PLANT SCIENCE TODAY
Vol 13(2): 1-19
https://doi.org/10.14719/pst.11630

eISSN 2348-1900

REVIEW ARTICLE

Smart targeting of nanopesticides: Advancing environmental protection and sustainable agriculture

Hayyawi WA Al-juthery[1*], Nabil R Lahmoud[2] , Hassanein H Al-juthery[3], Diaa F Hassan[4], Mustafa Qais Hamid[1] & Rand AHG Al-Taee[5]

[1]Department of Soil Science and Water Resources, College of Agriculture, University of Al-Qadisiyah, Al-Diwaniyah 58000, Al-Qādisiyyah, Iraq
[2]College of Agriculture, University of Wasit, Kut 52001, Wasit, Iraq
[3]Department of Science and Technology Parks, Al-Qasim Green University, Al-Qasim 51013, Babylon, Iraq
[4]College of Engineering, Al-Qasim Green University, Al-Qasim 51013, Babylon, Iraq
[5]College of Agriculture and Forestry, University of Mosul, Mosul 41002, Nineveh, Iraq

*Correspondence email - hayyawi.aljutheri@qu.edu.iq

Received: 04 September 2025; Accepted: 20 January 2026; Available online: Version 1.0: 22 March 2026; Version 2.0: 01 April 2026

Cite this article: Hayyawi WAJ, Nabil RL , Hassanein HAJ, Diaa FH, Mustafa QH, Rand AAT. Smart targeting of nanopesticides: Advancing environmental protection and sustainable agriculture. Plant Science Today. 2026; 13(2): 1-19. https://doi.org/10.14719/pst.11630

Abstract

The smart application of nanopesticides marks a significant shift toward environmentally responsible and sustainable pest management. By utilising nanotechnology to encapsulate and deliver active ingredients with high precision, nanopesticides offer targeted action against pests while minimising collateral damage to non-target organisms and ecosystems. Unlike conventional pesticides, these nanoscale systems reduce the overall chemical load required for effective pest control, thereby mitigating environmental pollution and human health risks. Advanced delivery strategies such as stimuli-responsive release, ligand-receptor targeting and controlled degradation enhance the specificity, stability and efficiency of these formulations. Innovative nanocarriers, including polymeric nanoparticles, liposomes and mesoporous silica nanoparticles, enable the controlled release of active compounds in response to environmental triggers such as pH fluctuations, temperature changes, or enzymatic activity. These technological breakthroughs align with the principles of sustainable agriculture by reducing chemical runoff, groundwater contamination and pesticide residues in the food chain. Additionally, the decreased frequency and quantity of applications contribute to lower carbon emissions and resource consumption. To ensure the safe integration of these technologies, robust regulatory frameworks and comprehensive risk assessment models are essential.

Keywords: controlled release; environmental protection; environmental nanotoxicology; sustainable agriculture; smart nanopesticides; targeted delivery

Introduction

The agricultural sector has long depended on synthetic pesticides to ensure effective crop protection and to enhance agricultural productivity. Despite their extensive application, conventional pesticide formulations exhibit several fundamental limitations, including low target specificity, rapid degradation, leaching into soil and aquatic systems and unintended toxicity to non-target organisms. These shortcomings contribute to environmental pollution, biodiversity loss and potential risks to human health through occupational exposure and food residues (1). Against this backdrop, nanotechnology has been proposed as a new paradigm for improving the intrinsic values of pesticides by enhancing their delivery and reducing negative environmental and human health influences. Nanopesticides, those pesticide products containing nano-sized active ingredients or materials with nanostructural properties, are an innovative development for agrochemical formulation. Through controlled and stimuli-responsive release, higher stability and targeted delivery, nanopesticides can improve bioavailability at the site of action while reducing overall pesticide inputs (2, 3).

On the other hand, the production of biodegradable and bio-based nanocarriers has made it possible to design greener pesticide formulations being less persistent and toxic to the environment. These are promising developments in which nanopesticide technology is being adapted to the requirements of sustainable agriculture and possible ways to continue crop production while reducing environmental disturbance and human health hazards (4-6). Smart targeting: It is the ability of delivery systems and formulations based on nanotechnology to specifically focus AIs at a target or a site of insect pests or pathogens, leaving minimal irrelevant exposure to non-target organisms, intended for environmental risk reduction. This selectivity is accomplished through several ways, such as identification of pest- and pathogen-specific biomarkers, the use of ligand-functionalized nanocarriers, pH-triggered release systems and sophisticated surface-engineering approaches (7). These controlled pesticide-releasing mechanisms not only improve the bioavailability and efficacy of insecticide formulations but also reduce the amount applied and frequency of application, thereby significantly the overall chemical load into the environment (8).

In addition to smart targeting, nanopesticides also act in protecting the environment by solving several drawbacks of typical pesticide formulations. Such as nanoencapsulation shields the active ingredients from volatilisation and photodegradation, extending their half-life and therefore needing to be applied less frequently (9). Furthermore, controlled-release formulations facilitate slow and sustained release of pesticides in response to environmental stimuli, such as moisture or enzymatic activity, to reduce off-target leaching into groundwater and deposition in balancing ecosystems (10, 11). Hence, the times of a nanophysicist can be useful in dealing with problems concerning the pollution of the environment and the development of environmentally friendlier and safer insect control practices. In addition, recent research has shown that nanophysics agents are capable of altering the toxicity profile of existing active components. (12). The use of nano-formulated chlorpyrifos and tuberconazole in the soil organisms exhibited distinct differences in accumulation and bioavailability, signifying the highs and lows of the use of the two. This is supported by the fact that there is a need for hard-working research in the environment to ensure that the use of nanopicistics has a different cost than is not anticipated (13, 14).

In short, nanopesticides represent a pioneering development in agri-tech, their targeted action and minimal off-target effects providing much-needed solutions to the ever-growing emphasis on sustainable and precision agriculture. As the research progresses, there is a need to tread carefully between innovation and safety; nanopesticides should fulfil their promise without compromising environmental integrity.

Nano-pesticides: Environmental fate –transport, aggregation, dissolution and interactions with soil components

Soil transport and mobility of soil

The environmental transport of nano-pesticides is a function of both physical movement by soils, as well as the interaction with soil components. In porous media such as soil, nanopesticides can move by advection (carried with the water velocity), diffusion and dispersion, mobility being much influenced by particle size and surface coatings and also the conditions of soil, like pH or ionic strength (15). Although smaller-sized, surface-modified nanoparticles typically have greater mobility under saturated flow, this transport efficiency might be, however, mitigated by association with soil particles or the presence of organic matter (15). It has been recently revealed that, if not immobilised by interaction with soil solid phases, nanoaggregates reach deeper horizons of the soil, though their depth migration is extremely variable depending on soil type and environmental conditions (15).

Aggregation and stability

Aggregation and heteroaggregation are key controls of the fate of nano-pesticides in terrestrial systems. Nanoparticles added to the soil can homoaggregate (particle-particle) or aggregate with natural colloids, such as clay minerals and humic substances, thereby modifying their effective sizes and surface properties (16). These aggregations are affected by electrolyte effects and divalent cations as well as DOM (dissolved organic matter) naturally dissolved in water, which can change surface charge and attenuate electrostatic repulsion (16). In this case, the mobility was reduced while sedimentation was increased , resulting in a lower bioavailability but greater retention within the diamond soil matrix (16).

Dissolution and release of active ingredients dissolution

The dissolution and release of active ingredients (e.g., pesticides, biocides, etc.) is an important property of nano-pesticides, especially metal/metal-oxide based formulations, which can significantly affect their behaviour in the environment. These studies support other recent observations showing oxidative dissolution and redox reaction in the soil will affect post-release of ionic species or, in some cases, toxicity profiles (17). Rates of dissolution depend on characteristics such as soil pH, redox potential and the existence of stabilising organic coatings (17). On the other hand, dissolution in polymer-based nano-carriers is often associated with a controlled-release profile either as a result of environmental cues (e.g., humidity or enzymatic activity). Although controlled dissipation increases the effectiveness of pest control and reduces treatment frequency, long-term release might prolong environmental exposure, suggesting comprehensive risk assessments are warranted.

Interaction with soil OM

The geochemistry of nano-pesticides is greatly influenced by soil organic matter (SOM). Organic coatings and humic materials can adsorb onto nanoparticle surfaces to form an organic corona, which changes surface charge, stabilises against aggregation of the nanoparticles and tunes transport (15, 16). This SOM coating can either increase particle mobility via steric stabilisation or decrease mobility through the processes of heteroaggregation and soil matrix sorption. The overall effect is determined by the amount and composition of SOM available, environmental conditions (including pH and ionic strength), etc.(15, 16).

Interactions with clay minerals

Nano-pesticide behaviour is substantially affected by clay minerals, especially montmorillonite and kaolinite, as they have huge surface areas and charge differences. New evidence has shown that nano-pesticides can be easily adsorbed onto clay surfaces via electrostatic interactions and ligand exchange, with ensuing heteroaggregation and decreased mobility (15). Such adsorption can immobilise nano-pesticides, preventing their deeper penetration but potentially forming hot spots of high concentration that affect the microbial communities and geochemical processes (15). Retention on clays, combined with interaction with organic matter, frequently yields a complex pattern of transport and fate processes that are dependent on soil texture and chemistry.

Environmental fate considerations of transport, aggregation, dissolution and interactions with soil components provides a broad framework for predicting nano-pesticide fate in terrestrial systems. Nano-pesticides can show greater mobility than conventional pesticides, but their environmental fate will be affected mainly by aggregation with soil particles, exchange with SOM and clay minerals and the dissolution pattern that can change within the environment (15-17). There is a direct relation of these processes with bioavailability, potential groundwater contamination and ecological risk, highlighting the requirement for mechanistically (risk assessments) and environmentally informed design of future nano-formulations.

Mechanisms of interaction, toxicity, food transport and dissolution of pesticide nanoparticles: Implications for environmental safety

The eco-toxicological aspects of pesticide nanoparticles are controlled by their interactions with living organisms, their ability to cause chronic toxicity, the impact on trophic webs through the food chain and dissolution/transformation behaviours in environmental compartments that have been assessed. Together, these integrated processes govern exposure routes, bioavailability, persistence and ecological risk.

Effects on biological systems

The interaction of pesticide nanoparticles with biological systems is a result of physicochemical processes mediated by their surface. Crucial mechanisms are electrostatic attraction, hydrophobic interaction and specific ligand–receptor binding that mediate adhesion to biological surfaces, such as plant cuticles, insect exoskeletons and the epithelial tissues of aquatic and terrestrial organisms (18). Nanoparticles obtain a biomolecular corona of proteins, lipids and polysaccharides on interaction with biological fluids that tend to rapidly modify their surface characteristics, eventually affecting cellular uptake, biodistribution and toxicity (19). Cellular uptake might be followed by endocytosis, passive diffusion of liberated ions or molecules, or carrier-mediated transport depending on particle size, surface charge and coating composition (20). Although these interactions have the potential to improve pest control against pest species, such mechanisms can also be present in non-targets, creating possible risks for side effects.

Chronic toxicity and sublethal effects

Besides the acute toxicity, chronic exposure to pesticide NPs may cause various types of sub-lethal effects that are ecologically important. They also cause oxidative stress and changes in enzymatic activity, immunotoxicity, endocrine disruption, as well as genotoxic effects, which could result in inhibiting the growth, reproduction, development and behaviour over long-term exposure (21). Chronic effects have been of particular interest, mainly because nanoparticles could remain in soil, sediment or the organisms themselves for a long time and at low doses. New insights Recent publications highlighted that nano-formulations might shape toxicological profiles differently than classic pesticides, i.e., favouring bioavailability or extending exposure via controlled-release (4, 18). As a result, the typical toxicity assessment paradigm using only acute endpoints may overlook ecological hazards of nano-pesticides.

Food transport pathways and subsequent trophic transfer

Pesticide nanoparticles can transport to the food web via various pathways. In terrestrial environments, nanoparticles could be uptaken by roots and translocate to the aerial tissues where herbivores and higher trophic animals feed from (22). In aquatic environments, however, nanoparticles can be readily taken up by plankton or benthic organisms and transferred to predators via food (23). Trophic transfer is often associated with physicochemical transformation of the nanoparticles (NPs), for example, aggregation, surface coating and partial dissolution that can alter NP bioavailability and toxicity at higher trophic levels (24). While the biomagnification of whole particles in general is restricted, repeated oral exposure may cause the accumulation of particles or released ions with potential chronic risks for consumers.

Dissolution behaviour and transformation processes

Dissolution behaviour of NPs is one of the main controlling factors for NP fate and toxicity, especially in the case of metal- and metal-oxide–based pesticide formulations. Environmental factors such as pH, redox potential, ionic strength and interactivity with organic matter and minerals have a large effect on dissolution rates and released ionic species (17). Toxicity is, in many cases, due to a combination of particle-specific effects and dissolved ions, which makes hazard evaluation complex. For polymeric or encapsulated nano-pesticides, the release kinetics of active ingredients are controlled by dissolution and degradation processes, which affect the duration and intensity of exposure (18). Although controlled dissolution can decrease application frequency and off-site losses, long-term release can prolong exposure in the environment and thus must be well studied for future risk assessment.

Environmental safety implications

The interaction mechanisms, chronic toxicity potential, food transport pathways and dissolution behaviour of pesticide nanoparticles are interrelated, which need to be evaluated together in the context of environmental risk assessments (18, 21). Although nano-pesticides also open prospects for improving pesticidal efficacy and decreasing the use of chemicals in nature, changes in their physicochemical characteristics concerning conventional formulations may result in modified transport, persistence and bioavailability patterns from those associated with classical formulations and also possibly provide new challenges related to long-term environmental impacts on ecosystem functioning (18, 19, 22). Namely, chronic and sublethal effects, trophic transfer within food webs and dissolution-mediated transformation could also cause longer exposure to non-target organisms at different trophic levels (23, 24). Therefore, to predict ecological exposure quantities accurately and develop control strategies for more environmentally benign nano-formulations in a targeted way, there is a critical need to understand mechanistically the interplay between these processes and regulatory frameworks capable of addressing novel risks faced by nano-enabled pesticides (17, 18).

Comparative nanopesticide types, constraints, costs and regulatory feasibility

Nanotechnology-based pesticide products include diverse formulations such as carrier systems (for instance, polymeric nanocapsules, lipid nanoparticles and nanoemulsions) and inorganic or mineral nanomaterials. While this diversity allows for tuning delivery efficacy and controlled release, it also results in significant variability in environmental fate and risk profiles (20, 25). As summarised in Table 1, different nanopesticide groups have unique benefits, technical barriers, cost characteristics and regulatory requirements. Technically speaking, the > complexity of the formula is quite critical to feasibility. Systems including polymeric and stimuli-responsive carriers have limitations, such as reproducibility, long-term stability or predictability of release in a relevant environmental context Table 1 (26). Simple systems -like nanoemulsions, mineral-based nanocarriers- are usually more scalable and cheaper to produce but less versatile. These technical limitations hinder both overall field performance and the production of regulatory-ready datasets, particularly in cases associated with nanoform identity alteration during environmental ageing. Adoption potential is also economically driven. For example, higher cost for production and quality-

Table 1. Critical comparison and key gaps across nanopesticide types

Nanopesticide type (examples)	Typical advantages	Key technical constraints	Cost/scalability (indicative)	Regulatory feasibility (indicative)	Critical evidence gaps to address
Nanoemulsions (oil-in-water pesticide nanoemulsions)	High spreading/coverage; improved solubilization of hydrophobics and relatively industry-ready processing	Kinetic instability (Ostwald ripening); sensitivity to water chemistry; surfactant/ecotoxicity concerns	Low–Moderate (scalable mixing; depends on surfactant system)	Moderate–High (often treated as formulations; nano-specific claims require stronger characterisation)	Field-aged stability; non-target surfactant effects; residue fate on crops and runoff (28)
Polymeric nanocapsules/ nanospheres (e.g., chitosan)	Controlled release; protection from photolysis/volatilisation and potential dose reduction	Complex synthesis; solvent residues; batch variability; uncertain degradation products; release depends on soil microbiome	Moderate–High (multi-step synthesis; QA/QC costs)	Moderate (requires strong identity + degradation/dissolution profile)	Chronic/sublethal effects; transformation products; harmonised methods for release in realistic media (25, 28)
Lipid-based carriers (SLN/NLC)	Biocompatible components; good encapsulation and potential for stimulus-responsive release	Oxidative instability; temperature sensitivity; polymorphic transitions affecting release	Moderate (scalable, but stability controls needed)	Moderate	Long-term stability; food-chain transfer of carrier-associated residues; standardised characterisation (20, 28)
Mesoporous silica/silica NPs (as carriers)	High loading capacity; tunable release via pore chemistry and physical robustness	Surface modification controls; aggregation in natural waters; potential persistence	Moderate (materials cost moderate; functionalization adds cost)	Moderate (nanoform definition + fate testing required)	Long-term persistence; soil colloid interactions; environmentally realistic dissolution/ transformations (28, 29)
Clay/mineral-based nanocarriers (nanoclays, layered double hydroxides)	Strong sorption; slow release; potentially lower cost and compatibility with soils	Variable natural composition; intercalation reproducibility; release depends on competing ions/DOM	Low–Moderate (often inexpensive feedstocks)	Moderate (composition variability can complicate identity)	Release under variable pH/ionic strength; impacts on soil microbiome; particle-size distribution control (28, 29)
Metal/metal-oxide nanoparticles (e.g., CuO, ZnO; sometimes antimicrobial)	Intrinsic bioactivity and dual function (carrier + activity) in some concepts	Dissolution and redox transformations drive variable hazard, non-target toxicity concerns and persistence in soils/ sediments	Moderate (materials scalable; safety testing costs high)	Low–Moderate (hazard concerns + identity/ion vs particle issues)	Separation of ionic vs particle-driven effects; chronic toxicity; bioaccumulation/trophic transfer; transformation in soils (25, 28)
Stimuli-responsive “smart systems (pH/enzyme/moisture-triggered release; multi-component)	Highly efficient targeting/release; reduced application frequency (potentially)	High design complexity; difficult to predict behaviour after environmental ageing; multi-component identity issues	High (R&D and QA intensive; complex manufacturing)	Low (uncertainty in identity boundaries; difficult read-across)	Standardised test methods for trigger-based release; field validation; regulatory clarity for multicomponent nanoforms (20, 27)

control maintenance was expected to be correlated with those nanopesticides that required multi-step synthesis, special polymers or high-energy process in Table 1. In comparison, nanoemulsions and clay-based carriers can be a cheaper substitute but also need to be thoroughly evaluated for the environmental stability and non-target effects (20).

Regulatory practicality is still one of the most important challenges facing commercialisation. For a large number of nano-enabled pesticide formulations, especially the multimodal systems or those that respond to stimuli can be difficult to define the registrable substance and establish equivalence between test material and the served product, as well as using read-across Table 1 (27). Regulatory evaluation is increasingly focused on thorough physicochemical characterisation, dissolution and transformation testing, along with chronic ecotoxicity data – especially where metal-based NP or complex carrier systems are concerned (28, 29). Overall, Table 1 indicates important evidence gaps for all nanopesticide classes, especially concerning long-term toxicity data, environmentally driven transformations and a lack of standardised testing methodology adapted to nano-specific behaviours. Closing these gaps is necessary to progress safer-by-design nanopesticides and avoid technologies outpacing regulatory decision-making.

Nanopesticides development: Polymer nanoparticles and nanocarriers

Polymere nanoparticles are one of the most studied nanocarriers, which are the most studied nanocarriers in nanopicide, which are due to active ingredients (30) because of their ability to increase the effect, stability and target distribution. Main features of polymer nanopacans Fig. 1. Controlled liberation, polymeric nanocapsules can provide a constant or stimulation ex-release of pesticides, which improves insect control efficiency by reducing the frequency of application (31). Increased stability, this nanotechnology has protected active ingredients from environmental decline as photo grading and hydrolysis, which extends their effective lives (9). Better solubility and bioavailability, many insecticide compounds are soluble in poor water. Polymer carriers help increase solubility and spread, improve absorption and bioavailability (19). Targeted distribution, surface functionalization enables specific pests or plant parts to reduce the risk of non-dimensions and environmental pollution (32). The use of biodegradability, plgas such as kitosan, alginet and biodegradable synthetic polymers ensures environmentally friendly decline without harmful residues (9). Use of agriculture: Polymeric nanoparticle-based pesticides can be used to replace leaf spray, soil application and insecticides in seed treatment, causing leaching and stopping insecticides due to promoting leaching and runoff and permanent agriculture (19).

Nanocarriers in nanopesticide development: solid lipid nanoparticles (SLNs).

Fixed lipids are part of Nanokarde, made of nanopathy (SLN) bio-sustainable and biodegradable lipids that remain solid at room and body temperature, Fig. 2 (30).

Important features of solid lipid nanoparticles:

Better stability of active ingredients, SLNs protect active pesticides against photodegradation, oxidation and hydrolysis and extend the performance of durability and field (9). The controlled and continuous liberation, due to their solid lipid matrix, can provide a slow and even release of SLN plant protection, which reduces the need for frequent applications and reduces environmental pollution (9). High load capacity for lipophilic compounds, SLNs are particularly suitable for lipophilic (oilless) pesticides, offering high encapsulation efficiency and offers better distribution to target pages (18). Biodegradability and biodegradation, made of natural or synthetic lipids, are environmentally friendly and broken down into non-toxic by-products, suitable for them for permanent agriculture (19). Increased recording and adhesion, SLN has good adhesion for plant surfaces, improves pesticides and reduces damage due to runoff or evaporation (32). Application in Agriculture, SLNs have been studied for the encapsulation of fungicides, insecticides and herbicides, such as botanical pesticides, to enhance their efficacy and reduce noxious side effects (33).

Nanocarriers in nanopesticide development: silica and metal -based nanoparticles.

Silica and metal nanoparticles are inorganic nanocarriers that command the wide interest of scientists for their unique physicochemical properties, such as high surface area, reactivity and mechanical strength. Both are used as carriers as well as active components in nanotechnology-based delivery systems of pesticides (30). Silica nanoparticles, silica nanoparticles (SINPS), especially mesoporous silicon dioxide nanoparticles (MSN), with their high load capacity, chemical stability and surface modification, are promising carriers for pesticides (34). High surface region and scams: MSN plant protection agents (35, 36). Effective load of functionalization and continuous liberation: Their surfaces can be modified for targeted distribution and controlled liberation, to reduce pH or temperature (1).

Metal-based nanopathy, metal and metal oxide nanoparticles, such as both ZNO, Cuo, AG and Fe_3O_4, can serve the role of nanocarriers and potentially internal pesticides or antimicrobial activity, as shown in Fig. 3 (32). These nanoparticles can carry pesticides while also acting as antimicrobial or insecticidal agents themselves.

Controlled release and protection

Metal-based carriers can stabilise sensitive active ingredients and control their release over time and magnetic properties (e.g., Fe_3O_4) allow for targeted application using magnetic fields, minimising non-target exposure (37-39). Environmental considerations, while inorganic nanoparticles offer significant advantages, their long-term environmental behaviour and toxicity must be carefully evaluated to ensure sustainable use (30, 40).

Nanoencapsulation and encapsulation techniques in nanopesticide development

Nanoencapsulation is the process of enclosing active pesticide molecules in a nanoscale delivery system to stabilise, enhance their bioavailability and regulate release. It is one of the primary technologies for the effective and environmentally friendly delivery of pesticides (40). Nanoencapsulation methods are employed to safeguard active molecules against environmental degradation, minimise non-target toxicity and target delivery to the pest or plant tissues (9).

Common encapsulation techniques

Emulsions (nanoimals), nanoemulsions are oil-in-water or water-in-oil colloidal screens, with less than 200 Nm specific small drops.

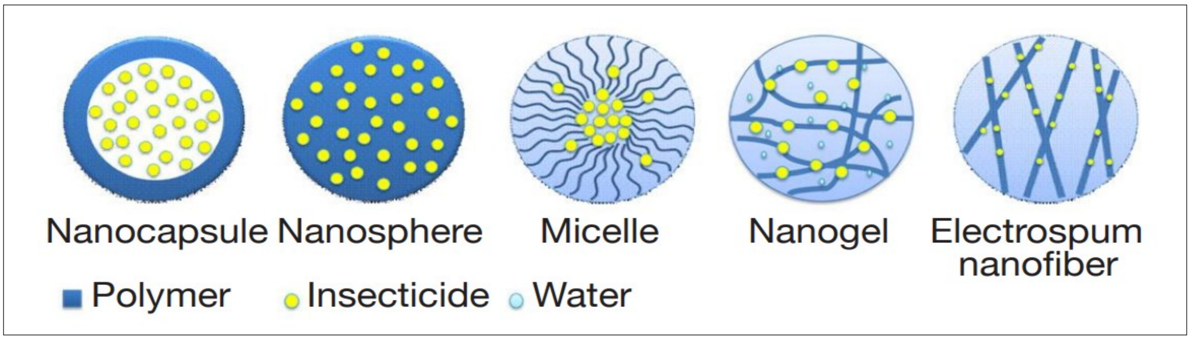

Fig. 1. Different structures of polymeric nanoparticles and polymer-based nanopesticides (20).

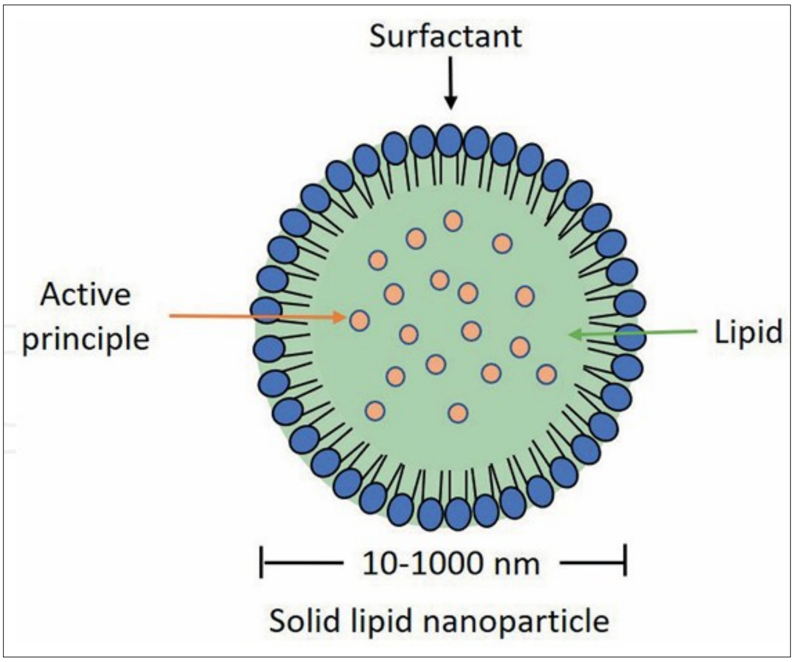

Fig. 2. General schematic diagram of solid lipid nanoparticles (21).

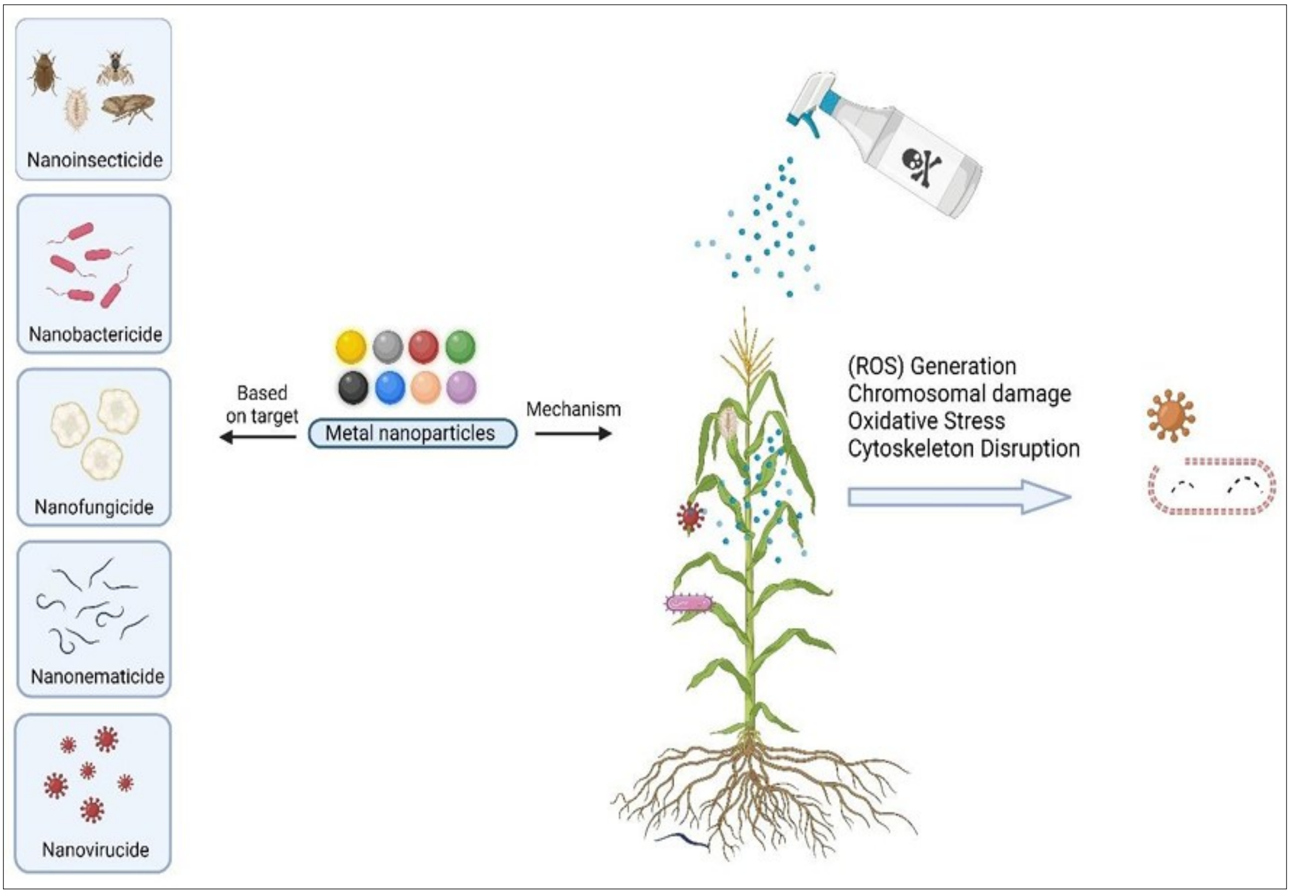

Fig. 3. Metal-based nanoparticles used as pesticides (25).

They are surface-active, stable and apply in the enclosure of hydrophobic pesticides (41). High surface area and stability, enhanced bioavailability and penetration and Suitable for seed treatment and foliar sprays. Example: Neem oil and pyrethroids were encapsulated in nanoemulsions for extended insecticidal activity (42). Nanospheres are matrix-type particles where the pesticide is evenly dispersed in a polymeric matrix (41).Controlled and slow release of active ingredient and Protection from UV degradation and hydrolysis. The Materials like Biodegradable polymers like chitosan, PLA and PLGA was used**.** Nanocapsules are a core-shell type in which the active substance is confined to a core that is enveloped by a polymeric shell (9).Fig. 4 shows the Benefits, Highly controlled release kinetics, minimised burst effect and Selective release triggered by environmental stimuli (e.g., pH, temperature). These pesticide delivery systems improve pesticide efficacy and minimise environmental and health risks (33).

Mechanisms of action in nanopesticide performance enhancement: Improved solubility.

One of the most important means that nanopicist times improve performance is by increasing active components. Most traditional pesticides are insoluble in water, limiting their bioavailability, sharpness and efficiency in the environment (43, 44). Nano technology removes the particle size and also removes the surface of active ingredients and removes chemistry, increasing their solubility and spreading in the water. In the larger surface area, Nanolewell, pesticides have a fairly large surface-to-volume ratio that increases their wet capacity against water and plant surfaces (32). This improves their resolution rate and enables them to distribute equally, especially in soil and leaf applications. Nanoimanson and Michaels: Nanoinkaplation techniques such as nanoimals and micro-systems can dissolve hydrophobic pesticides in water, increasing their bioavailability without the employment of toxic organic solvents (45). For example, hydrophobic pesticides such as pyrethroids were difficult when using polymer missiles and emulsified lipid carriers (46). Made of biodegradable compounds such as polymer -based nanocarners, polymer nanoparticles, especially kitosons and plga, to meet hydrophobic pesticides and have been used to allow them to allow them to allow water solutions and systemic absorption (47).Stabilisation of volatile compounds, better solubility, also contributes to the stabilisation of lobel compounds, reduces the decline and improves distribution to target organisms (42,48).

Mechanisms of targeted action and their effects on nanopesticide performance and crop growth

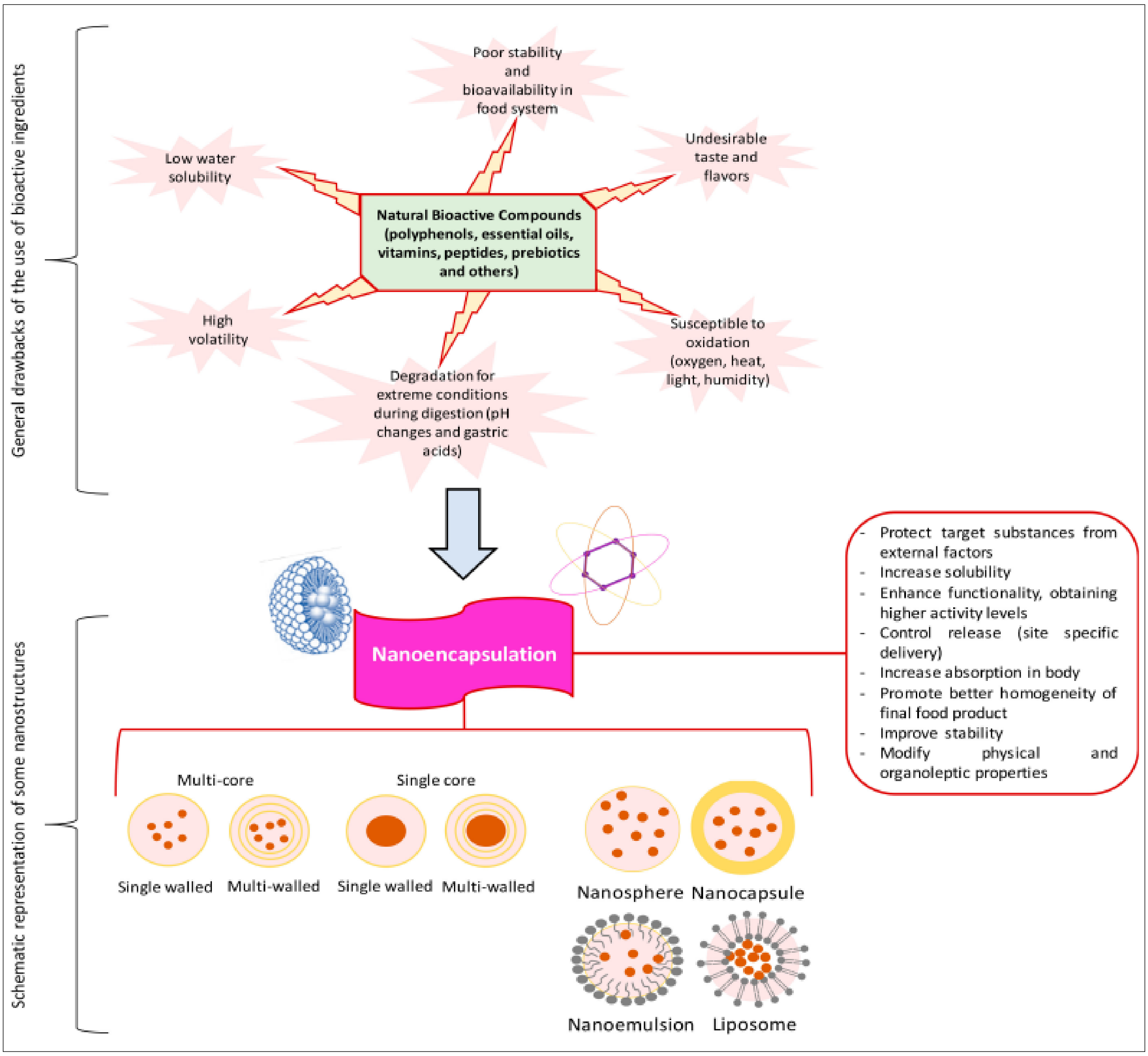

Fig. 4. Limitations of bioactive compounds (BACs) in the food industry and the advantages of nanoencapsulation for enhancing their applicability (31).

One of the most significant advances in nanopesticide technology is the development of targeted delivery mechanisms that enhance pesticide efficacy while minimising non-target effects. Targeted distribution enables the preferential accumulation of active ingredients at the pest, infected plant tissue, or specific site of action, thereby reducing pesticide losses, lowering application rates and improving overall crop protection efficiency (49, 50).

Surface functionalization and ligand-mediated targeting

Nanoparticles can be surface-functionalized with biological ligands such as peptides, polysaccharides, antibodies, or lectins that selectively bind to receptors on insect cuticles, microbial pathogens, or plant tissues. This ligand-mediated recognition enhances site-specific adhesion and cellular internalisation, resulting in increased bioavailability of the pesticide at the target site and improved pest control performance (2, 4). Such functionalization also contributes to prolonged residence time on leaf surfaces and improved uptake by plant tissues, which can positively influence crop growth and yield stability.

Stimuli-responsive release systems

Stimuli-responsive nanopesticides are designed to release their active ingredients in response to specific environmental or biological triggers, including pH variation, enzymatic activity, temperature, or light exposure. These smart delivery systems ensure that pesticide activation occurs primarily under conditions associated with pest presence or infection, thereby enhancing target specificity and reducing premature release (3, 5). For example, pH- or enzyme-sensitive carriers can selectively release fungicides in pathogen-infected tissues, leading to improved disease suppression and reduced chemical inputs.

Interactive carriers: magnetic and photoresponsive targeting

Advanced interactive nanocarriers provide external or spatial control over pesticide delivery. Magnetic nanoparticles, such as iron oxide (Fe_3O_4), allow directed transport and localisation of pesticides using external magnetic fields, offering precise targeting in controlled or experimental agricultural settings (51). Similarly, photoresponsive nanocarriers release active compounds upon exposure to specific wavelengths of light, enabling spatial and temporal control of pesticide activity and reducing off-site exposure (52).

Reduction of non-target and environmental risks

By directing pesticides toward intended biological targets, nanopesticides significantly reduce leaching, volatilisation and runoff into soil and aquatic systems. This targeted behaviour lowers environmental contamination and minimises adverse effects on beneficial organisms such as pollinators, soil microbiota and natural pest predators (53, 54). Reduced non-target exposure not only improves environmental sustainability but also supports healthier agroecosystems, indirectly contributing to improved crop growth and resilience.

Smart targeting of nanopesticides: Revolutionising pest control with precision

Nanotechnology has revolutionised many areas, where agriculture is one of the most promising areas for application. Nanopesticides that benefit from nanoscale materials to increase the effectiveness of pesticides have emerged as a new solution for many challenges facing traditional pesticides. The most exciting progress in nanopet technology is smart targeting, a strategy designed to distribute pesticides with accuracy, which reduces environmental impact and maximises efficiency. This article examines the mechanism behind smart targeting, its applications, recent advances and challenges in the development of smart nanoparticle agents.

Smart targeting of nanoparticles, the term smart targeting, includes pesticides that can choose active ingredients for pests or pathogens, which can reduce the off-target effects and reduce the loss to favourable organisms (30). Smart targeting of stimulation benefits from similar materials, which release their active agents when specific factors such as pH, temperature or the appearance of enzymes (40) are triggered. This controlled liberation ensures that the pesticide is only active when and where required. Recent studies have shown that nanoparticles can surround pesticides, which allows controlled liberation to meet in the environment or an insects' body (32). This method not only increases the efficiency of pesticides but also reduces the general chemical load in the environment, making it an important component of permanent agriculture (55).

Smart targeting mechanisms, nanopings are designed to respond to different stimuli, ensuring that the pesticides are released at the right time and place. The most common mechanisms used in smart targeting here are: Tension Existence-Ex-Nanocarners, Stimulation-Post-Nanocarers, which change the properties of response to environmental stimuli so that they can release the content in a controlled manner. Some common types include: PH response systems: These systems use polymers or materials that change the structure in response to ph changes. For example, the nanoparticle designed to be acidic in nature can target the acidic environment of the digestive system of insects or the rhizosphere of plants, where pesticides are released directly (41). The carrier material undergoes phase infections at some temperature and when it reaches the desired location, ensures controlled release of pesticides. Enzyme-Nordic systems: can free up some enzymes found in the digestive system of plague or plant cells. This targeted response increases the unique in pesticides (42).

Light-response system

Photonic nanoparticles react to specific wavelengths of light. This system is useful for targeting pests that are active at some time of day, which allows controlled release based on light risk (53). Metal organic framework (MOF) is a porous material that can be designed to surround pesticides. The large surface area of MOF and Table Chemical Properties allows them to make them functional for smart release. They can respond to various stimuli, such as pH, temperature or specific chemical agents, making them ideal candidates for a controlled pesticide distribution system (44, 45). Recent studies have shown the use of MOF to target high precision pests, which has increased pesticide efficiency and reduced environmental pollution (46).

Nanopicidides has led to significant progress in pest control. Below are some of the most important developments: increased efficiency and selectivity, stimulation-exclusive nanopysts to improve the effect of insect control and selectivity. For example, stimulation of pesticides-post-existing-nanoformulation has more effectively targeted the activity of pesticides, more effectively, aimed at specific insects, reducing poisoning to non-target organisms (51). In addition, nanopings can be constructed to interact with the surface of insect cells, which increases their accuracy in targeting and reduces environmental pollution. To improve the efficiency of agricultural inputs, nanopicistickides are mixed with fertilisers, often combined with double-functional systems. These systems not only protect pest crops, but also provide important nutrients. Nanoparticles can facilitate controlled release of both pesticides and fertilisers, which can reduce the need for frequent applications and reduce environmental footprints to agricultural practices (53). This integration of smart nanoparticles with fertilisers provides an innovative and durable approach to modern agriculture. Nanopist times are increasing attention in the development of biodegradable and environmentally friendly materials and the use of biodegradable and environmentally friendly materials. Nanoparticles based on natural polymer or lignocellulosic materials can break into the environment, which results in non-toxic sub-products (52). These yogas not only reduce environmental pollution capacity, but also support permanent agricultural practices by reducing the accumulation of harmful chemicals in soil and water.

Challenges in the development of smart nanopesticides. Although the advantages of smart nanopesticides are well known, several challenges remain in their development and widespread adoption: Regulatory Issues. One of the significant roadblocks to the commercialisation of nanopesticides is the complex regulatory landscape. Nanopesticides need to be rigorously tested so that they can be determined to be safe for application in agriculture, which tends to be a prolonged and costly process. The regulatory approval process is more time-consuming than in the case of conventional pesticides, with resultant delays in market entry (54). Another consideration is the potential toxicity of nanoparticles to non-target organisms. Despite the objective of smart targeting to minimise off-targeting effects, the long-term environmental fate of nanoparticles is a concern. An extensive study has to be carried out in order to analyse the risks of nanopesticides, namely their accumulation in soil, food chains and water (53).

Economic viability, production of advanced nanomaterials can be expensive and scaling production processes to meet the requirements of the agricultural sector presents financial challenges. Research in cost -effective production methods will be important to use more easily accessible materials of smart nanoposticides (51). Future perspective, the future of smart targeting in nanopystids lies in overcoming these challenges and ensuring that these technologies are economically viable and environmentally durable. Constant research in biodegradable materials, cost-effective production processes and regulatory structures will help to facilitate the integration of smart nanopicistides into mainstream agricultural practices. Collaboration between researchers, industry interests and regulatory bodies will be necessary to ensure that nanopicistics can provide a viable, long -term solution for global challenges for insect management.

A recent field study in Iraq provided practical evidence of the effectiveness of smart nanopics for suffering applications. Scientists converted the traditional herbicide oxadiazone used in rice cultivation for magnesium-based nanocarriers (MGOX-NPS and MGOTA-NP) to a nano-shaped version. This nano wording significantly improved herbicidal effects against Barnard-Grass (Ichinocoa Cruc-Galli), which is a large weed in Paddy field, at a particularly low concentration (50 mg/L). Compared to traditional emotionalisation, Nano-oxidizone therapy resulted in increased suppression of weeds, improved the growth properties of the rice plant and, as confirmed by HPLC analysis, a rapid decrease in residue. Toxic assessment, including hemolysis and antioxidant activity, indicated environmental protection of nanoformulation. These results support the integration of smart nanopastimes into durable weed management strategies, especially for herbicide-resistant species (43).

Mechanisms of action in nanopesticide performance enhancement controlled release

Controlled release is perhaps the most critical means by which nanopesticides make pesticides more effective while reducing their impact on the environment. Through controlled manipulation of the rate and timing of release of active ingredient, nanopesticide products can maintain prolonged protection, minimise frequent reapplication and lessen non-target exposure (30).

Time-controlled and sustained delivery

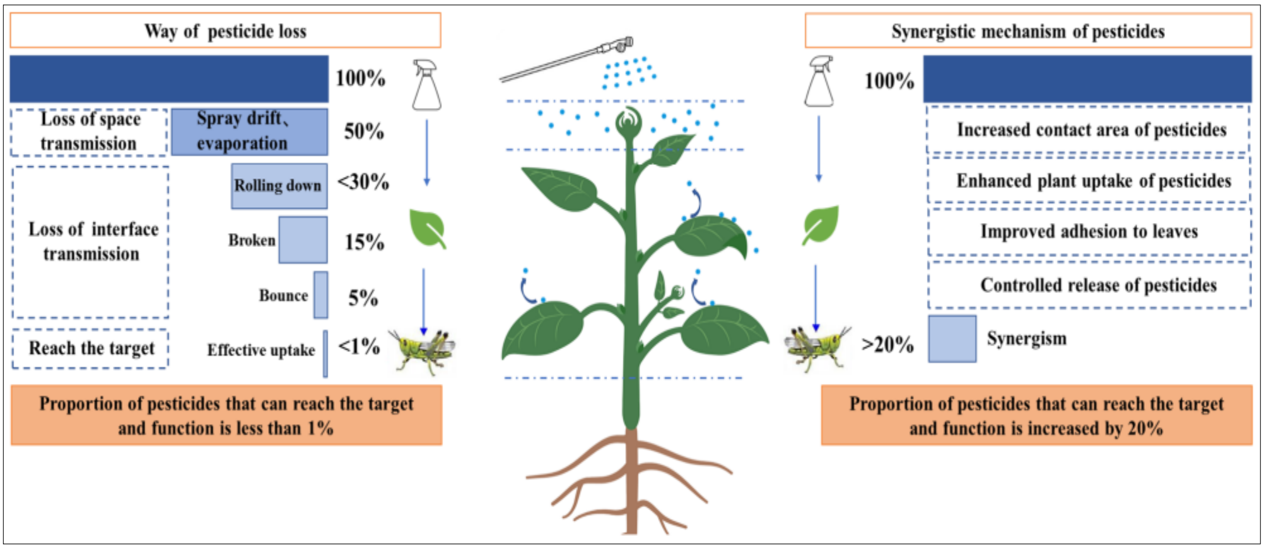

Fig. 5. Schematic diagram of pesticide loss pathways and synergistic approaches to improving pesticide utilisation. The left panel illustrates pathways of pesticide loss, while the right panel shows synergistic mechanisms enhancing pesticide efficiency. The percentages (e.g., 100 %, 50 %) indicate pesticide utilisation rates (44).

Nanocarriers such as polymeric nanoparticles, nanocapsules and solid lipid nanoparticles are capable of delivering their pesticide payload in controlled release for extended periods. This ensures maintenance of field efficacy over a longer period, even under adverse environmental conditions like rain or sunlight exposure (47) (Fig. 5).

Environmentally responsive release

Some nanopesticides are engineered to respond to environmental signals, such as pH, temperature, or enzyme activity. Such stimulus-sensitive systems release their payload only under optimal conditions, such that the activity of the pesticide is maximised at the site of action (42).

Reduced burst effect and loss

Traditional pesticides do not release the active ingredient at the right pace, leading to a burst effect and rapid loss or degradation. Controlled-release nanocarriers prevent this by slow diffusion of the active ingredient, reducing phytotoxicity while improving efficacy (42).

Carrier materials for controlled release

Materials like chitosan, alginate, PLGA and silica are conventionally employed as carriers due to their biodegradability and capability to be engineered with desired release profiles (43). The carrier protects the pesticide against premature degradation and allows adjustment of release kinetics.

Classification of nanopesticides

Nanopesticides may be classified by composition, formulation type and mode of action Table 2. These classifications allow for understanding their functional roles, environmental interactions and regulatory requirements (1, 56).

Classification of nano-herbicides

Nano-herbicides are herbicide products that apply nanotechnology to increase solubility, stability, delivery to target sites and environmental safety. They can be classified by carrier type, release mode and origin of active ingredients Table 3 (57, 58). Polymeric and liposome-based systems enable extended and controlled release of herbicides with reduced application numbers (59). Metal-based and silica-based systems can enhance uptake or exhibit bimodal action as adjuvants as well as herbicides (54, 48). Green synthesis approaches aim to reduce environmental toxicity and promote biodegradable formulations (52, 57).

Physiological effects of nano-Herbicides on plants

Nanoepithetics: A category of nanotechnology-mediated agrochemical forms, wherein herbicide molecules are either formulated in the nanoformulation or encapsulated in the nanostructure for superior delivery, potency and environmental acceptability. Their interactions with plant systems can result in a diversity of physiological responses, which could be beneficial or harmful, depending on the plant species, nanoparticle material, dose and mode of administration. The physical effects of nano-herbicides are presented in Table 4.

The inhibition of photosynthesis and oxidative stress are generalised effects shown by some nano-herbicides, generally by induced ROS production and interaction of nanoparticles with chloroplasts (56, 60). Plant growth suppression and hormone imbalance inhibit the survival and growth of the plant, especially that of non-target species, if not managed properly (58, 59). Cell membrane and organelle damage, as well as other cytotoxicity effects on nanoparticle concentration and composition depending more (61, 62).

Classification of nanopesticides based on composition and function

Nanopesticides are a significant advancement in agricultural technology since they enhance their effectiveness, reduce their environmental degradation and provide controlled release mechanisms. They can be classified according to their structure and function according to Table 5-7. Nanopesticides may be

Table 2. Classification of nanopesticides based on composition and structure

Type	Description	Examples	References
polymeric Nanoparticles	Biodegradable carriers made from polymers like chitosan, Poly (lactic-co-glycolic acid) and alginate	Chitosan-based insecticides	(45)
Solid Lipid Nanoparticles (SLNs)	Lipid-based matrices encapsulating active ingredients	SLNs loaded with pyrethroids	(22)
Nanoemulsions	Oil-in-water or water-in-oil emulsions with nanoscale droplets	Neem oil nanoemulsions	(46)
Nanocapsules/nanospheres	Reservoir or matrix-type systems controlling the release of pesticides	Atrazine nanocapsules	(47)
Silica-based nanoparticles	Porous silica used for controlled delivery and protection of actives	Mesoporous silica carriers	(48)
Metal-based nanoparticles	Metals like silver, copper and Zinc oxide with inherent antimicrobial or pesticidal activity	Silver nanoparticles for antifungal activity	(49)
Carbon-based nanocarriers	Include fullerenes, carbon nanotubes (CNTs) and graphene derivatives	CNTs loaded with pesticide molecules	(50)

Table 3. Classification of nano-herbicides based on carrier type and mechanism

Type of nano-herbicide	Description	Examples	References
Polymeric nanocarriers	Herbicides encapsulated in biodegradable polymers like chitosan, Poly (lactic-co-glycolic	Atrazine-loaded chitosan nanoparticles	(52)
Lipid-based nanocarriers	Use of liposomes or solid lipid nanoparticles for encapsulation	SLN for metribuzin	(29)
Nanoemulsions	Herbicides dispersed as nanoscale oil-in-water or water-in-oil emulsions	Clove oil nanoemulsion	(53)
Silica-based nanocarriers	Mesoporous silica is used for the controlled release of herbicides	Mesoporous silica carrying diuron	(48)
Metal/metal oxide nanoparticles	ZnO, CuO, or Ag nanoparticles exhibiting intrinsic herbicidal effects or carriers	ZnO NPs with phytotoxic activity	(54)
Green synthesised nanoparticles	Plant-extract-mediated nanocarriers or herbicides with eco-friendly synthesis	Neem extract-based nanoformulations	(46)
Carbon-based nanomaterials	Use of carbon nanotubes or graphene for herbicide delivery	Glyphosate on CNTs	(50)

Table 4. Physiological effects of nano-herbicides on plants

Physiological effect	Description/outcome	Plant type/example	Nano-herbicide type	Reference
Oxidative stress induction	Increased reactive oxygen species (ROS) and lipid peroxidation in weed tissues	*Amaranthus retroflexus*	ZnO nanoparticles	(54)
Photosynthesis inhibition	Reduction in chlorophyll content, photosynthetic rate and stomatal conductance	*Zea mays*	Glyphosate-loaded nanoparticles	(50)
Growth suppression	Inhibition of shoot/root elongation and dry biomass accumulation	*Lactuca sativa* (lettuce)	Paraquat-loaded chitosan nanoparticles	(52)
Membrane damage	Loss of membrane integrity due to nanoparticle interaction	*Arabidopsis thaliana*	Ag nanoparticles	(55)
Alteration of enzyme activity	Changes in antioxidative enzymes like Superoxide dismutase (SOD), peroxidase (POD) and catalase (CAT).	*Triticum aestivum* (wheat)	Nano-copper herbicide formulation	(56)
Hormonal imbalance	Altered levels of auxins and gibberellins, affecting cell elongation	*Glycine max* (soybean)	Nanoemulsion-based herbicide	(53)
Cellular ultrastructure disruption	Damage to chloroplasts, mitochondria and nuclei was observed via transmission electron microscope (TEM)	*Pisum sativum* (pea)	SiO_2-based nanoformulations	(46)

Table 5. Classification of nanopesticides based on composition and function

Category	Description	Examples	References
Nanocarrier-based pesticides	Active ingredient (AI) encapsulated or adsorbed on nanocarriers	Polymeric nanoparticles, nanoemulsions, SLNs	(1, 4)
Nanosized active ingredients	AI itself is nanosized without a carrier	Nanosulfur, nano-copper	(35)
Nanoemulsions	AI dispersed in nanosized oil-in-water or water-in-oil emulsions	Neem oil nanoemulsion	(5)
Inorganic nanoparticles	Metal or metal oxide NPs used as AI or adjuvants	ZnO, Ag, TiO_2 nanoparticles	(10)
Biopolymer-based nanopesticides	Use of natural polymers for delivery and controlled release	Chitosan–pesticide conjugates	(29)
Green-synthesised nanopesticides	NPs synthesised using plant extracts for eco-friendly pest control	AgNPs from neem or tea extracts	(46)

Table 6. Classification based on target function

Function	Example pesticide	Nanotechnology used	Reference
Nano-insecticides	Lambda-cyhalothrin nanoformulation	Polymeric nanocarrier	(58)
Nano-fungicides	Mancozeb nanosuspension	Nanoclay-based formulation	(59)
Nano-herbicides	Atrazine-loaded chitosan NPs	Biopolymer encapsulation	(52)
Nano-nematicides	Silver NPs for nematode control	Plant-based green synthesis	(46)

Table 7. Physiological effects of nano-insecticides on plants and insects

Physiological effect	Description/outcome	Target organism	Nano-insecticide type	Reference
Reduced insect feeding	Decreased herbivory due to ingestion of nano-formulations, leading to toxicity	*Spodoptera frugiperda* (Fall armyworm)	Imidacloprid-loaded polymeric nanoparticles	(60)
Neurotoxic effects	Disruption of neural functions and behaviour, causing paralysis and death	*Drosophila melanogaster* (Fruit fly)	Nanoencapsulated pyrethroids	(61)
Cellular damage	Membrane disruption, oxidative stress and apoptosis in insect cells	*Anopheles stephensi* (Mosquito)	Silver nanoparticles	(62)
Behavioral changes	Altered locomotion and feeding behaviour, due to nanoparticle uptake and toxic effects	*Tribolium castaneum* (Red flour beetle)	Carbon nanotube-based formulations	(63)
Growth inhibition	Reduced growth and development due to nanoparticle toxicity	*Helicoverpa armigera* (Cotton bollworm)	Nanoencapsulated cypermethrin	(64)
Metabolic disruption	Altered enzyme activity and ATP depletion in insects	*Culex pipiens* (Mosquito)	Zinc oxide nanoparticles	(65)
Immune response modulation	Altered immune responses, leading to susceptibility to other pathogens or stress	*Bemisia tabaci* (Whitefly)	Chitosan-based nanoformulations	(66)

classified based on the target organism or the action they are designed to take within the agroecosystem. Classification facilitates understanding their spectrum of application, mechanism of action and impact on other pests, as illustrated in Table 6. Nanocarrier systems (e.g., dendrimers, liposomes, solid lipid nanoparticles) enable targeted delivery, reduced dosage and prolonged release(30). Metal oxide and metal nanoparticles are amenable to use both as active ingredients and adjuvants to conventional pesticides (32). Products green-synthesised are of interest because they can be synthesised sustainably and are less toxic (46). The next is Table 7 of the physiological effects of nano-insecticides on plants and insects

Neurotoxic and growth ban effects are common in many insect species when they are exposed to nanochelated pesticides, which often include pyrethroids, imidacloprid or cypermethrin (60 -67). Behavioural changes that convert feeding and movement can affect the existence and reproduction of insects to a large extent (67, 68). Cellular damage and oxidative stress have significant toxic effects when metal-based nanoparticles, such as silver and zinc oxide, are used in nano-flu (68-70).

Effect of nanopesticides on soil microorganisms

Nanoparticles can significantly affect microbial communities in the Earths' ecosystems due to their small size and increased reactivity. These effects can be both beneficial and harmful, which can occur based on the type of nanoparticles, their concentration, exposure time and physical and chemical properties of the soil.

Discussion of microbial social structure

The use of nanoparticles can change the diversity and abundance of microbial taxa. For example, silver nanops (baitps) is known for its broad -spectrum antimicrobial properties. However, their nonspecific activity can lead to a lack of favourable microbes in the soil (71). Studies suggest that Agnps reduces the abundance of nitrosomonas and nitrobacter, which are important for nitri -fraction (72).

Enzyme activity prohibitions

Soil microorganisms produce external enzymes needed for cycling nutrients. It has been reported that nanops such as ZNO and CuO interfere with enzymatic activities such as dehydrogenase, urine and phosphate, affecting the Earths' fertility (73).

Oxidative stress and cell damage

It can cause reactive oxygen species (ROS) from nanopathy, causing damage to oxidative stress and microbial DNA, protein and membrane (74). This mechanism leads to microbial biomass and a reduction in activity.

Indirect effects

Through soil changes, in addition to direct poisoning, binding soil particles to nanomaterials can change the availability of pH and nutrients, which indirectly affects microbial population (2).

Potential for adaptation and resistance

Some microbes may develop resistance or can be adapted**.**

Local context

A successful study at the University of Kirkuk (2024) demonstrated the effectiveness of chitosan as a safe and effective pesticide against a prominent economic indicator, a recognised indicator of Iraqi warehouses and a safe and efficient pesticide. The use of chitosan in low concentrations, from 0.5 to 0.5–1.5 ppm, reduced the emergence of insects in the long-term incubation period and partly reduced the number of eggs, with the number of eggs under 314 to 61 to 61. The compound also reduced the damage to grain in different components, including poisoning. These results support strategic and intelligent use of different polymer-based biopesticides to protect agricultural products during storage, achieving one of the agricultural targets (75).

Nanopesticides: Environmental behaviour and impact - environmental fate

The environmental fate of nanopesticidal agents refers to the way these materials behave, change and remain in different environmental compartments such as soil, water, air and biota. Compared to traditional pesticides, nanopicistickides often show changed dynamics, fall passages and bioavailability, which can affect both their efficiency and environmental protection (30)

Transport and dynamics, size, surface charging and structure of nanocherirs affect the dynamics of nanopiciader in soil and water. For example, people with small particles or hydrophilic coatings can move on through soil layers, which increases the risk of pollution of groundwater (49). However, the relevant formulation design can reduce this risk by more accurately targeting the pesticide statement.

Fixedness and decline, nanopitis pages can persist in the environment for a long time compared to traditional yogas, depending on the biological degradation of the carrier and releasing canteix. Biologically degradable polymers, such as Chitosan or PLA, finally appear in harmless byproducts, while inorganic carriers, such as silica or metals, can live in the environment for a long time (76). Can occur through the fall: photo grading (sunlight -inspired breakdown), hydrolysis and biodegradation (microbial effect). Controlled liberation properties of nanopicistides can reduce the frequency of applications, thus reducing cumulative environmental impacts (66).

In a conversation with soil and water, nanopicistides can adsorb on soil particles or organic materials, which can either reduce their dynamics or slow, continuous liberation (75).

Nanopesticides: Environmental behaviour and effects - biochemulation and toxicity

While nanopesticides provide better efficiency and reduce chemical use, their interaction with non-target organisms increases concern for two cycles and toxicity. The unique physical and chemical properties of nanocarners, including their small size, high surface area and reactivity, can lead to unexpected toxic consequences in both terrestrial and water environments (30). Bioacumulation in Creator and Terrestrial Organizations is based on some nanopic carriers, especially those, such as silver (AG), zinc oxide (ZNO) and titanium oxide (TIO_2), to accumulate in live tissues, aquarium, algae and involved. For example, nanoparticles can cross the biological membrane and accumulate in the organs, causing oxidative stress and metabolic disorders (77). Toxicity for non-targeted species can have toxic effects on favourable soil organisms such as nanopical earthworms, microbes and pollinators. These effects may include cell damage, enzyme ban, reproductive failure and mortality (78). In particular, metal-based nanocarriers are associated with DNA damage and disruption of immune response in non-measurements (79). Trophic transmission and pollution of the food chain, biochemated nanomaterials can be transmitted through the food chain and possibly when high trophic levels, including humans. For example, plants that come into contact with nanopesticides have been seen to absorb and translate nanopathy, suggesting a possible passage for human risk (69). The effects of nanocaria properties, particle size, surface charging, particle size, coating material and solubility determine bio-template and toxicity (80). Biodegradable nanocarriers (e.g., PLGA, Chitosan) are safe, while continuous-R-law or bioactive nanometric risk.

Nanopesticides: Risk assessment and regulation

Since Nanopicistides quickly enter the agricultural markets, it has become important to assess their potential risks and establish appropriate regulatory structures. Nomatorial novels can result in unique environmental and health risks as a result of physical chemical properties - such as increased reactivity, bioavailability and dynamics, which are often not sufficiently addressed by traditional pesticides (30). Challenges in risk assessment, traditional pesticide risk assessments depend on data from bulk chemical coercion, which may not represent the behaviour and toxicity of nanoscale materials. Nanopesticides require an assessment of case to case that includes: size, surface area and charging characterisation, symptoms of size, surface area and charging, behaviour in different environmental matrix and interaction with biological systems (49). In addition, standardised test protocols are still under development to assess nanomaterials, making comparison of cross -country studies and regulatory decisions more difficult (81). Specific nanopian rules are missing, currently regulating many countries' nanopiasticoids under existing pesticides or chemical safety laws, such as the EUs' EU plant protection product regulation (EC) number 1107/2009 or U.S. Fifre of the EPA. However, these frameworks often do not clearly consider nanoscale properties, causing potential regulatory holes (82). Some efforts, such as the European Food Safety Authority (EFSA) and OECD, aim to include nanospecific ideas in risk evaluation guidelines, including exposure modelling and poisoning tests, adapted nanomaterials (83, 80).

Environment and human health ideas, risk evaluation should evaluate both intended effects (eg, insect control) and unexpected results, such as non-scorching poizoning for soil and aquatic organizers, biochemulation and podetiallation and potholation and pothic runding and podethic runding and podethic runding and podethic rund. Routes (65, 69). Transparent and adaptive regulation is required; experts emphasise the importance of caution, but still an innovation-friendly approach that balances agricultural productivity with the environment and public health protection. This includes compulsory nanospecific labelling and reporting, monitoring after the market and life cycle analysis and public engagement and ethical ideas (84, 85).

Nanopesticides: Future directions

The future of nanopesticides lies in promoting permanent agriculture through innovative, targeted and safe insect control strategies. The purpose of continuous research and technological development is to cross the current boundaries related to effect, safety and regulation, in accordance with the global environment and food security goals (86, 87). The development of biodegradable and green nanocarriers, one of the most promising directions, includes biodegradable, bio-based nanocarriers such as kitosan, starch and alginet, which reduces environmental focus and toxicity risk (66). These ingredients can be designed for pH-neutral or enzyme-triggered release, ensuring that active ingredients are only distributed in the presence of dimensions pests (47).

Integration of exact agriculture and smart delivery systems, accurate agriculture can enable the integration of nanotechnology smart insecticidal medium distribution systems that react to environmental signals such as temperature, humidity or insect appearance. For example, stimulation ex-neokar is only detected to release pesticides under specific biotic or abiotic conditions, thus reducing over-applications (88, 89). Cinergist formulations and multifunctionality, future nanopesticides can also be designed for multifunctional properties, such as pesticides, fungi and a combination of nutritional effects in the same formulation. In addition, the subsidising of pesticides and nanoscience is studied to increase crop health by reducing chemical input (90).

D. Better risk assessment tools, progress in methods of toxic testing and nanospecific modelling devices are necessary to assess the long -term ecological effects of nanopia. The development of standardised protocols and international databases will support transparent assessment and regulatory decisions (49, 91). Regulatory Harmony, Public Engagement and Emerging Organisational Challenges Ensuring the safe and sustainable development of nano-enabled pesticides requires not only scientific advances but also a harmonised global regulatory framework capable of addressing nano-specific risks while fostering innovation. Current regulatory approaches remain fragmented across jurisdictions, with differing definitions, data requirements and assessment methodologies for nanomaterials, which can hinder international trade, slow product authorisation and create uncertainty for developers (18, 27). Greater regulatory convergence, particularly on nanoform identification, physicochemical characterisation, dissolution behaviour and long -term ecotoxicity testing, is therefore essential to balance precaution with technological progress. Beyond regulatory alignment, public commitment and stakeholder participation are increasingly recognised as central to responsible innovation. Engagement of farmers, researchers, regulators, industry and the broader public is critical for building trust, improving risk communication and ensuring that nano-pesticide development aligns with societal expectations and real-world agricultural needs (21). Transparent communication regarding benefits, uncertainties and safeguards can reduce public scepticism and support informed decision-making, particularly in regions where pesticide use directly affects livelihoods and food security (26).

From an organisational and governance perspective, several emerging challenges must be addressed. One key concern is the detection and monitoring of nanoscale waste in environmental compartments. Conventional analytical methods are often insufficient to reliably detect, quantify and distinguish engineered nanoparticles from natural background particles in soils, waters and biota (19). This limitation complicates compliance monitoring, post-market surveillance and enforcement of regulatory controls, especially for nano-pesticides designed to transform or dissolve after application. Another critical challenge is the integration of nano-specific considerations into life-cycle assessment (LCA) frameworks. Traditional LCA methodologies are not well equipped to capture nano-specific properties such as particle number concentration, surface reactivity, transformation during use, or chronic low-dose effects

(18). Recent studies emphasise the need for adapted or hybrid LCA approaches that incorporate fate, exposure and hazard data specific to nanomaterials across the entire product life cycle from synthesis and formulation to application, degradation and waste management (92).

Addressing these organisational and regulatory challenges will require coordinated international efforts, standardised methodologies and sustained investment in analytical capacity and risk assessment science. Ultimately, regulatory harmony combined with inclusive stakeholder engagement and robust life-cycle thinking will be essential for enabling the responsible development, deployment and societal acceptance of nano-enabled pesticides.

The role of nanopesticides in reducing pollution and protecting the environment

Nanoparticles, due to their unique physical and chemical properties such as small particle size, large surface area and controlled liberation skills, provide a promising approach to improve agricultural stability and reduce environmental pollution. Exact targeting and low doses, nanopicistides can be designed for controlled and slow liberation, which allows lower doses than traditional pesticides. It reduces the total amount of chemicals released in the environment and reduces contamination of land and water deposits (1). Increase their high bioavailability and targeted distribution efficiency and reduce the capacity of non-objectives (32). Low risk of runoff and leaching, traditional pesticides often suffer from damage caused by leaching, evaporation and surface runoff, causing groundwater contamination. Nanoparticles with enhancing active ingredients or surface modifications show increased binding for soil particles, lowering dynamics and environmental lens (33). Non-targeted poisoning, at least, traditional pesticides often damage beneficial insects, aquatic life and soil organisms. In contrast, nanopesticides can be designed with a smart delivery system (e.g., pH or enzyme response) that releases active compounds only under specific circumstances, which reduces contact with non-target organisms (32, 93).

Reduced evaporation and reduction, volatile pesticides often evaporate before reaching their goals. Nanophormal reduces the loss of evaporation, where the active substance needs to function, where the need is necessary and to protect the active ingredients from premature decline due to sunlight or bacteria (49, 94).

The role of nanopesticides in sustainable agriculture

The goal of sustainable agriculture is to increase food production by preserving environmental quality, human health and biodiversity. Nanopesticides-pasticides prepared using nanotechnology insect handling support this goal by offering better effect, low environmental impact and increased accuracy.

Enhanced efficacy and reduced chemical load

Nanopesticides provide controlled and targeted delivery of active ingredients, reducing the frequency and quantity of pesticide applications. Their nano-scale size and large surface area enhance absorption by pests, making them more effective at lower concentrations (42). This supports sustainable agricultural practices by minimising excessive chemical input.

Increased agricultural efficacy and reduced chemical burden

Nanopesticides provide a targeted and controlled release of active compounds, anything being reduced to the lowest levels of pesticide use. Due to the nano-scale size and high surface area, they are better absorbed by the target pests, thus enabling efficacy even at very low concentrations (42, 94). It promotes sustainable agriculture through reduced chemical overuse.

Lower environmental pollution

In contrast to most conventional pesticides that tend to cause runoff and leaching, nanopesticides are formulated for slow release and improved soil sticking, lessening the pollution of water bodies and non-target environments (30). Encapsulation systems like chitosan or silica-based carriers ensure that active substance release is accomplished only when required (8).

Conservation of non-target organisms

Ecological balance is the goal of sustainable agriculture. Nanopesticides facilitate targeted delivery and reduced toxicity to beneficial insects, soil fauna and pollinators in comparison to broad-spectrum traditional chemicals (32). Such targeted action maintains biodiversity in agroecosystems.

Harmonisation with integrated pest management (IPM)

Nanopesticides are harmonious with IPM methodologies, whereby pest control is achieved through the integration of biological, cultural and chemical means. Their specificity and harmony with biopesticides and microbial products make them compatible for use in environmentally safe farming systems (35, 95).

Long-term crop and soil health

Overuse of traditional pesticides has resulted in soil loss and pest resistance. Nanopesticides reduce such pressure by requiring fewer rounds of application and decreasing chemical accumulation in the soil, thus conserving soil fertility and microbial balance (96, 97). In an area experiment performed in Iraq, scientists sprayed chitosan-nanocomposites loaded with a mixture of NPK fertilisers and plant extracts (green tea or net) on potato crops to evaluate plant physiological and productive performance. The results indicated significant improvements in vegetative growth parameters, including an increase in the height of the plant and the number of plant trunks and tubers. The productivity of the average area reached more than 50 t/ha when using 15 % chitosan with 4 g/L green tea extract. These results demonstrate the ability to use bio-nanocarriers as a smart joint delivery system for pesticides and nutrients, increase pesticides and reducing spray time and production costs. This is in line with the goals of accurate agriculture and integration of agricultural entrance (98).

Nanopastides' role in achieving targets for sustainable development (SDG)

Nanopicistickides is an agricultural technique that enables several goals for sustainable development (SDG). By increasing the efficiency of pesticides and reducing the environmental and human health risk, they offer realistic alternatives for permanent agriculture and environmental protection.

SDG 2- Zero hunger: Nanopesticides improve food security and crop yields by more efficient management of pests with lower application rates and longer residual periods. Targeted delivery and controlled release properties protect crops throughout the complete growing stage, which is needed to feed an increased population (99).

SDG 3- Good health and well-being: Reduced pesticide use through nanoformulations avoids poisonous exposure to farmers, consumers and the environment. Lower applications and dosages reduce the health effects from employing conventional pesticides (100).

SDG 6- Clean water and sanitation: Nanopesticides are designed to limit leaching into water bodies and therefore minimise water pollution. Their higher soil binding and slower release reduce runoff and groundwater and surface water pollution, ensuring safer water quality (8).

SDG 12- Responsible consumption and production: With increased efficacy at reduced doses, nanopesticides are intended to minimise waste and enhance efficiency in crop inputs. Targeted application is facilitated by encapsulation and nanocarriers, with minimised overuse and environmental persistence (100).

SDG 13- Climate action: Reduced production, transport and multiple use of pesticides cut the carbon footprint of agriculture. Efficient input utilisation and reduction in breakdown of pesticides into greenhouse gases promote climate-resilient agricultural practices (101).

SDG 15- Life on land: By reducing damage to off-target organisms and soil loss, nanopesticides preserve biological diversity and sound ecosystems. Their target specificity reduces the impact on useful insects and microorganisms (102).

Challenges and future prospects of nanopesticides

Nanopesticides offer new options for sustainable agriculture but also raise scientific, regulatory and environmental challenges. They are important to be aware of these limitations to use them safely and effectively and new research suggests promising directions for the future.

Challenges

Regulatory uncertainty: Current pesticide regulations have been established for typical formulations and may fail to adequately quantify the new properties and risks of nanopesticides. There is a lack of standardised testing protocols to quantify nanopesticide toxicity and environmental fate (103).

Possible health and environmental hazards: In spite of lowered consumption levels, the long-term destiny and toxicity of nanoparticles within ecosystems are not fully understood. According to some research, some nanoparticles have the possibility of being accumulated in soil and water with the potential to harm non-target organisms and microbial communities (55, 1).

Limited mechanistic understanding: The mechanistic foundation for nanopesticide interactions with plants, insects, soil and environmental components is limited. This limits the formulation of very selective and low-toxicity formulations (104).

Cost and scalability: Mass production of nanopesticides is expensive and technologically demanding. Cost-effectiveness and farmer affordability limitations limit widespread application, especially in developing agricultural regions (105).

Public perception and acceptance: Nanotechnology in agriculture is received with scepticism due to toxicity, food residue and ecological concerns that influence consumer and policy acceptance (106).

Future prospects and roadmap for nanopesticide development

Future nanopesticide development is expected to progress through coordinated advances in delivery design, environmental safety, precision agriculture integration and regulatory science.

Smart and targeted delivery systems represent a primary research priority. Stimuli-responsive nanopesticides capable of releasing active ingredients in response to pH, enzymes, moisture, or light offer improved targeting efficiency and reduced off-target effects; however, their performance must be validated under realistic field conditions (2, 49). The transition toward environmentally friendly and biodegradable nanocarriers is critical for sustainable deployment. Bio-based materials such as chitosan, alginate and cellulose have demonstrated lower toxicity and improved environmental compatibility compared to conventional synthetic carriers, supporting their safe and long-term use in agriculture (3, 4).

Coupling nanopesticides with precision agriculture technologies is expected to enhance application efficiency. Integration with sensors, drones and variable-rate application systems can optimise timing, dosage and spatial delivery, thereby improving crop protection while minimising chemical inputs and waste (107, 108). Improved risk assessment frameworks are essential to enable wider adoption. Advances in nanotoxicology, environmental fate modelling and tiered risk assessment approaches will improve exposure prediction and support the design of safer products and more robust regulatory systems (109, 110). Finally, large-scale adoption will depend on supportive policy frameworks, interdisciplinary research and public engagement. International regulatory harmonisation, transparent communication of risks and benefits and coordinated research efforts are necessary to balance innovation with societal acceptance and global implementation (111, 112).

Conclusion

Strategic distribution of smart targeted nanopicistides represents a transformative advance in agricultural insect management and is consistent with the goals of permanent agriculture and environmental management. This study has shown that the inclusion of nanotechnology in distribution systems for pesticides can significantly increase the effect of insect control by significantly reducing the negative effects associated with traditional agriculture. Our findings show that nanoprets, when functionalized with stimuli-responsive or ligand-targeted mechanisms, show superior precision to deliver active ingredients to special pest-planting tissue. This targeted action not only improves insect mortality, but also reduces the necessary total pesticides, which reduces the risk of off-target effects, environmental pollution and the development of pesticide resistance.

In addition, smart nanopicistides provide promising routes to integrate environmental sensations and controlled features, leading to real -time adaptation capacity by changing agricultural conditions. This responsibility contributes to resource -efficient cultivation practices, reduces the frequency of pesticides and supports the conservation of beneficial insect populations and soil microorganisms. Despite their clear benefits, however, there are many challenges before they are widely adopted. These include potential uncertainty about the need for manualized regulations to evaluate the risk of nanopartan, the risk of biochemulation and the need for standardised regulations to evaluate safety and effect. To meet these challenges, interdisciplinary collaboration requires strong risk evaluation and active involvement with stakeholders, including decision makers, farmers and the public.

Finally, smart targeted nanopicistides stand as a promising innovation to cover the double imperative on agricultural productivity and environmental protection. Future research should focus on adapting the design of nanopathy, environmentally friendly synthesis methods and promoting field-level verification studies to secure these new solutions. By doing this, we can get closer to a flexible, permanent agricultural system that meets global food security requirements and preserves ecological integrity.

Authors' contributions

HWAA, NRL, HHA, DFH, MQH and RAHGA contributed equally to the writing and preparation of the manuscript. Each author was involved in the preparation of the original draft. All the authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

References

1. Kah M, Tufenkji N, White JC. Nano-enabled strategies to enhance crop protection and agricultural sustainability. Nat Nanotechnol. 2019;14:532–40. https://doi.org/10.1038/s41565-019-0438-0
2. Nuruzzaman M, Rahman MM, Liu Y, Naidu R. Nanoencapsulation, nano-guard for pesticides: a new window for safe application. J Agric Food Chem. 2016;64(7):1447–83. https://doi.org/10.1021/acs.jafc.5b05214
3. Grillo R, Abhilash PC, Fraceto LF, dos Santos NZ. Nanotechnology applied to bio-based pesticides: advances and challenges. J Agric Food Chem. 2021;69(45):13658–72. https://doi.org/10.1021/acs.jafc.1c04805
4. Campos EVR, Proença PLF, Oliveira JL, Pereira AES, Ribeiro LNM, Fraceto LF. Chitosan nanoparticles as delivery systems for agricultural applications: a review. Environ Chem Lett. 2020;18:1–17. https://doi.org/10.1007/s10311-019-00933-8
5. Kah M, Kookana RS, Gogos A, Bucheli TD. A critical evaluation of nanopesticides and nanofertilizers against their conventional analogues. Nat Nanotechnol. 2018;13:677–84. https://doi.org/10.1038/s41565-018-0131-1
6. Al-Juthery HWA, Hassan AKH, Musa RF, Sahan AH. Maximize growth and yield of wheat by foliar application of complete nano-fertilizer and some bio-stimulators. Res Crops. 2018;19:387–93.
7. Dahham IT, Kareem HA, Khair AM, Hamid MQ. Evaluation of hydrological properties of gypsiferous soils cultivated with wheat under varying gypsum content. Plant Sci Today. 2025;12(4). https://doi.org/10.14719/pst.11180
8. Grillo R, Pereira AES, Nishisaka CS, de Lima R, Oehlke K, Greiner R, et al. Chitosan/tripolyphosphate nanoparticles loaded with paraquat herbicide: an environmentally safer alternative for weed control. J Hazard Mater. 2014;278:163–71.
9. Campos EVR, Oliveira JL, Fraceto LF, Singh B. Polysaccharides as safer release systems for agrochemicals. J Agric Food Chem. 2014;62(28):5793–800.
10. Kah M, Hofmann T. Nanopesticide research: current trends and future priorities. Environ Int. 2014;63:224–35.
11. Al-Shahmani AMK, Al-Juthery HWA. Response of rice (*Oryza sativa* L.) to silica fertilization and spraying with nano-potassium and calcium. IOP Conf Ser Earth Environ Sci. 2021;735:012068.
12. Mahmoud S, Hundi H, Razzaq R, Hamid M. Effect of zinc and potassium humate spraying on growth and yield of tomato (*Solanum lycopersicum* L.). Plant Sci Today. 2025;12(4). https://doi.org/10.14719/pst.11104
13. Wu J, Fan N, Liao H, Zhang Y, Xiao Z, Wang Z. Risk assessment of metal/bio-based nanopesticides: plant growth, soil environment and non-target organisms. Environ Sci Nano. 2025;12(1):105–22.
14. Al-Juthery HWA, Al-Shami QMN. Impact fertigation of nano NPK fertilizers, nutrient use efficiency and nutrients distribution in soil of potato (*Solanum tuberosum* L.). Plant Arch. 2019;19(1):1087–96.
15. Islam S, Zhang Y, Chen J, Wang X. Transport, transformation and toxicity of engineered nanoparticles in agricultural soils: roles of organic matter and clay minerals. Front Nanotechnol. 2025;7:1622228. https://doi.org/10.3389/fnano.2025.1622228
16. Ouyang S, Li H, Xu Y, Liu F. Nanocolloids in soil environments: aggregation, transport and interactions with soil constituents. Soil Biol Biochem. 2024;189:109307. https://doi.org/10.1016/j.soilbio.2024.109307
17. Haydar MS, Nowack B, Lead JR. Environmental transformations of metal-oxide nanoparticles in soils: dissolution, redox processes and interactions with organic matter. Sci Total Environ. 2025;924:171573. https://doi.org/10.1016/j.scitotenv.2025.171573
18. Kah M, Tufenkji N, White JC. Nano-enabled strategies to improve pesticide sustainability: environmental fate and risk considerations. Nat Nanotechnol. 2023;18:1017–26. https://doi.org/10.1038/s41565-023-01478-9
19. Lowry GV, Hill RJ, Harper S, Rawle AF, Hendren CO, Klaessig F, et al. Guidance to improve the scientific value of environmental nanoscience research. Environ Sci Technol. 2023;57(1):28–45. https://doi.org/10.1021/acs.est.2c06323
20. Wei Y, Zhang X, Liu Y, Wang L, Li H. Nano-enabled insecticides for efficient pest management: definition, mechanisms and safety assessment. Nanomaterials. 2025;15(13):1050. https://doi.org/10.3390/nano15131050
21. Nederstigt TAP, Brinkmann BW, Peijnenburg WJGM, Vijver MG. Sustainability claims of nano-enabled pesticides require a more thorough evaluation. Environ Sci Technol. 2024;58(5):2163–5. https://doi.org/10.1021/acs.est.3c10207
22. Wang Y, Liu J, Chen C, Xing B. Interactions between engineered nanoparticles and soil components: implications for mobility and bioavailability. J Hazard Mater. 2023;451:131091. https://doi.org/10.1016/j.jhazmat.2023.131091
23. Dang F, Yuan Y, Huang Y, Chen Q, Li X. Trophic transfer of nanomaterials and their effects on higher trophic-level organisms. NanoImpact. 2023;32:100489. https://doi.org/10.1016/j.impact.2023.100489
24. Zhang L, Cui Y, Xu J, Li Y, Chen Z. Ecotoxicity and trophic transfer of metallic nanomaterials in aquatic food webs. Sci Total Environ. 2024;924:171660. https://doi.org/10.1016/j.scitotenv.2024.171660
25. Abed RH, Kareem HA. Effect of zeolite addition on infiltration rate and saturated hydraulic conductivity in gypsum soil. Pak J Agric Res. 2025;38(1):85–91. https://doi.org/10.17582/journal.pjar/2025/38.1.85.91
26. Kapeleka JA, Mwema MF. State of nano pesticides application in smallholder agriculture production systems: human and environmental exposure risk perspectives. Heliyon. 2024;10(20):e39225. https://doi.org/10.1016/j.heliyon.2024.e39225
27. Hunt N, Kestens V, Rasmussen K, Badetti E, Soeteman-Hernández LG, Oomen AG, et al. Regulatory preparedness for multicomponent nanomaterials: current state, gaps and challenges of REACH. NanoImpact. 2025;37:100538. https://doi.org/10.1016/j.impact.2024.100538

28. OECD. Advanced and integrated approaches for the assessment of nanomaterial risks. Paris: OECD Publishing; 2022.
29. Urbani D, Evangelisti M, Bebi C, Rovegno C, Parenti MD, Varchi G, et al. Collection and review of information on nanomaterial-based and nano-enabled plant protection products, biocidal products and fertilising products (ECHA-24-R-16-EN). Helsinki: European Chemicals Agency; 2024.
30. Kah M, Beulke S, Tiede K, Hofmann T. Nanopesticides: state of knowledge, environmental fate and exposure modeling. Crit Rev Environ Sci Technol. 2013;43(16):1823–67.
31. Al-Juthery HWA, Lahmoud NR, Alhasan AS, Al-Jassani NAA, Houria A. Nano-fertilizers as a novel technique for maximum yield in wheat biofortification: article review. IOP Conf Ser Earth Environ Sci. 2022;1060:012043.
32. Ghormade V, Deshpande MV, Paknikar KM. Perspectives for nano-biotechnology enabled protection and nutrition of plants. Biotechnol Adv. 2011;29(6):792–803.
33. Hamid MQ, Abd EH, Al-Salihi ZK, Muhammed RJ, Hassan DF. Effect of organic conditioners on the physical properties of sandy soil under drip irrigation conditions. Sarhad J Agric. 2025;41(3):1133–42. https://doi.org/10.17582/journal.sja/2025/41.3.1133.1142
34. Al-Shahmani AM, Al-Juthery HW. Response of rice (*Oryza sativa* L.) to silica fertilization and spraying with nano-potassium and calcium. IOP Conf Ser Earth Environ Sci. 2021;735:012068.
35. Grillo R, Pereira AES, de Melo NFS, et al. Controlled release system for ametryn using polymer microspheres: preparation, characterization and release kinetics in water. J Hazard Mater. 2014;278:372–9.
36. Gonzalez-Melendi P, Fernandez-Pacheco R, Coronado MJ, et al. Nanoparticles as smart treatment-delivery systems in plants: new tools to fight old enemies. Pest Manag Sci. 2008;64(2):112–8.
37. Gangwar SK, Singh RP, Mishra PK, Ahmad R, Singh AK. Effect of foliar application of nano-fertilizers on growth and yield of wheat (*Triticum aestivum* L.). Adv Biores. 2022;13(3):190–3.
38. Paradva KC, Kalla S. Nanopesticides: a review on current research and future perspective. ChemistrySelect. 2023;8(26):e202300756.
39. Smaili N, Kabbaj A. Enabling semantic interoperability for smart farming. Agron Res. 2025;23(1):479–92.
40. Singh N, Liu YH, Das D, Shameem N, Parray JA, Li WJ, et al. Nano-enabled strategies for plant stress management and sustainable crop production: a review. Agron J. 2025;117(6):e70230.
41. Chaudhary S, Shukla AK, Sharma RK. Nanotechnology for agriculture: crop production and protection. J Plant Sci Phytopathol. 2017;1(1):62–74.
42. Sun C, Zeng Z, Cui H, Verheggen F. Polymer-based nanoinsecticides: current developments, environmental risks and future challenges. Biotechnol Agron Soc Environ. 2020;24(2):59–69.
43. Hernández-Es R, N-Tovar G, Z-Hernández E, Bañuelos PA. Solid lipid nanoparticles (SLN). In: Nanocomposite materials for biomedical and energy storage applications. London: IntechOpen; 2022. https://doi.org/10.5772/intechopen.102536
44. Campos EVR, Oliveira JL, Fraceto LF. Polymeric and lipid-based nanopesticides for agricultural applications: a review. Environ Chem Lett. 2015;13(3):253–70.
45. Al Hasnawi RA, AlJanaby ZAA, Jaafer AA, Mohammed RJ. Effect of nitrogen fertilization and irrigation water quality on some soil characteristics, growth and yield of sunflower. Plant Arch. 2020;20(1):2703–5.
46. Yadav IC, Devi NL, Syed JH, Cheng Z, Li J, et al. Current status of pesticide pollution in global aquatic environments and their remediation: a review. Environ Sci Pollut Res. 2020;27(2):11955–81.
47. Shandila P, Mahatmanto T, Hsu JL. Metal-based nanoparticles as nanopesticides: opportunities and challenges for sustainable crop protection. Processes. 2025;13:1278.
48. Kumar S, Nehra M, Dilbaghi N, Marrazza G, Hassan AA, Kim KH. Nano-based smart pesticide formulations: emerging opportunities for agriculture. J Control Release. 2019;294:131–53.
49. Noman M, Ahmed T, Wang J, Ijaz M, Shahid M, et al. Nano-enabled crop resilience against pathogens: potential, mechanisms and strategies. Crop Health. 2023;1(1):15.
50. Kookana RS, Boxall ABA, Reeves PT, et al. Nanopesticides: guiding principles for regulatory evaluation of environmental risks. J Agric Food Chem. 2014;62:4227–40. https://doi.org/10.1021/jf500232f
51. De Oliveira JL, Campos EVR, Bakshi M, Abhilash PC, Fraceto LF. Application of nanotechnology for the encapsulation of botanical insecticides for sustainable agriculture: prospects and promises. Biotechnol Adv. 2020;43:107546. https://doi.org/10.1016/j.biotechadv.2020.107546
52. Wang Y, Cui H, Sun C, Zhao X, Cui B. Controlled release and targeted delivery of pesticides using photoresponsive nanocarriers. ACS Sustain Chem Eng. 2021;9:11260–72. https://doi.org/10.1021/acssuschemeng.1c03152
53. Ding Y, Wang Q, Zhu G, Zhang P, Rui Y. Application and perspectives of nanopesticides in agriculture. J Nanopart Res. 2023;25(8):159.
54. Handy RD, van den Brink N, Chappell M, et al. Practical considerations for conducting ecotoxicity tests with manufactured nanomaterials. Environ Toxicol Chem. 2018;37(7):1739–60. https://doi.org/10.1002/etc.4097
55. Al-Silmawy NA, Abd EH, Shahad RF, Mohammed RJ. Effect of using *Pseudomonas fluorescens* bacteria, *Glomus mosseae* fungus and liquid organic fertilizer on soil available nitrogen and phosphorus and some characteristics of fenugreek (*Trigonella foenum graecum* L.) and choline seed content. Agron Res. 2025;23(1):266–79.
56. Zhao X, Cui H, Wang Y, Sun C, Cui B, Zeng Z. Development strategies and prospects of nano-based smart pesticide formulations. J Agric Food Chem. 2014;62(41):10313–20.
57. Oliveira JL, Campos EVR, Bakshi M, Abhilash PC, Fraceto LF. Application of nanotechnology for the encapsulation of botanical insecticides for sustainable agriculture: prospects and promises. Biotechnol Adv. 2014;32(8):1550–61.
58. Grillo R, Pereira AES, Melo NFS, Rosa AH, Fraceto LF. Controlled release system for atrazine using polymer microspheres: preparation and characterization. Phys Chem Earth. 2014;72:84–90.
59. Pateiro M, Gómez B, Munekata PES, Barba FJ, Putnik P, et al. Nanoencapsulation of promising bioactive compounds to improve their absorption, stability, functionality and the appearance of the final food products. Molecules. 2021;26:1547.
60. Al-Juthery HWA, Alkhlefawi AMK, Al-Taey DKA, Al-Janabi HJK, Al-Jassani NAA, et al. Innovative soil, water and plant management promoting sustainable agriculture and environments: a review. IOP Conf Ser Earth Environ Sci. 2023;1259:012014.
61. Campos EVR, Oliveira JL, Fraceto LF, Bakshi M, Abhilash PC, Fraceto LF. Use of botanical insecticides for sustainable agriculture: future perspectives. Ecol Indic. 2015;65:667–72.
62. Najm SH, Al-Juthery HWA. Nano-fertilization of phosphorous and potassium, spraying Sepehr 4 nano-fertilizer and carbon nanotubes on some qualitative traits and active substances in the grains of rice (*Oryza sativa* L.). IOP Conf Ser Earth Environ Sci. 2023;1259:012041.
63. Kookana RS, Boxall ABA, Reeves PT, Ashauer R, Beulke S, Chaudhry Q, et al. Nanopesticides: guiding principles for regulatory evaluation of environmental risks. J Agric Food Chem. 2014;62(19):4227–35.
64. Chen H, Liu Y. Stimuli-responsive delivery systems for controlled pesticide release. J Agric Food Chem. 2016;64(2):334–41.
65. Liang Y, et al. Smart nanopesticides for sustainable pest control: advances and challenges. Environ Sci Nano. 2023.
66. Hu S, et al. Enzyme-responsive nanocarriers for targeted pesticide delivery. Front Chem. 2023.

67. Shanmugavadivu P, Tsai HH, Chakravarthi BR. Recent trends in multisensory systems for smart agriculture. Agron Res. 2024.

68. Zhang Y, et al. Metal–organic frameworks for nanopesticide delivery: recent developments. Nanotechnol Rev. 2023.

69. Hundi HK, Hamid MQ, Noori AAM. Role of *Ochrobactrum* bacteria and organic matter in plant growth and the content of N, P and K under soil salinity stress. J Environ Earth Sci. 2025;7(5):130–9. https://doi.org/10.30564/jees.v7i5.8777

70. Zhang N, et al. Smart controlled-release nanopesticides based on metal-organic frameworks. Chem Commun. 2024.

71. Toman RT, Al-Gburi BKH. Detection of new strains of *Echinochloa crus -galli* resistant to ALS-AHAS and ACCase weedicides for the first time in Iraq. Membr Technol. 2025;(1).

72. Yin J, Su X, Yan S, Shen J. Multifunctional nanoparticles and nanopesticides in agricultural application. Nanomaterials. 2023;13:1255.

73. Drebee HA, Abdul Razak NA, Mohsen AA. Maize production forecasting in Iraq: a Box-Jenkins approach for the period of 2022–2026. IOP Conf Ser Earth Environ Sci. 2023;1259(1):012128.

74. Barik TK, Sahu B, Swain V. Nanosilica—from medicine to pest control. Parasitol Res. 2008;103(2):253–8.

75. Sharma S, Rana VS, Pawar R, Lakra J, Racchapannavar V. Nanofertilizers for sustainable fruit production: a review. Environ Chem Lett. 2021;19(2):1693–714.

76. Drebee HA, Razak NAA, Shaybth RT. Understanding the causes of the decline in the Iraqi agricultural sectors' contribution to the GDP. IOP Conf Ser Earth Environ Sci. 2022;1060(1):012146.

77. Rai M, Yadav A, Gade A. Silver nanoparticles as a new generation of antimicrobials. Biotechnol Adv. 2012;27(1):76–83.

78. Hamid MQ. Response of physical properties of sandy soil treated with different levels of natural soil conditioners zeolite and perlite. Sarhad J Agric. 2025;41(2):591–9.

79. Chhipa H. Nanofertilizers and nanopesticides for agriculture. Environ Chem Lett. 2017;15(1):15–22.

80. Rashidipour M, Maleki A, Kordi S, Birjandi M, Pajouhi N, et al. Pectin/chitosan/tripolyphosphate nanoparticles: efficient carriers for reducing soil sorption, cytotoxicity and mutagenicity of paraquat and enhancing its herbicide activity. J Agric Food Chem. 2019;67(20):5736–45.

81. Kaur P, Garg T, Rath G, Goyal AK. Development and evaluation of clove oil-based nanoemulsion as a safe and effective herbicide. Colloids Surf B Biointerfaces. 2010;81(2):563–70.

82. Cicek E, Yildirim B, Sumnu G. Phytotoxic effects of zinc oxide nanoparticles on weeds. Environ Sci Pollut Res. 2021;28(6):7334–44.

83. Rico CM, Majumdar S, Duarte-Gardea M, Peralta-Videa JR, Gardea-Torresdey JL. Interaction of nanoparticles with edible plants and their possible implications in the food chain. J Agric Food Chem. 2011;59(8):3485–93.

84. Dimkpa CO, McLean JE, Britt DW anderson AJ. Nano-CuO and nano-ZnO induce similar oxidative stress responses in roots of wheat (*Triticum aestivum* L.). Plant Physiol Biochem. 2012;50:48–57.

85. Ola HR, Al-Juthery HWA. Effect of nano-manganese, EM Bokashi fertilization and spraying nanoparticles of iron and carbon nanotubes in soil sustainability, enhancing some growth parameters and yield of broccoli. IOP Conf Ser Earth Environ Sci. 2025;1449:012106.

86. Kranthi S, Kranthi KR, Jain R. Nanotechnology in pest management: an overview. Indian J Entomol. 2020;82(2):217–23.

87. Alzreejawi SAM, Al-Juthery HWA. Effect of spray with nano NPK, complete micro fertilizers and nano amino acids on some growth and yield indicators of maize (*Zea mays* L.). IOP Conf Ser Earth Environ Sci. 2020;553:012010.

88. Singh DK, Tiwari A, Agrawal M. Nanotechnology in agri-food: new frontiers and challenges. Indian J Agric Sci. 2015;85(8):979–85.

89. Tiwari R, Gupta P, Sinha A. The insecticidal impact of imidacloprid-loaded polymeric nanoparticles on *Spodoptera frugiperda*. Environ Sci Pollut Res. 2017;24(2):1178–86.

90. Goepfert S, Flemming H, Jäger D. Neurotoxic effects of nanoencapsulated pyrethroids in *Drosophila melanogaster*. Ecotoxicology. 2017;26(7):1089–97.

91. Shankar SS, Rhim JW, Lee WH. Silver nanoparticle toxicity in *Anopheles stephensi*: oxidative stress and cellular damage. Ecotoxicology. 2016;25(3):671–80.

92. Salieri B, Turner DA, Nowack B, Hischier R. Life cycle assessment of nanomaterials: current practices, challenges and future directions. J Clean Prod. 2024;418:139913. https://doi.org/10.1016/j.jclepro.2023.139913

93. Rocco D, Costa D, Costa M. Behavioral effects of carbon nanotube-based insecticides in *Tribolium castaneum*. J Nanosci Nanotechnol. 2019;19(8):4843–51.

94. Devnath S, Bandyopadhyay A, Bhattacharya S. Toxicological impact of cypermethrin encapsulated nanoparticles on *Helicoverpa armigera*. Environ Toxicol Pharmacol. 2017;51:13–9.

95. Zia N, Raza A, Ali A. Zinc oxide nanoparticles: implications in mosquito control (*Culex pipiens*). J Environ Sci Health B. 2017;52(7):518–24.

96. Rojas G, Fraceto LF, Alves CN. Chitosan-based nanoformulations for the management of *Bemisia tabaci*. Pestic Biochem Physiol. 2020;162:118–26.

97. Sary DH, Abd El-Aziz ME. Synthesis and characterization of nano-micronutrient fertilizer and its effect on nutrient availability and maize (*Zea mays* L.) productivity in calcareous soils. Sci Rep. 2025;15(1):25838.

98. Alzreejawi SA, Al-Juthery HW. Effect of spray with nano NPK, complete micro fertilizers and nano amino acids on some growth and yield indicators of maize (*Zea mays* L.). IOP Conf Ser Earth Environ Sci. 2020;553(1):012010.

99. Jiang X, Musante C, White JC, Rattner BA. Nanoparticle behavior in complex environmental matrices: implications for bioavailability and toxicity. Environ Sci Technol. 2013;47(20):11777–85.

100. Ge Y, Schimel JP, Holden PA. Evidence for negative effects of TiO_2 and ZnO nanoparticles on soil bacterial communities. Environ Sci Technol. 2012;46(18):9611–8.

101. Choi O, Hu Z. Size dependent and reactive oxygen species related nanosilver toxicity to nitrifying bacteria. Environ Sci Technol. 2008;42(12):4583–8. https://doi.org/10.1021/es703238h

102. Raliya R, Tarafdar JC, Biswas P. Enhancing the mobilization of native phosphorus in the arid soils by zinc nanoparticles through rhizosphere microbial activity. J Hazard Mater. 2016;325:108–14.

103. Kumar N, Shah V, Walker VK. Perturbation of an arctic soil microbial community by metal oxide nanoparticles. J Hazard Mater. 2011;190(1–3):816–22.

104. Hussein NA, Ali MF. Effect of nanochitosan on some biological aspects of *Oryzaephilus surinamensis*. Int J Appl Adv Agric Res. 2024;46(1):16–24.

105. Servin A, Elmer W, Mukherjee A, De la Torre-Roche R, Hamdi H, White JC, et al. A review of the use of engineered nanomaterials to suppress plant disease and enhance crop yield. J Nanopart Res. 2015;17:92.

106. Zhang W, Yao Y, Li K, Wang H, Zhang H. Influence of soil properties on the environmental fate and behavior of nanopesticides: a review. Environ Pollut. 2018;238:733–47.

107. Gebbers R, Adamchuk VI. Precision agriculture and food security. Science. 2010;327(5967):828–31. https://doi.org/10.1126/science.1183899

108. Li L, Zhang Q, Huang D. A review of imaging techniques for plant

phenotyping. Sensors. 2020;20(2):1–22. https://doi.org/10.3390/s20020542

109. OECD. Important issues on risk assessment of manufactured nanomaterials. Paris: Organisation for Economic Co-operation and Development; 2022.

110. EFSA Scientific Committee. Scientific opinion on the risk assessment of nanoscience and nanotechnologies in the food and feed chain. EFSA J. 2014;12(5):3739.

111. Hawkins NJ, Bass C, Dixon A, Neve P. The role of regulation in the sustainable management of pesticide resistance. Pest Manag Sci. 2020;76(4):1181–8.

112. OECD. Guidance document on the testing of manufactured nanomaterials. Paris: OECD Environment Directorate; 2013.

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonepublishing.com/journals/index.php/PST/open_access_policy

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

Publisher information: Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.