

Yadollahi, A., Arzani, K., Khoshghalb, H. (2010). The role of nanotechnology in horticultural crops postharvest management. *Acta Hortic*., 875: 49-56. https://doi.org/10.17660/ActaHortic.2010.875.4.

Yadu, B., Xalxo, R., Chandra, J., Kumar, M., Chandrakar, V., Keshavkant, S. (2021). Applications of Nanomaterials to Enhance Plant Health and Agricultural Production. In: Singh, V. P., Singh, S., Tripathi, D. K., Prasad, S. M., Chauhan, D. K. (eds), *Plant Responses to Nanomaterials. Nanotechnology in the Life Sciences*., Springer, Cham., 1-19. https://doi.org/10.1007/978-3-030-36740-4_1.

Zhang, J., Sun, T., Sun, Z. P., Li, H. Y., Qi, X. X., Zhong, G. H., YI, X. (2018). Azadirachtin acting as a hazardous compound to induce multiple detrimental effects in *Drosophila melanogaster*. *J. Hazard. Mater.*, 359: 338–347.

Zhang, Q., Ding, L., Li., M., Cui, W., Ding, W., Luo, J., Zhang, Y. (2013). Action modes of *Aloe vera* L. extracts against *Tetranychus cinnabarinus* Boisduval (Acarina: Tetranychidae). *Agricultural Sciences*., 4(3): 117-122.