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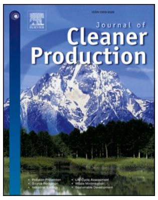

Review

Metal-organic framework-enabled pesticides are an emerging tool for sustainable cleaner production and environmental hazard reduction

Yasser Vasseghian[a], Priya Arunkumar[b], Sang-Woo Joo[a,**], Lalitha Gnanasekaran[c,d], Hesam Kamyab[e,f], Saravanan Rajendran[c,*], Deepanraj Balakrishnan[g], Shreeshivadasan Chelliapan[h], Jiří Jaromír Klemeš[i]

[a] Department of Chemistry, Soongsil University, Seoul, 06978, South Korea
[b] Department of Chemical Engineering, KPR Institute of Engineering and Technology, Coimbatore, 641027, India
[c] Departamento de Ingeniería Mecánica, Facultad de Ingeniería, Universidad de Tarapacá, Avda. General Velásquez, 1775, Arica, Chile
[d] Saveetha School of Engineering, Saveetha Institute of Medical and Technical Science, Chennai, 60210, India
[e] Malaysia-Japan International Institute of Technology Universiti Teknologi Malaysia, Jalan Sultan Yahya Petra, 54100, Kuala Lumpur, Malaysia
[f] Department of Biomaterials, Saveetha Dental College and Hospital, Saveetha Institute of Medical and Technical Sciences, Chennai, 600 077, India
[g] Department of Mechanical Engineering, College of Engineering, Prince Mohammad Bin Fahd University, Al Khobar, 31952, Saudi Arabia
[h] Engineering Department, Razak Faculty of Technology and Informatics, Universiti Teknologi Malaysia, Jln Sultan Yahya Petra, 54100, Kuala Lumpur, Malaysia
[i] Sustainable Process Integration Laboratory (SPIL), NETME Centre, Faculty of Mechanical Engineering, Brno University of Technology - VUT Brno, Technická 2896/2, 616 00, Brno, Czech Republic

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ABSTRACT

Two of the most important challenges of the new millennium are the sustainability of agricultural output and the security of global food supplies. The ability of agro-ecosystems to adapt to a rapidly changing climate and improve the global food supply while limiting unintentional environmental damage is critical to addressing these issues. Nanomaterials that can encapsulate and transport active pesticide ingredients (AIs) responsively (e.g., regulated, targeted, and synchronized) offer new opportunities to improve the efficacy and efficiency of traditional pesticides. Completed analysis of the essential traits of nanopesticides in pest management for crop enhancement in comparison to their non-nano scale analogues for sustainable, cleaner production. Cleaner production projects contribute to sustainable development through the development of novel and smart technologies. Nanopesticides outperform non-nano size pesticides in terms of total efficacy against target organisms by 32%, including a 19% improvement in outdoor studies. Notably, the toxicity of nanopesticides is 43.2% lower for non-target organisms, showing a reduction in environmental collateral damage. A 22.2% decreased potential for leaching of AIs into soils is combined with a reduction of 41.5% in the premature loss of AIs before reaching target organisms (Wang et al., 2022). This study seeks to answer the question of how the use of nanopesticides can lead to improved sustainable cleaner production. This study focused on the characteristics of numerous non-nanoscale analogues to a wide spectrum of nanopesticides used to manage agricultural pests. Also, to address several new biotic and abiotic threats in a constantly changing climate, the responsive nanoscale platform is given special consideration. Pesticide particles smaller than 500 nm are referred to as nanopesticides in this investigation. The benefits of nanopesticides can lead to an increase in agricultural yields, which can support sustainable agriculture and help ensure global food security.

1. Introduction

Globally, several factors, especially plant pests, adversely affect agricultural productivity. One of the most promising options for protecting plants from fungi, bugs, and other irritants is the use of pesticides. However, chemical pesticides have adverse effects on the environment and public health (Rojas et al., 2022). More people and governments are worried about how often chemical pesticides are used.

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* Corresponding author.
** Corresponding author.

E-mail addresses: sjoo@ssu.ac.kr (S.-W. Joo), khesam2@live.utm.my (H. Kamyab), srajendran@academicos.uta.cl (S. Rajendran).

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This has led to the effective and safe use of pesticides, as well as the right kind of control over how they are used in different situations. There are several limitations when it comes to the conventional spray accumulation of pesticides, such as the potential for retention on the vegetation layer, focused transportation, and accumulation segments of spray atomisation (Wang et al., 2022). A variety of computational paradigms have been effectively applied in industry to shed light on how fluids flow over various shells and to track the movement of particles and their linkages, as well as the surfaces of plants. The most crucial factors that need to be taken into account when thinking about computational paradigms are the surroundings of the spray accumulation, the connections between the many scattering particles, and the effects of the surrounding vegetation's landscape (Sharma et al., 2022). Due to ecological system damages caused by excessive and uncontrolled use of pesticides, several issues harm animals. Although organic farming can address the aforementioned problems relating to chemical pesticide use, it is not the most effective solution because large areas of land would be required to produce sufficient food (Liang et al., 2021). Several challenges, such as inadequate infrastructure, a lack of data, cultural prejudices, existing policies, and practical issues, limit the implementation of organic agriculture and its ability to be a viable strategy in terms of guaranteeing food security. As a result, even using less traditional pesticides, it can be difficult to ensure crop yield and quantity (Gao et al., 2021).

The advancement of technologies involved in separating water from salt or oil-water emulsions is made possible by the manipulation or control of transportation at nanoscales. Phase-change approach, such as liquid to vapour or ice changes, are utilised to separate salt ions from water in the treatment of highly salinized water, whereas field-intervened methods are favoured for the desalination of less salinised water (Christopher et al., 2020). Because crops are vulnerable to attack by insects, bacteria, fungi, and rodents, a variety of insecticides, bactericides, herbicides, fungicides, rodenticides, and fungicides have all been used extensively to manage rodents, weeds, microbes, and other pests. Fungicides have also been used widely to control fungus. Benzimidazoles, dithiocarbamates, and phenylpyrrole are known fungicides, as are nitrialestriazines, phenoxychloroacetanilides, and benzoic acid, as are organophosphates, organochlorines, and carbamates, which are known insecticides (Gao et al., 2021). Research studies worldwide aimed at reducing the use of pesticides have led to a nearly (43%) reduction in pesticide usage without negative consequences on the productivity and efficiency of arable farms. It has been widely acknowledged, however, that controlled use and a negligible amount of fertilizers and pesticides applied through an environmentally responsible strategy can increase productivity in a wide range of production scenarios while also ensuring their precise delivery in predetermined areas (Rehman et al., 2022).

Since substances are dealt with at the nanoscale to achieve extraordinary physicochemical properties, nanotechnology is a developing and popular technology that can be used to pursue the best answer. Agrochemicals have been developed from nanomaterials with novel physical, mechanical, and chemical qualities (Neme et al., 2021) using nanotechnology. They can overcome several limitations imposed by current products, including those related to usability, price, production strategies, and overall performance. As a direct consequence, a plethora of new products have become available in a variety of industries, including but not limited to those in electronics, agriculture, pharmaceuticals, medical, materials science, and food processing technologies (Radhakrishnan et al., 2022). For instance, the distribution of balanced crop nutrients in response to their deficiency, scrutiny of water quality, germination, pest control, fertilizer delivery, exposure to agrochemical toxicity, and reduction of fertilizer toxic potential are just a few ways in which nanotechnology has the potential to revolutionize the agriculture sector (Dong et al., 2021a,b). In addition, there are more opportunities in agri-food industries, which include animal husbandry, interactive food packaging, and uses that are more environmentally friendly (Ponnuchamy et al., 2021).

Recently, much research has focused on colloidal nano-delivery systems that contain active pesticide ingredients to improve efficacy using little pesticides and to maximise economic benefits through increased yields (Chauhan et al., 2022). They can also be used to protect crops from damage caused by diseases, insects, and other types of pests. Pesticide-entrapped agrochemicals with nanotechnology capabilities have helped in many ways, including increased efficacy, a longer shelf life, better distribution, lower toxicity, the ability to degrade naturally in the soil, and better wettability. In response to rapid innovations in pesticide-loaded nano-enabled agrochemicals, scientists and agronomists have developed nanostructures that include pesticides but do not make them more hazardous to the environment or reduce their effectiveness (Camara et al., 2019). Using pesticide-loaded nano-enabled agrochemicals, specific locations can be targeted for treatment with minute amounts of pesticide, minimising damage to untargeted plants. The authors have discussed various forms of pesticide-loaded nano-enabled agrochemicals in this chapter, emphasizing cutting-edge initiatives using nanostructures as active components and biopesticides. Both human and nonhuman biota types are included while reviewing the associated ecological barriers to conventional pesticides (Aris et al., 2020).

Standard formulations typically fail to reach the intended target due to early decomposition, evaporation or spray drift. Nanocarrier-based pesticide formulations are needed that precisely deliver pesticides to their intended targets. By limiting off-target losses, such pesticide delivery nanosystems have the potential to reduce the environmental concerns associated with pesticides (Tripathi and Prakash, 2022). Core-shell nanoparticles are increasingly attracting interest from a variety of nanocarriers due to their benefits in terms of integration or the ability to mix two separate materials into one creative nanoplatforms. With their porous cores and versatile shells, core-shell nanoparticles can easily be modified in terms of their physicochemical properties. When it comes to the development of precise pesticide delivery systems, core-shell nanoparticle flexibility is highly sought after (Sarkar et al., 2022).

Metal-organic frameworks (MOFs), one of the most distinctive porous crystalline materials, have been extensively explored for gas storage, separation, catalysis, and drug delivery due to their unusually high porosity and surface area. MOFs have been produced from metal (Ag, Zn, Cu, Fe, Cr, Zr, Ti, etc.) nodes and organic linkers by the application of coordination bonds (carboxylate, phosphonate, N-donor linkers, etc.) (Rasheed et al., 2020). Compared to other MOFs that have been published, MIL-101(Fe), which is composed of 1,4-benzene dicarboxylate (BDC) and Fe_3O secondary building units, is better suitable for usage in pharmaceutical applications. The MIL-101 structure has a large surface area (SLangmuir 5900 300 m^2/g), large pores (cages 29 and 34, pentagonal and hexagonal windows 12.0 and 14.7 16.0), and it is biocompatible with nontoxic Fe(III) carboxylate (rat oral dose: 0.1 mg/kg). Since 2006, when it was first made to carry ibuprofen, DL50 (MIL-101(Fe) has been used as a porous nanocarrier to deliver drugs, chemicals used in agriculture, and siRNA. It has a very large capacity for loading drugs (1.44 g of substance can be loaded onto each gram of MIL-101(Cr)) (Kumar et al., 2019). Compared to other inorganic or organic materials, silica offers more benefits in agricultural applications when utilised as shell materials on top of a porous core. Sodium silicate is considered a "green" synthesis process due to the ease with which silica can be produced in aqueous solutions. Silica shells can add to the usefulness of core materials by improving their stability, water dispersibility, ability to perform a variety of specific tasks, and biocompatibility. Furthermore, silica has received extensive research attention in agriculture for its potential to boost plant growth, stress tolerance, and pest resistance (Kumar et al., 2019).

With the fast growth of stimulus-responsive release technology, smart core-shell nanocarriers offer another way to give pesticides in a precise way. Specific microenvironmental triggers can kill these nanocarriers. Pesticide nanocarriers must be designed with an awareness of how the material interacts with the environment in which it is used (Chauhan et al., 2022). Numerous lepidopteran insect pests, such as Spodoptera frugiperda, Helicoverpa armigera, and Plutella xylostella, are well-known crop pests that significantly reduce crop production all over the world. It has been demonstrated that the particularly alkaline gut of phytophagous lepidopteran pests (pH level up to 12) can be used as a biological trigger to ensure correct insecticide delivery (Dong et al., 2021a,b). In general, MOFs with carboxylate-based ligands and high-valent metal ions, such as PCN-222, and MIL-101, demonstrate poor stability in an alkaline environment. Furthermore, siloxane linkages (Si O Si) in silica are known to be hydrolyzed by bases to create soluble silanols (Si-OH). To increase the effectiveness of pesticide delivery, MOF and silica hybrid nanocomposites can be employed as smart nanocarriers to carry insecticides, particularly to the alkaline stomach of insect pests (Neme et al., 2021). Nanopesticides are a new technological discovery that has the potential to improve pesticide performance and durability and reduce the amount of active chemicals required. Nanopesticides are thought to be able to make up for the weaknesses of current ways to get rid of insect pests. They should be able to penetrate the insect's body, stay active and stable in the target ecosystem, and be harmless to non-target organisms. They should also be cost-effective and lessen the pests' ability to defend themselves.

In this study, we evaluated key characteristics of numerous non-nanoscale analogues to a wide spectrum of nanopesticides used to manage agricultural pests. The characteristics compared were direct inhibitory efficiency, toxicity to non-target organisms, early loss, foliar adhesion, and AI leaching. The responsive nanoscale platform is given special consideration to address several new biotic and abiotic threats in a constantly changing climate. Pesticide particles smaller than 500 nm are referred to as nanopesticides in this investigation. Although there is no agreement on what constitutes a nanopesticide, a review of the literature indicates that substances with a maximum size of 500 nm are considered to have properties and functions that are unique to the nanoscale.

2. Biopesticides for improvement cleaner production

For crop protection, the use of chemicals with low toxicity and environmental friendliness, such as biopesticides, is very desired from the standpoint of environmental protection. Biopesticides should be preferable to synthetic organic pesticides for minimising negative impacts, such as those on biodiversity, living things, and human health. Biocontrol organisms and plant-sourced biopesticides are two different categories of biopesticides (Rehman et al., 2022). The most effective nanoformulations were those derived from plants, but they had little effect on fungus. Microbial-based formulations are becoming increasingly popular as a method of treatment for fungal infections and/or insect infestations. Biopesticides like thaxtomin A (made from Streptomyces spp.), glycerol monocarpate (made from animal or vegetable fat), citronellol (made from plant essential oil), and 4-allyanisol (made from basil oil) have been approved by the US Environmental Protection Agency (EPA) (Wang et al., 2022). The effectiveness of rhizosphere bacteria against Phytophthora nicotianae, *Meloidogyne incognita*, and root knot-black shank in tobacco crops was reported. These biopesticides had several beneficial qualities, the most notable of which were their selectivity to their intended targets, their toxicity to non-target organisms, and their ability to remain in the environment. In terms of their cost of manufacturing and ease of use, the combination of biocontrol agents is a little difficult for managing disease complexity (Liang et al., 2021). Biopesticides, on the other hand, are susceptible to environmental factors (such as soil conditions, weather conditions, etc.) that can affect their long-term stability (and may cause premature degradation). Considerable research has been conducted to develop diverse nanocarriers for the regulated, targeted administration of biopesticides,.

Additionally, a substantial amount of research on the use of essential oils for the herbicidal effect against the germination of various types of weeds has been published. This research has been presented in several different forms. Other than being more environmentally friendly and pollinator-friendly, these natural pesticides also had the added benefit of repelling insects and posing no danger to bees or other beneficial insects (Yu et al., 2022). The essential oil of S. hortensis was synthesised into a nanoemulsion utilising a low-energy method. Natural weed control by S. hortensis was made possible in part by the plant's carvacrol, a powerful inhibitor. The nanoemulsion of essential oils has a detrimental effect on the germination, physiological functions, and growth of weed species. Essential oils' phytotoxicity and bioherbicidal action, on the other hand, may be influenced by the type of soil in which they grow. For instance, P. boldus essential oil significantly reduced the germination of P. oleracea seeds in both sand and clay textures (at a lower concentration of 0.125 L/mL) (Malik et al., 2021). In soil-less and soil-cultured P. oleracea seed germination, lemon essential oil did not show any herbicidal activity. Numerous studies have also been done to look at the essential oils' ability to control pests. The effects of essential oils on the feeding and oviposition behaviour of Anticarsia gemmatalis (A. gemmatalis) Hubner were discussed in detail (Sangeetha et al., 2020). The effect of nanomaterials on crop growth is given in Table 1. The antifeeding effects of garlic essential oil and cinnamon mint thyme essential oil were reported to be 80% and 50% when assessed for A. gemmatalis. Essential oils that have been nano encapsulated are more effective at repelling pests due to their acaricidal and oviposition activities than unencapsulated compounds (such as carvacrol and linalool). Essential oils from *Achillea millefolium* L. that have been encapsulated in chitosan nanocapsules, for instance, are believed to be able to kill adult Tetranychus urticae Koch for an extended period. This is because the employed essential oils are released slowly and steadily (Nehra et al., 2021).

3. Nanoparticles for agricultural use: sources and synthesis

Modern development and the rise of new technology have ushered in a new era. The nano-revolution makes it possible to create eco-friendly nanoparticles for use in agriculture using many different natural reducing agents for cleaner production. Numerous natural resources have drawn undeniable interest in the quest to create biocompatible, environmentally friendly nanoparticles for use in agricultural techniques (Asif et al., 2021). Even though several new technologies are currently being created to overcome production constraints and improve crop output in modern agriculture, the question of whether or not the use of nanoparticles in crop production is sustainable is still being contested. When selecting nanoparticle synthesis strategies from a variety of processes, including chemical, physical, biological, and hybrid methods, it is important to take into consideration not only the required functionality of the produced nanomaterials but also the biosafety of the produced nanomaterials (Sabry, 2020). Some metal-oxide NPs significantly impacted biomass, shoot, root, seed, and plant yield within specific concentration ranges. A large number of state-of-the-art manufactured metallic NPs (such as graphene-silver NPs, CeO_2-NPs, Ag NPs, Au NPs, Cu/CuO NPs, TiO_2 NPs, carbon NPs, Fe NPs, Zn NPs, Mg NPs, Si NPs, K- NPs, etc.) as well as numerous lipid-polymer hybrid (nano-capsule) reduces the presence of hazardous chemicals biocompatibility, and these chemically produced nanoparticles are ultimately unsuitable for use in crops (Lima et al., 2021). In addition, the bulk of the physicochemical approaches that have been utilised for the production of NPs have relied on the use of powerful radiation, extremely concentrated reductants, and stabilizing agents. Both the environment and human health are harmed by these. There is a need for a method of producing nanoparticles that is chemical-free, secure, and acceptable to the environment to lessen the risk that the numerous chemicals used in physical and chemical processes would be harmful to the environment. In recent years, green synthesis protocols—those based on microbes and plants—have been used to create nanoparticles for use in agriculture

Table 1
Effect of nanomaterials on the growth of crops.

Nanomaterials	Crop	Substrate	Effects due to nanomaterials	Ref.
ZnO	Nicotiana tobacco*Triticum aestivum*	Hydrophonic Soil	Increased plant anatomy, physiology, metabolites, enzymatic activity, and growth	Grillo et al. (2021) (Tripathi and Prakash, 2022)
	Coffee arabica	Soil	Increased Yield and biomass accumulation Increased biomass accumulation, total photosynthesis rate, and growth.	
Fe_2O_3	Glycin Max Oryza sativa Cucumis Melo –	Soil Soil Soil Soil	The length of a plant's root increased significantly increased as well as the photosynthesis rate. Significantly increased roots growth than the Control and its bulk counterparts. Plants that are exposed to environmental stress can increase their ability to scavenge over-accumulated reactive oxygen species. Slow release of Fe.	Sarkar et al. (2022) (Rehman et al., 2022) (Grillo et al., 2021)
CeO_2	Brassica Napus	Soil	Increased photosynthesis rate, Chlorophyll Content, and Improved biomass.	Sarkar et al. (2022)
TiO_2	Spinacia Oleracea	Moistened Pearlite	Enhanced photosynthesis rate, Oxygen activity, chlorophyll formation, and increased dry weight of the plant.	Sarkar et al. (2022)
Ag	Oryza sativa Cucumis Melo	Soil	A lower dose of Ag NPs also enhances the root growth. Changed metabolite profile of the plant.	Kumar et al. (2019)
MWCNTs	*Arachis hypogaea*, Zea mays, and Trificum qestivum Glycine max, Zae mays	Soil Sterile agar medium	Enhanced biomass aggregation and germination. Increased growth of seeding and germination.	Neme et al. (2021) (Wang et al., 2022)
ZnS	–	Soil	Slow release of Zinc.	Tripathi and Prakash (2022)
Urea Clay	–	Water	Slow release of Nitrogen	Sharma et al. (2022)
Nanoporous Zeolite	Zae mays	–	Urea and Zeolite mixtures provide the nutrients for more than four weeks.	Neme et al. (2021)
Mesoporous Silica	Zae mays	–	Long-time supply of Nutrients and then absorption of silica released slowly.	Sharma et al. (2022)
Nanofibers	Grapholita molesta	–	Controlled release.	Dong et al. (2021)

(Sharma et al., 2021). This single-step bio-reduction technique for producing chemical-free and secure nanoparticles. The biosynthesized NPs have been prevalent in agricultural usage because of their features, which include biocompatibility, biosafety, and environmental safety. Through the use of ecologically safe stabilizing agents, non-hazardous reductants, and green alternative solvents, green synthesis techniques can produce products with such advantageous characteristics. The bottom-up, basic sol-gel approach used by green approaches allows for the spontaneous scaling up of the nanoparticles that are produced (Usman et al., 2020).

3.1. Nanopesticides features: a platform for sustainable cleaner production

Conventional pesticides are used to boost the productivity of agricultural production; however, the efficacy of traditional pesticides is restricted. Nanopesticides, which are plant protection chemicals, are now being explored to replace conventional pesticides. It's possible to make these using a wide range of surfactants and organic polymers, inorganic metal nanoparticles and their spheres, polymeric nanocapsules, nanogels, and other nanostructured materials (Agathokleous et al., 2020). Using nanoformulations of present pesticides and fungicides, these nanoparticles provide pesticides with great efficacy and low consumption. In addition, they are an efficient instrument for the production of hydrophobic insecticides with improved solubility. Research has shown that silver nanoparticles (AgNPs) can prevent plant pathogen growth in a dose-responsive way because of their well-known antibacterial characteristics (Sarkar et al., 2021). It has been discovered that the dose-dependent titanium-alumina-copper (TiO_2-Al-Cu) NPs are inhibitory against a variety of pests while promoting plant development and stress tolerance. It has been demonstrated that copper and silica nanoparticles are incredibly effective in the production of nanopesticides. Therefore, the development of the new formulation of nanopesticides could be a very beneficial approach to integrated pest control; however, before it can be marketed, issues with biosafety and environmental risk assessment need to be resolved (Bindra and Singh, 2021). Similar to how applying nanoherbicides can be a good alternative for getting rid of weeds and boosting crop productivity. Pesticides and herbicides can be delivered to plants with efficiency using the nano silicon carrier made of diatom frustules. Zinc- and aluminum-layered double hydroxide layers can be used to create nanohybrid molecules that contain two herbicides at once.

3.2. Nanopesticides' physical and chemical characteristics

The ability of nanotechnology to boost the efficiency of NMs by capitalising on the unique nanoscale properties they possess while simultaneously lowering the risk of potential nano-specific side effects is one of the many advantages of this field (Bratovcic et al., 2021). The history of nanopesticides and their application is shown in Fig. 1. The physicochemical properties of NMs have an impact on their effectiveness, fate, transport, and impacts on the environment. Size, homogeneity, and surface properties are all interesting qualities that both types of nanopesticides have. Additional unique characteristics of type 2 nanopesticides, such as loading efficiency, encapsulation efficiency, and release efficiency of AIs, affect the amount of AI that is released for pest control purposes. Generally speaking, nanopesticides have a size between a few and 500 nm, while there are several outliers (Li et al., 2019). Transmission electron microscopy (TEM) and dynamic light scattering (DLS) measurements of Ag- and Cu-based (Type 1) nanopesticides yielded mean sizes of 22.8 nm, 53.5 nm, 59.2 nm, and 153.2 nm. The mean TEM and DLS diameters of Type 2 nanopesticides, which vary in size from 166.7 to 251.5 and 273.0–358.6 nm, are significantly greater than those of Type 1 nanopesticides. Specifically, the Type 2 nanopesticides' 75th percentile size is 450 nm (Chhipa, 2019). The polydispersity index indicates how homogeneous the particle size distribution is in a dispersion (PDI). A restricted size range of particles is indicated by a PDI score of less than 0.2. When compared to Type 1 nanopesticides, the PDI values of Type 2 nanopesticides that contain nanocarriers are often lower. This is especially true for nanoformulations that are enabled by polymers. Chitosan, cellulose, and polylactide can make nano-formulations stable by steric and/or electrostatic repulsion with only a modest alteration to their PDIs (usually 10%), resulting in well-dispersed colloidal suspensions for months.

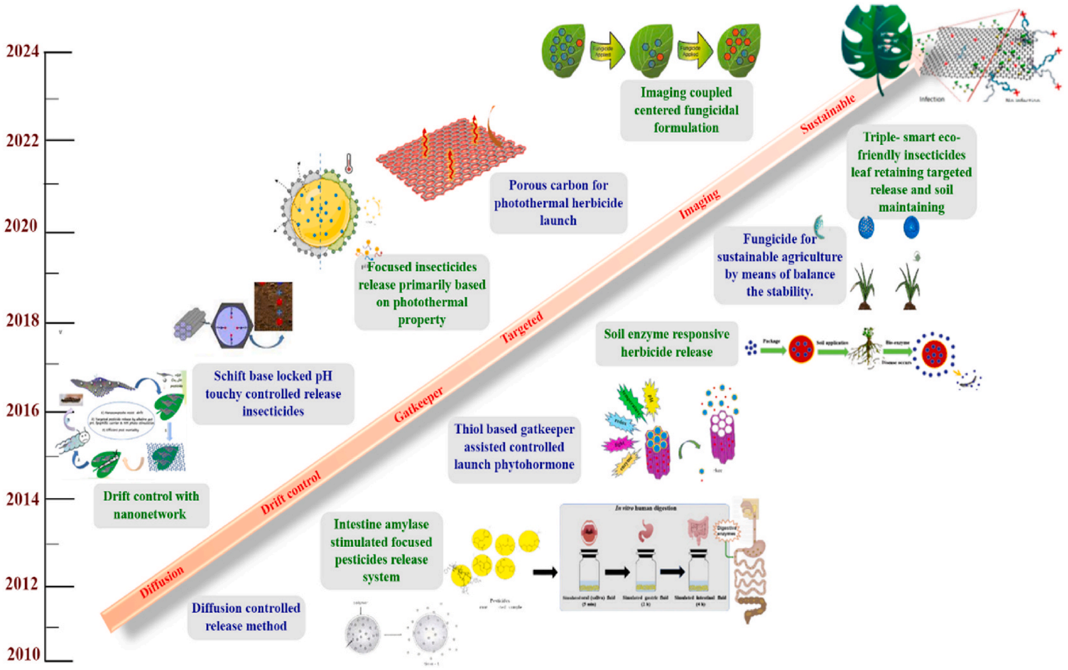

Fig. 1. Schematic representation of the history of nanopesticides and their applications.

Stabilising nano-formulations requires only a modest alteration to their PDIs (up to a year) (Yadav et al., 2022b).

3.3. Nanotechnology to control plant diseases

Nanobiotechnology tools and techniques have been studied a lot in agricultural research over the past 20 years, with many promising prospects in the form of nanostructures, which are currently being introduced for different areas of agricultural research. Small, man-made, or naturally occurring particles with a size between 1 and 100 nm are known as NPs (Jogaiah et al., 2021). Some of the distinguishing characteristics they exhibit include their size, shape, porosity, zeta potential, hydrophobicity, and hydrophilicity, as well as their enormous surface area, surface functionalisation, and surface functionalisation. These artificial carbon nanomaterials (CNMs) are employed extensively in fields ranging from electronics to nanomedicine to biosensors to micro agriculture due to their unique mechanical properties. The pros and applications of nanobiotechnology in agriculture are given in Table 2. Materials such as fullerenes, carbon nanotubes (CNTs), graphene, nano-onions, nanobeads, nanofibers, nanodiamonds, nanohorns, and carbon dots are all members of the CNM family of substances (Dangi et al., 2021). These materials exhibit unique physicochemical characteristics as well as quantum features at the nanoscale level. The cylinder-shaped carbon nanotubes (CNTs) have both open and closed ends. Both single-walled nanotubes (SWCNTs) and multiwalled nanotubes (MWNTs) are forms of nanotubes, but they are distinct from one another due to the number of concentric layers of coiled graphene sheets that make up their respective wall structures (MWCNTs). Although the use of these composite nanomaterials in the sectors of agriculture and culture is still in its early stages, impressive outcomes have been seen thus far. Since CNTs are internalised by plant cells and cell organelles, they can be employed as nanotransporters (Chhipa and Joshi, 2016). Numerous nanotools, such as buckyballs, dendrimers, and nanocapsules, are now being researched for their potential to facilitate accurate and efficient drug administration in the context of nanoveterinary medications. Chickens are free of the bacteria Campylobacter jejuni thanks to adhesion-specific nanoparticles. Iron nanoparticles are also fed to cattle and fisheries.

Table 2
Merits and application of agri-nanobiotechnology.

Merits	Applications	Ref.
Improved Productivity	Nanopesticides, Nanoherbicides Nano fertilizers.	Neme et al. (2021)
Biomonitoring	Nanosensors, Plant Physiological monitoring	Prabha et al. (2022)
Soil Improvement	Nanoclays, Nanozeolites, Biodegradable NPs	Tripathi and Prakash (2022)
Phytotoxicity	Cysosomal damage, ROS accumulation, Compromised Crop quality	Neme et al. (2021)
Crop protection and Tolerance	Nanobioremediation, Improved stress resistance, Pest Management	Singh et al. (2019)
Targeted controlled delivery	Targeted Nanodelivery of DNA, Protein-bound NPs	Tripathi and Prakash (2022)
Crop Enhancement	Nanomaterials assisted genetic Modification, Seed Priming, Nanobiofortification	Wang et al. (2022)

Around the world, plant diseases and pests cause the loss of 20–40% of crops each year (Flood, 2010). Pest management used in contemporary farming mainly relies on the use of insecticides, fungicides, and herbicides (Dubey and Mailapalli, 2016). It is essential to create insecticides that are effective, affordable, and less damaging to the environment. Pesticides may benefit from new ideas like nanotechnology by being less toxic, having a longer shelf life, and becoming more water-soluble, all of which may have favourable effects on the environment. The importance of agricultural nanotechnology, particularly for preventing illness and ensuring safety, has been previously covered. The potential nanotechnology application to aim at integrated pest management is shown in Fig. 2. The slow and continuous provision of agricultural nutrients to the plants is made possible in a controlled amount by conventional herbicides and pesticides with nanotechnology-based formulations (Raj et al., 2021). Additionally, NPs might be crucial in the management of host infections and insect pests. For the manufacturing production of nano-insecticides, several polysaccharides, including chitosan, alginates, starch, and polyesters, have

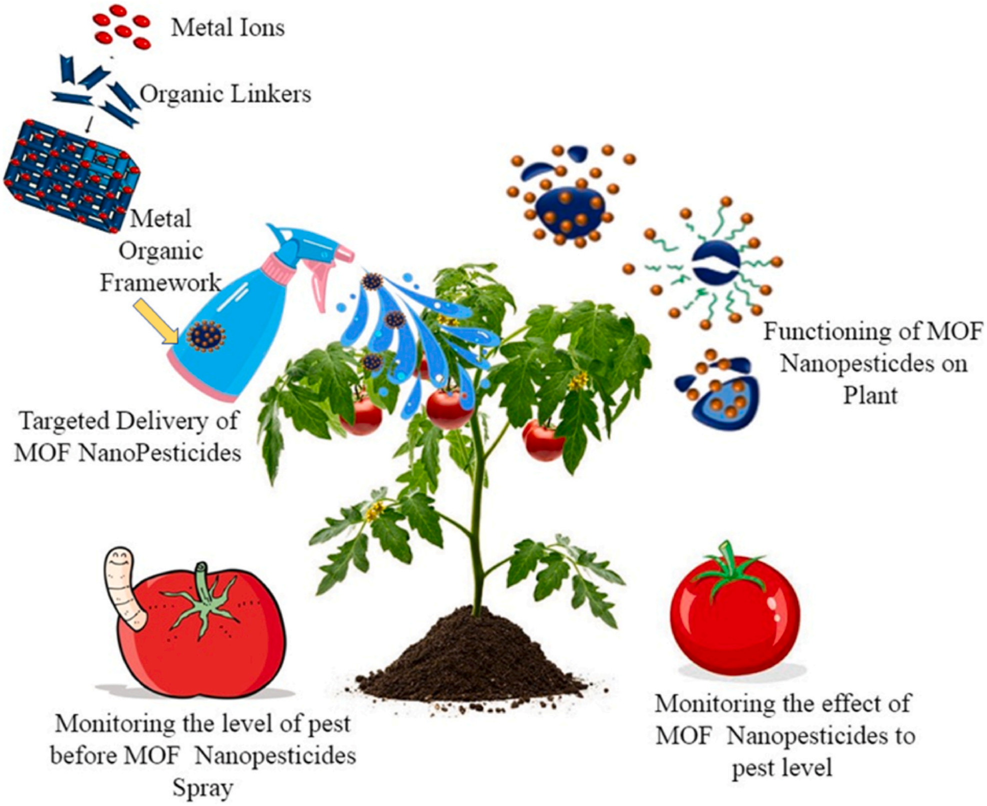

Fig. 2. Application of nanotechnology in integrated pest management.

been taken into consideration. In general, there are two ways that nanoparticles can be used to protect plants: either they protect crops themselves, or they act as carriers for pesticides already on the market and can be sprayed on the plants. However, there is little research on using nanomaterials to protect plants and provide food (Gahukar and Das, 2020).

3.4. Nanomaterials for the control of food and nutrition

Incredible outcomes have been achieved using nanoparticles in the food industry. It has significantly affected the food industry. The food industry has been revolutionized by the development of cutting-edge technologies such as microfluidics, microelectromechanical systems, and DNA microarrays (Chaud et al., 2021). These cutting-edge technologies enable the elimination of pathogens and contaminants, as well as the intelligent distribution of nutrients and the nanoencapsulation of nutraceuticals. Food goods with nanoparticles have better uniformity, physical performance, and nutritional content. They also extend the shelf life of products, prevent lump formation, remove food pollutants, and aid in lighter, stronger, and more functional packaging (Chhipa, 2017).

3.5. Fate of nanopesticides in the environment

Pollutants and environmental risks are significant global issues. Agricultural operations and other economic activities that release different toxins into the environment have created severe hazards. A major endeavour to feed the world's expanding population, sustainable development goals have been viewed as achievable with the help of nanotechnology. Overuse of agrochemicals like pesticides, fertilisers, and herbicides, on the other hand, may boost crop production (Sharma, 2017). Nanotechnology offers enormous potential to increase precision in nutrient delivery to a particular area at a particular time by using specially designed nanoparticles. Nanotechnology makes it possible to get the most out of the least amount of agrochemical inputs, such as nano fertilisers, nanopesticides, nano-herbicides, nano-fungicides, etc., without upsetting the balance of micronutrients and microbial communities. Nanotechnology is used in agriculture to create nanoparticles that help the crop in some beneficial ways. There are numerous applications for green nanomaterials in agriculture, including soil health management, nutrient delivery with precision, seed germination, and insect control, all of which are explored in this work (Kumar et al., 2019). Several plant growth indices, including germination rates, shoot lengths, root lengths, and fresh and dried weights, are positively impacted by the application of nanoparticles. Nanoparticles are crucial for plant growth and development as well as soil conditioning. The production and quality of crops are heavily influenced by a variety of factors, including the types of nanoparticles, the application dose, the plant species, and the cultivars. Nano-enabled agrochemicals with low potential toxicity can be improved by site-targeted distribution and regulated delivery of functional components, among other concepts (Diba et al., 2022). This paper also covers how nanotechnology can increase productivity by regulating the steady flow of nutrients, keeping an eye on the condition of the soil, and serving as insecticides to promote long-term agricultural development. The discussion makes it abundantly evident that the development of nanotechnology has become essential for the agriculture sector's long-term sustainability.

The acceptance of government rules, as well as the upgrading of agricultural sectors for nano agrochemical usages among the stackholders, are essential if agricultural production is to be accelerated through this exciting technology (Rachappa et al., 2007). However, it is difficult for policymakers to guide in a field where most of the information is either classified or under investigation. Although excessive regulation might impede progress, the absence of such need-based rules may also have detrimental effects on health. Nanotechnology's agricultural applications are currently not meeting global demand despite the good progress of the technology across many disciplines due to a lack of awareness, a lack of need-based regulation, and associated safety issues (Xu et al., 2022).

Nanomaterials might be useful for the cleanup and active detection of harmful pollutants. The use of efficient nanosensors as analytical tools to monitor various diseases, agrochemicals, heavy metals, and organic contaminants is now under investigation. For successful management, physicochemical parameters of agro-ecosystems are being monitored with nanosensors. This includes detecting and monitoring climate change, which includes changes in temperature, water safety and cloud cover, salinity and alkalinity, as well as pollution with metal toxicity in the environment (Chen et al., 2021). Nanomaterials are employed in the environment for a range of tasks, such as the development of more efficient solar cells, cleaner nanobiosensors for contaminants, and highly efficient renewable energy sources. They are also believed to disrupt the ecological dynamics and have a negative impact on several species. The global output of CNTs fluctuates between 55 and 3,300 t, according to research from 2014. Depending on the cell's surface charge, metal nanoparticles cause cytotoxicity (Khot et al., 2012). These compounds are soluble in organic solvents because of their hydrophobicity, which impairs the ability of plants to absorb the soil's contents and other pollutants. These compounds have the potential to contaminate water by accidently entering the environment or discharging garbage. The edaphic and physicochemical properties of the soil also play a role in the fate of CNMs in soil. In order to generalise and draw conclusions about the fate of CNMs in the environment, more research is required (Sharma et al., 2022).

3.6. *Risk assessment and toxicity of nanopesticides*

3.6.1. *Risk assessment*

Despite the positive outcomes of using nanotools in agriculture, there are still several concerns that need to be cleared up. Nanomaterial toxicity in agro-ecosystems is a major concern; as a result, it's important to address the toxicity of released NPs and their effects on the environment and plants. The impact of nanopesticides is shown in Fig. 3. The physicochemical characteristics of the soil are changed as a result of the interaction between NPs and soil (Usman et al., 2020). There are few reports on the impact of silver nanoparticle interaction on soil pH, organic soil content, and cation exchange capacity (AgNPs). Like this, applying ZnONPs to soil toxicity plants decreased their biomass. Intriguingly, the usage of TiO_2 and ZnONPs changed the makeup of the bacterial community, having a noticeable effect on the environment. Additionally, plants' extensive leaf and root surfaces interact directly with NPs, causing phytotoxicity (Kah et al., 2018). The tiny NPs have an adverse effect on the plant system because they adsorb onto plant tissue. The size and concentration of NPs affect their phytotoxicity. It has been found that NPs of a size between 5 and 10 nm are more hazardous. This means that before NPs can be used commercially for agricultural purposes, they must be studied for their three-way interaction with plants (soil), soil microbiota (soil), and NPs. This should be done before the commercial use of NPs in agriculture (Fraceto et al., 2020).

3.6.2. *Toxicity*

Nanopesticides kill pests, and because of this, they can be dangerous to organisms that they are not meant to kill. Non-target organism species, exposure route, concentration, duration, and environmental matrices all play a role in adverse effects and toxicity that might be detected. Nanopesticide characteristics also play a role. Commercially available Cu-based (Kocide 3000) and Ag-based (Zerebra Agro) nanopesticides can have detrimental effects on soil microbiota, microcrustaceans, and plants at the metabolic, physiological, and genetic levels (Kamle et al., 2020). The structural changes in plant tissues, the reduction in the amount of chlorophyll, the modifications to the antioxidant defence system, the metabolic reprogramming, and the genetic over-regulation are a few examples of these changes. Nanopesticides can help reduce microbial activity in the soil. Agriculturally relevant doses, on the other hand, were found to have fewer of these bad effects in one-year experiments. This may be because of the intrinsic resilience and self-recovery of soil (Javeed et al., 2022). Additional research is required about other nanopesticides and exposure scenarios that have somewhat high market potential. The toxicities and negative impacts of nanopesticides are also likely to exist outside of terrestrial systems (for example, aquatic ecosystems). Studies examining the detrimental effects of Cu-based nanopesticides in marine settings revealed that the bioavailable form of the nanopesticides was present when treated lumber (used as a nanofungicide) was transferred into saltwater. Furthermore, when the same Cu-based nanopesticides were used on benthic communities in lab tests, detrimental effects were discovered that were statistically significant (Gul et al., 2014). Despite the advantages of nanopesticides, they may have detrimental ecological effects when they are moved outside of agricultural systems, underlining the existence of data gaps that need to be filled.

In comparison to conventional pesticides, smart nanoformulation offers greater pesticide efficacy at lower AI dosages. As a result, these lessen the harmful threat that AIs pose to people and other living things. Additionally, nanoformulations lessen the risk of pesticide pollution because of their ability to break down pesticide residue following a

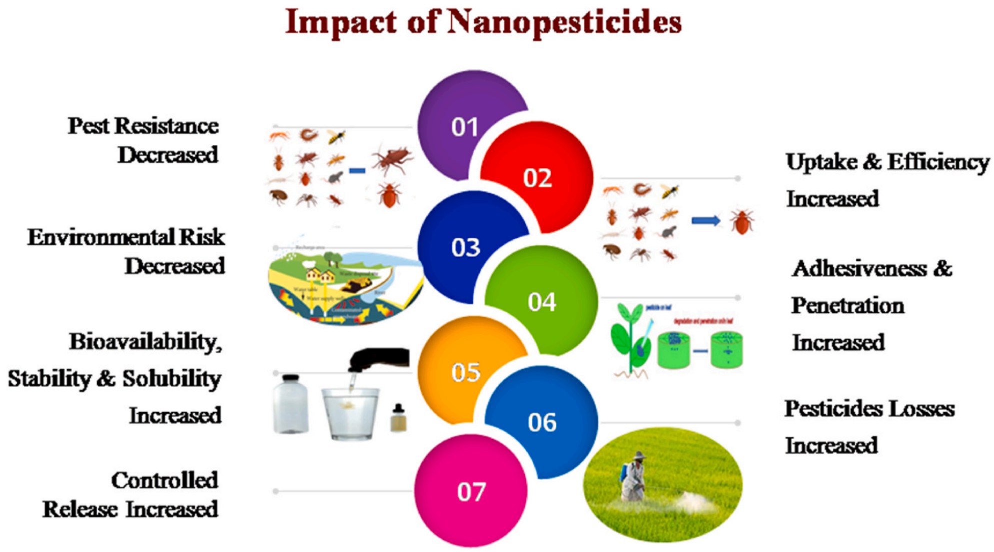

Fig. 3. Schematic representation of the impact of Nanopesticides on pests.

major discharge of Ais (Iavicoli et al., 2017). It would be impossible to completely outlaw the use of conventional pesticides while taking into account their potentially harmful consequences. However, nanotechnology offers solutions for converting conventional pesticides into more intelligent nanoformulations. The use of pesticide nanoformulations, which requires fewer organic solvents for production and guarantees the safe application of pesticides with good stability, is revolutionary. In addition to the numerous advantages of pesticide nanoformulations, there are several issues in commercialising such products. It is crucial to preserve the nanoformulations' stimuli-responsive behaviour as they scale up from the lab to the industrial level. For instance, because nanoformulations have such a large surface area, they can quickly deteriorate when exposed to sunlight, which reduces the efficiency of artificial intelligence. Like this, spraying crops with tiny droplets can greatly boost the amount of leaf surface coverage. However, this droplet size decrease may cause them to evaporate before they get to the intended leaf surface (Rajput et al., 2021).

Additional challenges are presented by the toxicological profile of these ingenious nanoformulations. Numerous toxicokinetic models have been developed so that researchers may evaluate the pace at which pesticides are released from nanoformulations, their dispersal in the environment, and the assessment of the number of pesticides that are taken in by the local environment. By modelling the equilibrium between chemical buildup and removal from all possible exposure routes, steady-state assumptions serve as the foundation for toxicokinetics models (Xin et al., 2020). Three categories of toxicokinetic models can be distinguished based on the steady-state approach: models based on bioconcentration factors, models based on fundamental empirical statistical relationships, and models based on quantitative structure-activity relationships. However, these steady-state methods do not perform well under particular environmental conditions, such as those involving significant changes in chemical exposure and occurrence. Toxicokinetic models are best described as a system of compartments, and this is the most sophisticated way to do so (Joshi et al., 2019). One type is based on actual data, such as concentration-time profiles of individual compartments, while the other is based on physiological descriptions of human anatomies, such as multi-compartment models (such as blood or another biological matrix). These models have received approval from national and international advisory organisations for use in the toxicological risk assessment of chemical exposure (Okey-Onyesolu et al., 2021).

Interspecies differences in exposure patterns can be examined using a combination of methodologies, including in vitro testing and toxicokinetic models. The amount of expression of xenobiotic-metabolizing enzymes, life cycle, and other factors can be used to specify the toxicological sensitivity to chemical formulations. Models were developed particularly for aquatic animals (fish species) and took into account a wide range of pollutants, such as metals, nanoparticles, biocides, chemical compounds, and so forth. These models are useful for analyzing how much stress an organism experiences after being exposed to various chemical and/or toxicant concentrations (Mishra et al., 2018).

It is believed that the accumulation of AIs-loaded nanomaterials in the cytoplasm and the electrostatic interactions that occur between them are the root cause of the toxicity. Chemical pesticides will be less dangerous when they are encased by nanocarriers than they would otherwise be, according to several research articles. The human body can easily absorb insecticides through breathing exposure (Yadav, 2021). In comparison to nonencapsulated insecticides, the health concerns associated with the use of nanocarriers for the controlled release of AIs have been described for several different nanoformulations. However, there aren't many thorough studies in the literature evaluating the effectiveness and environmental effects of pesticide nanoformulations in real-world settings. There are a few publications that can be found in the published literature that discuss the toxicity of pesticide nanoformulations to organisms that are not the intended target, as well as their impact on the environment. All published findings indicating enhanced efficacy, except a few field-based investigations of these nano-formulations, have been derived at the laboratory level (Prasad et al., 2017). A comparison was made between the in vitro toxicity of nanopermethrin to human peripheral erythrocytes and lymphocytes and the toxicity of its commercial bulk version, permethrin. Human blood cells exposed to these formulations exhibit morphological changes, a significant increase in echinocytes, and a decrease in cell viability. When compared to bulk permethrin, nano-permethrin had fewer cytotoxic and genotoxic effects, and these effects increased in direct proportion to the pesticide dosage [1].

4. Metal-organic framework as nanopesticides

MOFs have attracted a lot of attention lately because of their inventive structure-property relationships. For their ability to adsorb drugs in the pores, they have been regarded as highly targeted nanocarriers. They can be used to circumvent some of the limitations of conventional treatments, such as non-selective biodistribution and poor solubility, which may harm healthy tissue and result in cardiotoxicity (Yu et al., 2022). The MOFs exhibit several distinctive characteristics, including numerous topologies, efficient surface chemistry, strong thermal stability, and enormous surface areas. The various advantages of nano-pesticides-based MOF are shown in Fig. 4. In addition to MOFs, there are several different porous matrices, such as activated clay, activated alumina, adsorption resin, and activated carbon. The effective lives of AIs have been extended by these formulations. However, there is still more work to be done to address the non-biodegradable character of these materials. Encapsulating artificial intelligence can be more volatile, and an alternative method of doing so has been developed: MOFs. These earth-friendly MOFs are easily broken down in the water to their parts (Ca and Fe), which function as soil nutrients and, as a result, reduce the amount of environmental contamination that occurs. Metal clusters or ions that act as coordination centres and are coupled by organic ligands are commonly used to create MOFs [1]. For the delivery of active species, MOFs can provide a variety of active sites with varying intensities. They have high adsorption capacity, outstanding electronic characteristics, and greater ion exchange capabilities. The size of the encapsulated species has to be larger than the holes of the matrix to enable the successful encapsulation of AIs in a porous matrix and to avoid the leaking of AIs through pores. Two different synthetic techniques must be applied to support the circumstances of encapsulation: building the AIs inside the MOFs' pores and (ii) putting together the hollow MOFs that surround the AIs. The sort of AIs to be enclosed and the support's chemistry affects both encapsulation techniques. More research can be done on how MOFs can be used in ways that are good for the environment, such as by using metal ions that are safe for the environment or by delivering natural ingredients to solve the problem of toxicity. Both of these options have the potential to be investigated further (Gao et al., 2021). Porous structures (430 and 160 m^2/g) based on Ca^{2+} ions and lactate were loaded with the fumigant cis-1,3-di chloropropene and had good drug-release kinetics. The release kinetics of these sorption-based formulations were enhanced, with MOF-1201 releasing 100 times more slowly than MOF-1203. More research is required to investigate the potential for drug loading, toxicity to non-target plants, and residual content of MOF-based encapsulation.

4.1. Metal-organic frameworks as promising materials for cleaner production in agriculture

Metal-organic frameworks (MOFs), a revolutionary technology suggested in agriculture, have been important in the departments of sensing and the removal of agrochemicals (adsorption and/or photodegradation). With inorganic nodes (such as atoms, clusters, or chains) and organic linkers (such as carboxylates, nitrogenated, or phosphonates), MOFs are thought to be a remarkable family of extremely porous

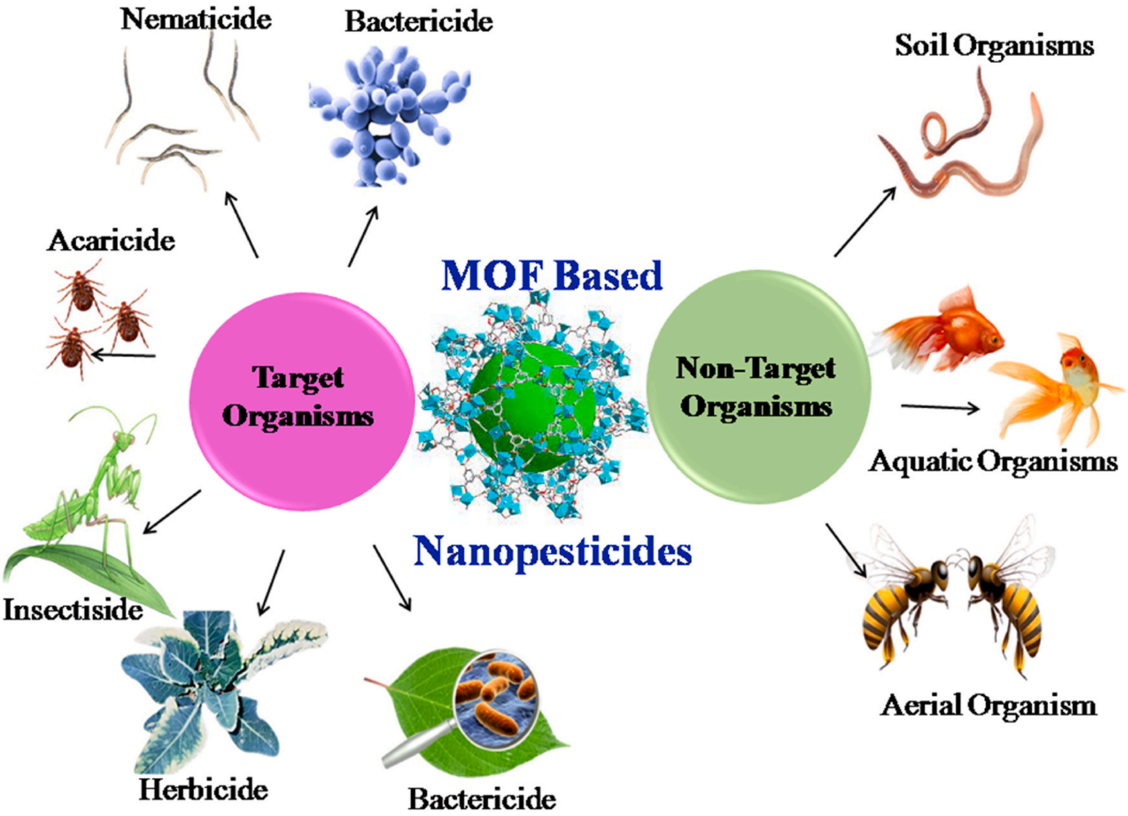

Fig. 4. Advantages of MOF-based nanopesticides.

coordination polymers that assemble into multidimensional periodic lattices. Many societally and industrially important uses, including adsorption, separation, magnetism, luminescence, conductivity, sensing, catalysis, energy, medication delivery, etc., have been proposed for MOFs (Sharma, 2017). Due to their intriguing properties, MOFs are particularly promising materials for use in agriculture (Enuh and Çelik, 2022). These properties include adaptable hybrid compositions that enable a wide range of combinations, (ii) large specific surface areas and pore volumes linked to exceptional sorption capacities, (iii) easily functionalisable cavities where specific host-guest interactions may occur, (iv) large-scale synthesis (some of them are already commercialised), and (v) an adequate stability profile, so they can withstand a variety (Konwar, 2022).

MOFs are a group of materials that are very porous and made of metal ions or clusters and organic ligands. MOFs coupled with other catalysts with merely large surface area and thermal stability cannot provide considerably improved catalytic performance and stability. MOFs have made a lot of exciting progress in the last ten years, especially in the areas of energy storage and conversion, photocatalysis, Fenton-like catalysis, and organocatalysis. This is due to their high porosity, low cost, excellent activity/performance, and modifiable structure/composites, which are very important in energy, environment, and chemical synthesis research.

5. Nanopesticides and sustainable agriculture

Managing global food and nutritional security, preventing climate change, and managing natural resources are all issues that necessitate the integration of farming with the chemosphere. Nanomaterial use has the potential to unintentionally and catastrophically affect water, related ecosystems, and soil bacteria, all of which require attention. The high-cost input is the second significant obstacle that faces agrinano biotechnology (Prabha et al., 2022). For instance, it is estimated that 50 mg of nanowire will be able to power 50 M mobile devices, whereas it might take 100 t of nitrogen fertilizer to cover 1 ha. In addition, the destiny and behaviour of nanoparticles such as zinc oxide and titanium oxide as nano fertilizers are unclear because of the possibility that they may disperse across a large region of the field and cause harm. One of the most important nanomaterials, carbon dot, is made from unprocessed biomass, which allows for the gathering of renewable energy while also having a wide range of applications in several industries, including agriculture. A broad mechanism is needed to increase the usage of C dots in sustainable biomass because their photoluminescence mechanism is not well understood. Although nanotechnology has great promise for use in agriculture, the discharge of these products into the environment is likely to pose toxicological risks (Tripathi and Prakash, 2022). These nanomaterials' effects on environmental issues, biosafety concerns, and human health are less well understood, necessitating extensive and in-depth research. The balance between improved crop production, sustainable environment, and sustainable agriculture. It is important to look into how NPs affect cells and genes, as well as how plants accumulate reactive oxygen species (ROS) as a consequence. Additionally, further research is needed to determine how engineered nanoparticles are absorbed by plants, where they are distributed, and whether the micronutrients contained in NPs are bioavailable. Since the application of NPs in agriculture is more complicated than it is in other fields, such as electronic or optical, it will take more time-consuming and specialised research to address these challenges (Hazarika et al., 2022).

6. Environmental issues with pesticides

Food production and crop yields have significantly increased as a consequence of the widespread usage of conventional pesticides and agrochemicals. This has enabled the global population to continue its rapid growth while still being fed. Instead of using high-yield crops, the increase in crop yields can be ascribed to the efficient use of insecticides to manage pests. Pesticides not only raise crop yields but also improve quality of life, require less labour and energy, and increase food safety (Ahmed et al., 2022). Agriculture is struggling to maintain the trend of rising yields in the twenty-first century due to several issues. Pesticide residues in the environment have been the subject of numerous research in recent years, as they have poisoned ecosystems and/or impacted the nutritional value of crops and food products. It is understood that 99.9% of pesticides seeped into the environment, while only 0.1% of them reached the intended pests (Singh et al., 2022). Organochlorine pesticides, such as DDT and its metabolites, have been shown to have detrimental effects on animals, including birds, mammals, reptiles, and aquatic and terrestrial amphibians (Kannuri, 2022). These effects can be androgenic or estrogenic. Beyond organochlorines, the main contributors to chronic toxicity (and thyroid disruption) in birds, rodents, fish, and amphibians are carbamates, organophosphates, thiocarbamates, pyrethroids, triazoles, and triazines. These endocrine-disrupting substances (EDS) have been linked to several transgenerational and epigenetic consequences in aquatic animals. For instance, two of the main organophosphates that are detrimental to animals are malathion and chlorpyrifos. Malathion and chlorpyrifos residues can make up more than 50% of all applied organophosphate pesticides that harm the salmon's olfactory system in neurobehavioral ways. Neo-nicotinoids (10 ppb thiamethoxam) were given to bumble bee colonies that provided less frequent visits and pollen collecting from apple trees (An et al., 2022). Ultimately, apples produced with fewer seeds (around a 36% drop) show the effect of diminished pollination services delivery. As a result, pesticide exposure reduces bees' capacity for pollination and upsets stable crop yields (and natural ecosystems). Even though pesticides provide many advantages for crop protection, improper pesticide application can have several negative consequences (such as harmful residues that pose potential health hazards and pollute the environment). Pesticides can enter the body of a person directly by oral, cutaneous, or inhalation exposure, as well as indirectly through occupational exposure and food consumption (Sridhar et al., 2022). In humans, exposure to pesticides has been linked to several health problems, including obesity, cancer, neurological disorders, endocrine abnormalities, and allergy asthma. The presence of AIs in the environment induced by AI loss via drift and volatilization can have harmful health effects not only on agricultural workers but also on the nearby population. High levels of agricultural pesticide exposure during pregnancy harmed birth outcomes, increasing them by 5–9%. The features of the AIs and how they are made, site circumstances and regional farming, the interval between applying pesticides and harvest, the type of crops, pest infestation, and plant health are a few factors that have a big impact on residue levels. High residue levels are most likely to be present in an underdeveloped crop (Dhyani et al., 2022). Numerous AIs present in apples, including Captan, Folpet, Iprodione, and Procymidone, are carcinogenic. Even after taking into account weight loss, exposure to organochlorine pesticides can significantly increase the risk of cognitive impairment, which is almost three times higher in elderly people (aged 70). The chance that organochlorine pesticides will enter brain neurons can also rise as a result of weight reduction. Maximum residue levels (MRLs) of pesticides are specified by several international standards, including those established by the European Union (EU), Codex Alimentarius, a joint body of the UN World Health Organization (WHO), and the Food Agriculture Organization (FAO), and other organisations., Attempts have been made over the years to either outlaw harmful compounds or lower the MRLs in food to prevent health problems. These efforts involve the creation of non-chemical pest management methods or more effective pest targeting using active chemicals with fewer adverse effects (Yadav et al., 2022a). However, some factors, such as the introduction of new chemicals (such as thiabendazole) and the existence of remaining compounds in the environment as a result of the repetitive and cumulative use of AIs in agriculture, have prevented the reduction of pesticide exposure from being sufficient. Determining the main exposure paths for both aquatic and non-aquatic species can be aided by taking into account the various pesticide release mechanisms in the field (Soni et al., 2022).

7. Future perspectives

Over the past decade, plant protection product development has advanced relatively quickly. To overcome the drawbacks of conventional pesticides, such as their limited water solubility, early breakdown, and increasing plant resistance, pesticide nanoformulations have garnered considerable interest. The use of NPs as pesticides and genetically modified crops are examples of the current trends in pesticide development. The goal of advanced pesticide formulations is to design and develop nanoproducts with improved biodegradability and fewer negative environmental consequences, leading to cleaner agricultural production. The use of such formulations may provide a practical way to mitigate long-term environmental harm (Gangola et al., 2022).

The use of nanobiotechnology in agriculture is relatively recent, and it faces significant obstacles that need extremely in-depth investigations and testing. Nanomaterials can be employed to improve the soil's nutritional capacity to enable sustainable, cleaner agricultural production and improve environmental safety. It is planned to develop nanomaterials that could speed up and target nutrient intake by plants. The wide-ranging potential exists for the designation and use of nano biopolymers in agricultural fields for seed coatings as a protector and soil stabilizer, preserving nutrients and water, in addition to increasing yield. Hydrogel and suspension forms of nanofabricated materials can be created for easy storage and convenient delivery (Anderson et al., 2016). Such materials can be utilised in nanoremediation to improve the ability of nanoparticles to attach to soil particles, such as calcium carbonate and iron nanoparticles. For example, the rehabilitation of soil contaminated with radionuclides, heavy metals, and pesticides can be achieved using zerovalent iron nanoparticles. Plant genetic improvements may also be accomplished using nanomaterials with genes and medication compounds delivered to targeted locations within cells using specially designed nanomaterials. nanoarray-based technologies can be utilised to regulate gene expression in plants and to create plants that are resistant to salinity and stress. It is necessary to develop nanotools for managing natural resources, intelligent agrochemical delivery systems, and intelligent food processing and packaging systems. Large-scale contaminated areas can be cleaned up, and contaminated water can be purified using nanoremediation (Singh et al., 2020). By eliminating the acidity of the soil, nano zeolites can improve soil quality. Although it is still in its infancy, the use of nanobiotechnology in agriculture is astounding. Crop yield and nutritional value can both be improved by the use of nano fertilizers. The development of nanopesticides and nanoherbicides, food preservation and packaging, contamination removal from soil and water, enhancing fruit and vegetable durability, bolstering natural fibres, effective gene delivery and expression for crop genetic improvement, regenerating soil fertility and reclaiming salt-influenced lands, preventing irrigation system acidification, and precise water management, and energy conservation are some of the other issues that need to be addressed (Mahanty et al., 2017). In a broad sense, increasing crop yield to ensure food security, improving energy efficiency via a sustainable economy, alleviating environmental problems, and promoting green technology are other key tasks to be achieved through such innovative methods that are anticipated to be achieved shortly if this technology is implemented and applied effectively and wisely. Before nanomaterials can be used commercially, their properties, including their dimensions, surface chemistry, immunological responses, and other consequences, have to be carefully examined with issues relating to exposure, dosage, accumulation, and retention,.

Although this cutting-edge technology has greatly benefited the agricultural industry, a significant gap remains between theory and practice. Future research must focus on addressing risk-related concerns and developing nontoxic, eco-friendly, and more effective nanomaterials to ensure sustainable, cleaner production (De Oliveira et al., 2018). To achieve these goals, the scientific community must collaborate to develop them using a practical approach. The safety limits of nanoparticles must be investigated to sustain agriculture and prevent toxicity. To address biosafety concerns, research should conduct on the physicochemical characteristics of soil and how it interacts with nanomaterials (Camara et al., 2019). Focusing on biologically produced nanoparticles, such as those produced by viruses, bacteria, fungi, algae, and higher plants, may provide promising solutions to the problems associated with NPs (Ganguly and Mondal, 2022). Future studies must concentrate on developing intelligent nanomaterials for targeted agrochemical delivery to increase their efficiency and intelligent plants that can act as sensors, as well as improving the function of plants and soil for sustainability via microbiome enhancement and increasing yields while maintaining environmental safety (Sarkar et al., 2022). Extrusion of nanoporous membranes for the synthesis of nanomaterials at scale remains technically problematic. The main problem is that despite having superior size control, the yield of nanoporous membrane extrusion is typically lower than other recognized nanofabrication processes. This is primarily because almost every nanoporous membrane extrusion technique depends on using nanopore channels to regulate the size of products. As a result, filtration residue from raw materials continuously accumulates on the feeding side of the nanoporous membrane, eventually blocking these nanochannels.

Therefore, future research should focus on the following issues: (a) safe use of NPs at allowed levels for agricultural benefits by modulating behaviour, bioavailability, and toxicity determining factors should be optimised; (b) a more practical long-term experimental scheme is a prerequisite for securing the safety limits and reducing nanotoxicity and (c) administration of biologically synthesised nanomaterials and assessment of their advantages as bio-cleaner production.

8. Conclusions

The use of nanotechnology to manage pests in agriculture was covered in this review. Revolutionary technologies based on nanotechnology aim to solve many other urgent issues, such as the energy crisis, diminishing water supplies, degrading soils, and, lastly, the consolidation of cleaner manufacturing. High agricultural productivity is one of these issues. Recent studies have focused on developing protocols to experimentally demonstrate the properties of nanopesticides, (ii) conducting extensive research on the persistence and bioavailability of nanopesticides, and (iii) evaluating existing methods for environmental risk assessment, followed by their appropriate improvement. Sustainable agriculture necessitates the employment of a variety of technologies, such as organic, conventional, or hybrid, to assure ample crop yields at competitive prices that both ensure farmers' incomes and reduce the environmental impact of agriculture. It is important to maximise the distribution of herbicides to their intended targets while minimising the harm to unwanted plants. The creation of nanoencapsulation media, such as polymers, lipids, clay, MOFs, green nanoformulations, and other nanomaterials, is projected to make it easier to distribute items precisely while reducing the risk that they would degrade too quickly due to environmental variables. In addition, the application of nanomaterials in AIs and biopesticides can be expected to result in effective management strategies that will outperform chemical pesticides in a variety of circumstances (e.g., water solubility, no premature degradation, and decreased plant resistance). An iterative process that starts with the identification of a pest continues with the development of pesticide nanoformulations and ends with the observation of side effects is the best way to apply new pesticide nanoformulations. The use of pesticide nanoformulations provides realistic and cutting-edge pest management options to solve contemporary issues of environmental degradation and irresponsible land reuse. Nanoformulations could change crop production in a big way by increasing crop yield, making plants more resistant to disease, and making sure nutrients are used correctly. For nanoformulations to be used safely and to gain widespread acceptability, interactions between them and intra- and extracellular sites of different plant species must be resolved. According to the WHO, numerous initiatives have been undertaken in recent years to create a national and worldwide risk assessment and management plans. These tactics will aid in addressing the possible risks associated with nanotechnology-based goods and/or methods. Beyond these risks, it will be important to more clearly define the precise role that nanoformulations play in a certain product to raise its market standing.

Declaration of competing interest

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

Data availability

All data has been reported in the article.

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