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The framework of nanopesticides: a paradigm in biodiversity

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Nanotechnology has imparted excellent substitutes in the area of agriculture for the management of insect pests without deteriorating the surrounding biota and thereby allows a more verdant environment. Particular idiosyncrasies have arisen in innovative nanoagrochemicals due to the viable applications of nanotechnology in a myriad of agricultural settings. Concerns have been raised about the need for novel products, therefore they have been predicted to have considerable potential to underpin the obligatory increase in worldwide food production in a sustainable manner. Conventional strategies like assimilated pest management employed in agriculture are inadequate and the application of chemical pesticides has pernicious impacts on the environment and mankind. There is a dire need to develop a repository of safe and propitious formulations to implement a regulatory paradigm for nanopesticides. Nanopesticides are well known in agriculture to reduce costs, improve the outcomes of agricultural products and enhance shelf life and nutrition. Much research has presented the innovation in a range of industrial domains that allows the improvement in the effective use of nanopesticides in water, nanocapsules for the delivery of biocides, nanosensors for the detection of pests, etc. Furthermore, the current consumption pattern of nanopesticides and their health repercussions has been elucidated. This much needed discussion will address the gap between the need for adequate control, environmental efficacy, associated benefits and the detrimental impacts of nanoagrochemicals.

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The use of nanotechnology in agriculture

Sustainability requires high agricultural yields with the resulting environmental repercussions in terms of water utilization, the contamination of ecosystems and land treatment by agrochemicals. Nanotechnology is on the horizon to transform present industries, including food, pharmaceuticals, agriculture, medical and other related areas. Research on the applications of nanotechnology in agriculture, particularly in the production of crops, has latterly received much attention, with the fundamental aim of attaining a more reasonable utilization of resources *via* the development of sensors or delivery systems for agrochemicals.^{1,2} There is a fundamental belief that agriculture has the ability to address these issues, yet there is scant agreement on how this can be attained in a sustainable manner. World food distribution and production result in environmental contamination, changing populations and the extortionate use of energy and water. Nanotechnology has currently been suggested to improve the protection of crops in agriculture by

taking corrective measures to mitigate the use of hazardous pesticides and to fabricate novel pesticide formulations to reduce their employment, with controlled delivery, to grains and plants. Nanomaterials can facilitate the destruction and detection of environmental contaminants by nanoremediation and nanosensor methods.³ The current nanotechnology tools and strategies have the potential to address the several “Gordian knots” of traditional pest management techniques which could revolutionize the agricultural domain. The lion’s share of nanopesticides and nanofertilizers produced up to now encompass reformulations of currently known active ingredients to attain enhanced performances compared to those of existing active ingredients, which will address the major stumbling block of present agrochemical products.^{4,5} Enhanced fertilizer efficacy and the targeted delivery of active ingredients to pests are among the approaches which will help or allow enhanced yields which much reduced rates of application, which will concomitantly address the damaging implications of agriculture on human health and ecosystems. Nanoparticles are well regarded for the control and management of insect pests. They allow the management of insect pests *via* formulations of nanomaterials based on insecticides and pesticides. The use of nanoparticle-mediated DNA and gene editing in plants to improve the heterogeneity in insect pest

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resistance and agricultural efficiency improvement by utilizing encapsulated nanoparticles for the steady exposure of plants to nutrients. Inadequate conventional techniques employed in agriculture for the integrated management of pests, such as the implementation of synthetic pesticides such as DDT (dichlorodiphenyltrichloroethane) and malathion, *etc.*, have had unpropitious impacts on mankind and animals and have resulted in a decrease in soil fertility.

It has been demonstrated that nanoagrochemicals may be excellent replacements for traditional products and much hope has been placed in the applications of nanotechnology. Nonetheless, no systematic comparison has yet been carried out on the framework of literature which has evolved over more than a decade. The increase in the global population has been estimated to reach 9.7 billion by 2050, which requires the gross production of agriculture to be increased by 60%, compared to the levels in 2005, to address the need for food, specifically in developing countries.⁶ Furthermore, there are ~815 million people which are presently undernourished and it is anticipated that an additional 2 billion people will be included in this classification by 2050. These circumstances call for significant changes in the nanotechnology domain to ameliorate the needs of agriculture by providing solutions to agriculture, enhancing the efficiency of agricultural inputs and addressing environmental challenges to food safety and productivity. Pesticides are essential to fortify our crops and thereby they enhance crop yields. However, the potency of chemical pesticides is deficient because of their vulnerability and substantial binding with organic matter in soil which manifests them ineffective or impedes the accumulation of residual pesticides at the root level where several pests reside.⁷ Prodigious amounts are required, which results in the accumulation of pesticides in the water, soil and agricultural products.⁸ Continuous exposure to these chemicals is damaging to human health and threatens the biodiversity of already endangered ecosystems.⁹ Therefore, changes in farming practices are required to distribute pesticides in a more effective manner.

The main emphasis of this exploration is to thoroughly analyze the properties of nanoagrochemicals compared with those of existing products, with a specific aim to focus on such properties which play a vital role in the environmental impacts and benefits associated with agrochemicals. This research aims to present the future of nanopesticides, to cast light on the impact of nanomaterials on soil systems and their translocation and uptake mechanisms.

Nanopesticides: state of the art

The understanding of nanopesticides has been thriving amidst researchers in commercial, scientific and public fields. There is a clear link between climate change and agriculture. In a pernicious negative cycle, the prevailing current agricultural practices exacerbate factors that negatively affect climate change, while the increases in environmental pressures and the influence of biophysical conditions affect both the quantity

and quality of production of food, thereby causing an escalation in food instability and impeding ample nutrition and the equitable distribution of food. The use of nanotechnology has led to the development of efficient medical imaging tools and drug delivery systems, and similar revolutions are now being implemented in intelligent agrochemical delivery systems designated as “nanopesticides”. Nanopesticides represent an emerging technological development that utilizes nanotechnology for the nano-based smart formulation of pesticides to realize applications in the agricultural field. The shape and peculiar properties of nanoscale materials are engineered to explore pesticide activities in innovative nanocarrier formulations based on several materials, such as metals, ceramics, carbon, copolymers, polymers, lipids, silica, *etc.* The benefits of the nanoformulation of pesticides are illustrated in Fig. 1. These comprise the utilization of nanomaterials for the conjugation, encapsulation, and adsorption of pesticides to meliorate the dispersion, permeability, stability and biodegradability of the active ingredients. The encapsulation of pesticides in nanoparticles obstructs their premature degradation and the dangers of the direct release of the active ingredients to mankind. Nanopesticides have a large surface area, contrary to conventional pesticides, which improves their potential for interaction with the target pests at lower doses. It is clear that conventional pesticides and nanopesticides vary in their environmental behaviour, so the extensive investigation of the fate of nanopesticides is required to corroborate that they comply with regulatory legislation and guidelines.^{10,11} Nanopesticides play a significant role in curtailing the environmental footprint by reducing the use of conventional pesticides. Nanopesticides can be classified into two major categories: (a) pesticides whose coherent ingredients are at the nanoscale, which typically contain a nano dispersant emulsion of active pesticides, and (b) pesticides loaded, encapsulated, doped or coated by nanomaterials. The aforementioned type of pesticides generally combines the potential benefits of conventional pesticides while also protecting, transporting and regulating the exposure of pesticides.^{12–14}

Conventional pesticides have poor stability, lower dispersibility, coarse particles for drug carriers, lower biological activity and their employment rate is below 30%, contrary to nanopesticides.^{15,16} Furthermore, nanocarriers of nanopesticides can not only ameliorate the dispersibility of pesticides but also accelerate the delivery of beneficial ingredients of pesticides to the targeted organisms to enhance their bioavailability.¹⁷ These benefits reduce the shortcomings of the low efficiency and large doses of conventional pesticides and hence nanopesticides have been extensively employed. It has been shown that nanopesticides may trigger health repercussions, which have been attributed by the US-based Environmental Protection Agency to: (a) the dermal absorption of nanopesticides due to their very minuscule size and their ability to cross cell membranes, (b) they can enter the lungs and travel to the brain by crossing the blood–brain barrier, (c) the reactive potential and longevity of some specific nanomaterials, which cause environmental concerns and (d) the lack of understanding of how to measure environmental exposure to nanomaterials.¹⁸ The range of nanopesticides being fabricated



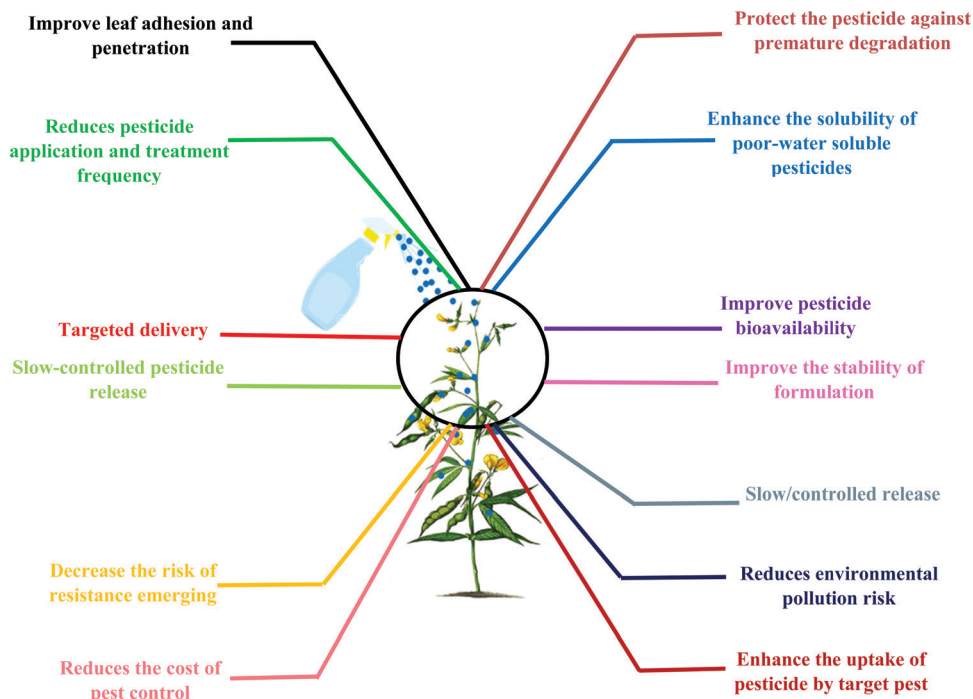


Fig. 1 Why the nano-formulation of pesticides is a benefit.

comprises reformulations of well known active ingredients with fungicidal, insecticidal and herbicidal properties.¹⁹ Most active ingredients are organic molecules; apart from this, some active ingredients are inorganic, for instance copper which has been employed for its fungicidal properties. Nanocarriers are usually soft nanoparticles, such as solid lipids; polymers *etc.*, but there are also several examples of hard nanoparticles *e.g.*, graphene oxide, silica and carbon nanotube nanoparticles.^{20,21} High dosages of employed pesticides does not achieve their target and the utilization of pesticides ordinarily results in the contamination of aquatic and terrestrial environments. One of the prime impulses for the implementation of nanotechnology is to reduce the amount of pesticides required to ensure the protection of crops, which can be attained in numerous ways, for instance by enhancing the bioavailability, controlled release, apparent solubility, targeted delivery, stability, and leaf adhesion of the active ingredients in the environment. The controlled delivery of pesticides reduces the amount of pesticide utilized and prevents the development of resistant pest species that result from the contamination of water and soil and overexposure to excess chemicals. In contrary to conventional formulations, controlled delivery ensures the release of the active ingredient at a predetermined rate to attain the desired efficacy lifespan for the nanopesticides in the field. To explore the efficacy for regulatory purposes, the commercialized or registered nano-formulation is required to be compared with a conventional formulation, which is used as a reference product, to construct an appropriate investigation of its relative advantages, ideally under field conditions following the label directions for a cropping system specified by the Australian Registration Scheme. A landmark report on

“diyarex gold” nanopesticides innovated using nanotechnology is prevailing in the market. It has been implemented as an antiseptic against powdery mildew and rust in several plants.²²

Fate of nanopesticides

Nanopesticides can influence the photosynthetic pathway in the biochemical or photochemical phases, depending on the physiochemical properties or dosage of the nanomaterials, which therefore affects the productivity of crops. The shape and size of nanoparticles are correlated with their mechanical impact on plants, restricting the nanomaterials to some specific sites on organ surfaces or in plants. However, the effects can be manifested throughout the vegetative body, which results in the inhibition or stimulation of plant growth. In the cytoplasm of the cell, nanopesticides interact with chloroplasts and therefore influence the photosynthetic reactions at specific sites in plants by binding to the photosynthetic apparatus and obstructing its functioning. Research has shown that metallic nanoparticles may be detrimental to photosynthesis by inducing functional and structural damage.²³ Therefore, comprehension of the interactions of nanopesticides with the photosynthesis mechanism could lead to an understanding of the electron transport inhibition of nanomaterials, photoinduced oxidative stress and the defense system of antioxidants in plants. For instance, 3 nm of CNTs can regulate tomato germination (*Lycopersicon esculentum* Mill.) owing to the effect of the water content in seeds on the entrance.²⁴ In contrast, carbon-based nanoparticles can induce growth inhibition by mechanical damage attributed to their



perforating impact on organelles or cellulose membranes, which also involves the primary mechanism of cytotoxicity.^{25–27} Furthermore, titanium-based nanoparticles or clay-based colloidal suspensions can affect the hydraulic conductivity of corn (*Zea mays* L.), which impedes the transpiration and growth of plants.²⁸ Hence, it is imperative to analyze the role of nanoparticles in pesticide nanoformulation and the anticipated behavior resulting from this. The following conditions can be contemplated when investigating the functioning of nanoparticles:

(a) The pesticidal properties of nanoparticles, silica derived plant growth regulators and nanometals like aluminum, copper and silver fungicides or bactericides, with titanium-based oxides being prime examples.^{29,30}

(b). The active ingredient is the major material in nanoformulation, which is bound to a nanocarrier which maintains a complex structure after spraying, followed by the release of the active ingredient in a targeted manner. Here, the pesticide fate is associated with nanoformulation that depends on the nanopesticide's durability *i.e.* the duration of the association between the active ingredient and the nanocarrier. There are several nanoformulations, such as lipid-based nanomaterials (nanostructured lipid carriers and liposomes), polymer-based nanomaterials (nanogels, micelles, nanospheres and nanocapsules) and clay-based nanomaterials (layered double hydroxides and clays).³¹

(c). The properties of the nanoformulation are controlled to enhance the apparent dispersion/solubility of the active ingredient or preserve it from degradation. This category includes nano-dispersions and nano-emulsions. Here, the product is referred to as a conventional pesticide in the risk assessment.^{32,33} Consequently, the standard methodologies employed for chemicals should be adequate to examine the fate of nanopesticides.

The characterization and detection of nanomaterials in complex matrices like soil are exceedingly challenging, for instance, due to the existence of natural colloids which are almost indistinguishable from nanoparticles.³⁴ Hence, the fate of nanopesticides in soils depends on the concentration of active ingredients. For instance, by evaluating the soil release kinetics, one may calculate the nanoformulation's durability in water or soil solution from soil pores which are further subjected to strategies to separate free and bound pesticides. The interaction of nanomaterials with plants may be phytotoxic or positive, which also depends on the concentration and nature of the material.^{35–37} The dynamic interaction of nanomaterials with the surrounding environmental media and the absorption/adsorption of various moieties on particle surfaces may also lead to a change in the particle characteristics. The biotransformation of nanomaterials in the environment, resulting from their interaction with bio-films, biological organisms and plants, can also play a major role in regulating their fate, behaviour and persistence in the environment. A number of transport and fate models, including FOCUS models like TOXSWA, MACRO, PEARL, PRZM, PEARL, *etc.*, are presently accessible for organic chemicals for different environmental compartments to aid decision-making.^{109,110}

Additionally, it has been elucidated that the majority of environmental and physiochemical parameters that affect the fate and behaviour of nanomaterials in general are common amongst the different type of materials, for instance,

- For the soil compartment: soil type, porosity, water flow, mineral composition, pH, microbial community, temperature, amount and type of natural organic matter – in particular humic acids – and electrolytes (especially divalent cations).
- For the aqueous compartment: pH, salinity, ionic strength, dissolved (and suspended) organic matter and microorganisms.¹¹⁰

Readers are directed to more critical reviews for the assessment of the fate of nanopesticides that are worth considering but are beyond the scope of this study.^{10,19,33,49,109–111}

Blueprint of next-generation nanoparticles in agriculture

Nanomaterials have potential applications in agriculture to improve the productivity of crops and to enhance soil health, which will be summarised in this segment. The ubiquitous existence of pesticides has resulted in the fabrication of pesticide resistance in insects, weeds and pathogens in the biota.³⁸ Nanomaterials are widely employed to eradicate pollutants from contaminated soils. Due to their high aspect ratio, the smaller size of nanoparticles and their excellent reactivity, there has been an increase in the attention paid to their use to treat contaminated soil *via* chemical oxidation, absorption and reduction.³⁹ Additionally, the recovery of nanomaterials for their reuse provides an opportunity to remove pollutants as it could minimize the remediation cost. Therefore, the innovation of nanomaterials that are efficient and stable and can retain their efficacy for numerous treatment cycles requires significant attention. Accordingly, the high magnetism of magnetic nanoparticles allows their easy and quick separation from the reaction medium when a magnetic field is applied, which allows their regeneration or recycling for additional treatment cycles.^{40–42} Several nanoparticles, such as graphene, carbon nanotubes, silver and copper, exhibit pest control functions and antibacterial properties. The proliferation in the interest into nanobiotechnology has exploited biological strategies for the fabrication of nanoparticles, utilizing algae, fungi and bacteria as well as some specific biomolecules from plants, such as lipids, proteins, carbohydrates and plant extracts, *etc.*, by employing low cost and highly available materials and ensuring low energy consumption and minimal production of byproducts.⁴³ The quest for green technology demonstrates the efficiency provided by the fabrication and implications of green nanomaterials in numerous fields, for instance the environment, food, agriculture, building, energy, biomedicine, *etc.*^{44–48} Nanoparticles have distinctive catalytic, physical and optoelectronic properties that facilitate improved photosynthesis, growth of plants and enhanced resistance of plants towards abiotic and biotic stress.

Nanoformulations can enhance the dispersion and solubility of lipophilic pesticides in water. Stable aqueous



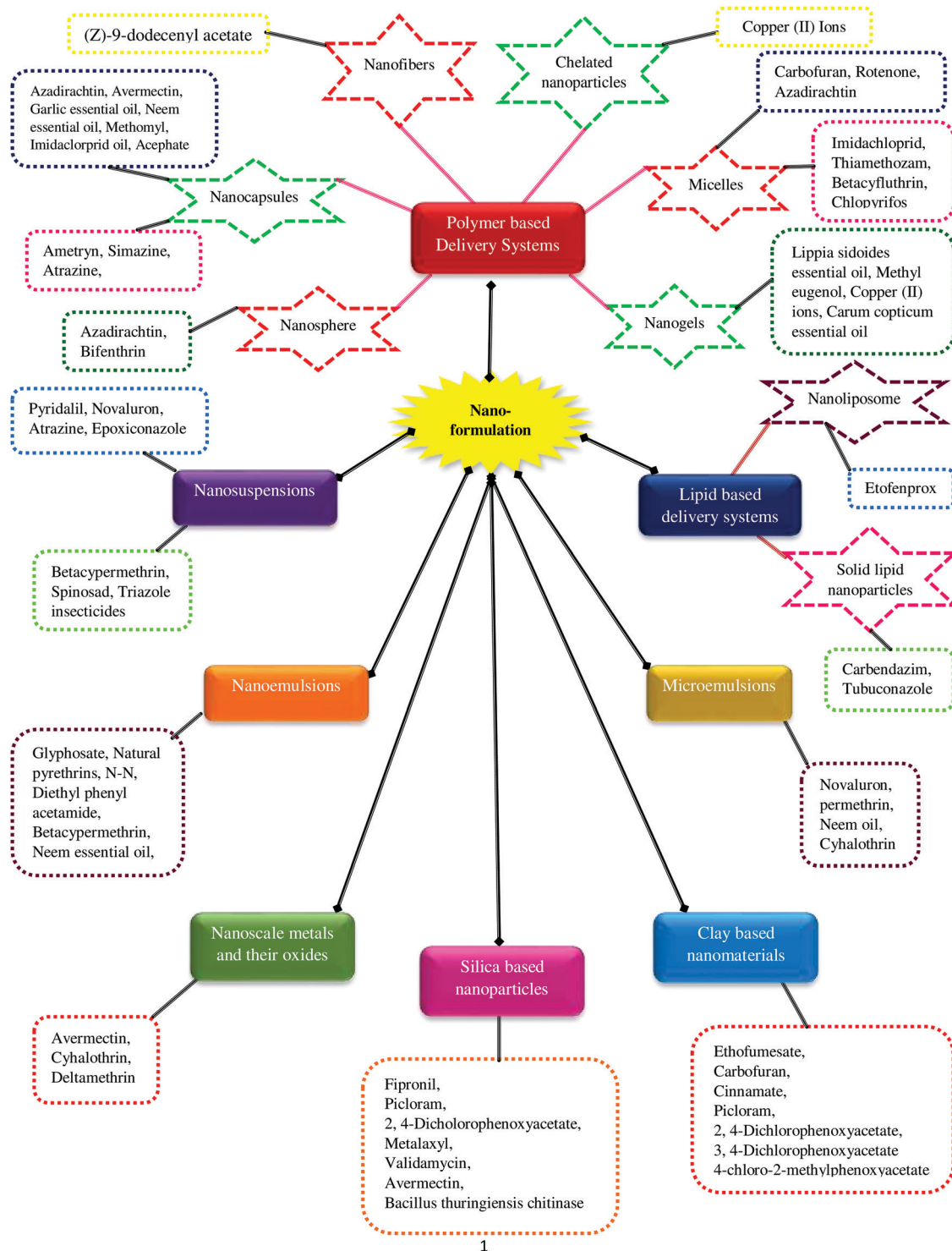


Fig. 2 Delivery of synthetic and natural pesticides, outlining the different types of nanocarriers.¹²⁷

nanodispersions of lipophilic materials can be synthesized by employing suitable surface-active agents, thereby eradicating the utilization of noxious organic solvents and enhancing the bioavailability of pesticides on land. There are numerous types of nanopesticide based formulations, as depicted in Fig. 2. For instance, imidacloprid is an extremely efficient insecticide

against various sucking insects. Furthermore, its nanoderivative is photodegradable, providing environmental benefits compared to the conventional one. Inevitably, nanoencapsulation bestows an opportunity to manage the release rate of pesticides to maintain the concentration of effective pesticides for a longer period. Also, premature degradation of pesticide protection can

be overcome by using nanoencapsulation. Undoubtedly, smart nanosized delivery systems, such as multifunctional delivery systems, permit a more judicious utilization of pesticides; since the amount of pesticides needed for effective pest control is remarkably decreased, the cost associated with the production of pesticides and the waste management of pesticides is reduced and similarly the possibility of resistance developing decreases too. A perennial aim of nanoformulations is to steadily release the active ingredients, otherwise they become unstable and mobile in field applications. In similar cases, the release of active ingredients from nanocarriers is a vital approach to regulate the environmental fate of nanopesticides.⁴⁹

Carbon-based nanomaterials have various properties which make them useful in pesticides. In particular, carbon dots show self-fluorescence, which permits them to be employed for the detection of stress, in contrast to commercial biochar. Lately, significant attention has been paid to immobilization by plants as a cost-efficient and straightforward technique for the remediation of contaminated soil.⁵⁰ Nanohydroxyapatite particles can immobilize metal contents in contaminated soil and segments by curtailing their exchangeable fractions, which diminishes their concentration in pore water.^{51,52} Nanoparticles have also been employed for the mineralization of organic pollutants and catalytic degradation in contaminated soil via an advanced oxidation process that utilized different oxidants. Iron nanoparticles, along with chelating agents, have been employed with modified Fenton oxidation for the remediation of pyrene in contaminated soil.⁵³ The efficiency of oxidation can be varied according to the nature of the chelating agent and the maximum is attained using sodium pyrophosphate. Biotic stresses, for instance herbivore attack and pathogen infection, are crucial factors that affect crop protection. However, the utilization of pesticides has enhanced agricultural productivity and production risk. With a broad spectrum of antibacterial characteristics, silver nanoparticles have acquired conspicuous attention in the field of nanopesticides. Ocosoy and co-workers fabricated DNA directed silver nanoparticles grafted on graphene oxide which decreased the cultured activity of *Xanthomonas perforans*.⁵⁴ This pathogenic bacterium facilitates a 10–50% reduction in yields by causing bacterial spots on tomatoes at a concentration of 16 mg l⁻¹. Under similar conditions, Cromwell *et al.* fabricated silver nanoparticles that exhibited efficiency against nematodes, a common soil-borne organism. The investigated *Meloidogyne spp* were exposed to 30–150 mg l⁻¹ concentrations of silver nanoparticles and it was observed that in six days 99% of the nematodes died. It was also elucidated that 150 mg l⁻¹ of Ag nanoparticles diminished the nematodes by 82% and 92% at days 2 and 4, respectively.⁵⁵ For other chemical pesticides, the production of nanoparticles with greener approaches is environmentally benign. Bacterial or plant extracts comprise numerous metabolites that play vital roles as capping and reducing agents in the synthesis of Ag nanoparticles.

Ali *et al.* fabricated Ag nanoparticles using *Artemisia absinthium* extract, which obstructed *Phytophthora* infection in

plants and meliorates the survival of plants.⁵⁶ In another study, Mishra and co-workers employed a *Serratia sp.*, a rhizobacterium that facilitates the growth of plants, to fabricate Ag nanoparticles using a biomimetic strategy and used them against *Bipolaris sorokiniana*, which demonstrated excellent antifungal activity (based on a spot blotch of the wheat pathogen).⁵⁷ Despite providing efficient results in agricultural settings, the potential toxicity of Ag nanoparticles in crop plants has caused apprehension. Some metal oxides, such as ZnO and TiO₂ (zinc and titanium dioxide), are photochemically active. TiO₂ has outstanding antimicrobial properties; when exposed to light excited electrons are developed in the presence of oxygen, which results in the formation of superoxide radicals via the direct transfer of electrons. Paret *et al.* investigated their antibacterial potential and remarkable photocatalytic properties against *X. perforans* (the pathogen which induces spot infections in tomato plants). Under a greenhouse environment, ZnO/TiO₂ nanoparticles effectively decreased the bacterial spots, in contrast to copper treated and untreated controls, at a concentration of 500–800 mg l⁻¹.⁵⁸ More recently, cerium based nanoparticles have been employed by Adisa *et al.*, who performed greenhouse analysis of the repression of *Fusarium wilt* in tomato plants. Tomato seedlings were exposed to cerium dioxide nanoparticles via the foliar and root pathways at concentrations of 50 and 250 mg l⁻¹. The results demonstrated that the severity of infection was decreased by 53 and 57%, respectively, by utilizing 250 mg l⁻¹ of CeO₂ nanoparticles.⁵⁹

The antifungal and antibacterial properties of copper nanoparticles are well known. *Escherichia coli* and *Bacillus subtilis*, which are bacterial pathogens, and plant fungal pathogens such as *C. lunata*, *Fusarium oxysporum*, *A. alternata* and *P. destructiva* can be treated by Cu(OH)₂ nanoparticles, which act as an active ingredient in Kocide 3000 commercial pesticide.^{60,61} Van *et al.* reported the insecticidal activity of copper nanoparticles on conventional cotton and Bt-transgenic cotton. The resultant nanoparticles improved the expression of the exogenous gene in the tissues of cotton plants encoding the Bt toxin, thereby improving resistance.⁶² On the other hand, silica-based nanoparticles have been used for the efficient and sustained release of pesticides and the focus is on deducing the required dose to attain the desired effect. Prado *et al.* attempted to fabricate a nanosized efficient delivery vector for herbicide. They used picloram, in which there are abundant functional groups that act as anchor points for the attachment of pesticides. Novel silylating agents containing carboxyl moieties were developed by the reaction of chloroacetic acid with 3-aminopropyltrimethoxysilane. They proclaimed that carboxyl derived mesoporous silica nanoparticles can control the release of herbicide.⁶³ Another study investigated the phytopathogen resistance of maize when exposed to silica nanoparticles, which facilitates the up-regulation of phenolic compounds, resulting in the higher resistance of plants towards *Aspergillus spp*.⁶⁴ The loading capacity plays a crucial role in the performance and efficiency of nanocarriers, since high loading permits the reduction of the dose of nanocarriers required to encapsulate the number of active ingredients.



Understanding of carbon-based nanopesticides in pest management

Carbon-based nanomaterials have been contemplated by the research community mainly as active and additive compounds, but they could be employed as efficient fungicides due to their antifungal characteristics. An efficient remediation method employing carbon-based nanomaterials has the potential to be a breakthrough in the decontamination of soil. Researchers have investigated the antifungal activity of six carbon-based nanomaterials, with concentrations of 62.5, 125, 250 and 500 mg l⁻¹, comprising activated carbon, SWCNTs (single-walled carbon nanotubes), MWCNTs (multi-walled carbon nanotubes), GO (graphene oxide), reduced GO and fullerenes, against two crucial pathogenic fungi, *Fusarium graminearum* and *Fusarium poae*, incubated for 5 and 12 h under darkness. SWCNTs, MWCNTs, GO and RGO with concentrations of 500 mg l⁻¹ exhibited excellent antifungal properties, although activated carbon displayed no antifungal activity. The resultant carbon-based nanomaterials also showed the induction of plasmolysis and inhibition of water uptake.⁶⁵ In another study, carbon dot functionalized Ag nanoparticles were fabricated *via* a greener approach employing *lycii fructus* for the development of a colorimetric sensor to regulate phoxin in fruit samples and the environment. This mechanism results in high selectivity, good recovery values (87% to 110%) and remarkable sensitivity with a low detection limit of 0.04 µM.⁶⁶ Tang *et al.* investigated cadmium toxicity with the integration of GO in *Microcystis aeruginosa* by increasing the generation of reactive oxygen species.⁶⁷

The utilization of fullerene nanoparticles disrupts the pathways of the transport and energy of electrons by suppressing the transcription of genes. In addition, the employment of MWCNTs is responsible for the formation of cell divisions and cell walls which affect water transport, but utilization at higher concentrations becomes toxic.^{68,69} A high degree of functionalized CNTs facilitates poor impacts and a considerable reduction of the growth of various plant species.⁷⁰ This is per the results of Tripathi *et al.* on the growth of *Cicer arietinum* L. upon treating it with water soluble MWCNTs. The investigation resulted in a reduction in the germination rate of rye and corn plants treated with MWCNTs, but the length of the roots was increased.⁷¹ The effects of engineered carbon nanomaterials with various dimensions on the germination of rice seeds were explored, which resulted in an increase in the rate of germination with increased uptake of water for treated seeds, in contrast to those of control seeds. For instance, the exposure of zucchini plants to MWCNTs did not reveal any detrimental impacts on root elongation and the germination of seeds, although a decrease in biomass was observed during further growth in the presence of SWCNTs.⁷²

Stipulations of polymers based nanopesticides delivery stratagems

Polymer-based nanoformulations have the prodigious potential for further growth and practical innovations have improved

their colossal efficacy in contrast to conventional formulations. Polymer-based nanoformulations enable a capacious range of objectives to be attained, which makes them appropriate for protection against degradation, low solubility and the slow release of active ingredients. On entering into the soil, nanomaterials can suffer biological, chemical or physical transformations, depending on their interactions and nature, with various components of soil. Aggregation is the prime difficulty with regards to physical processes, and it occurs spontaneously when the nanoparticles enter the soil. Aggregation reduces the surface area of nanoparticles, which as a result affects their reactivity. Mineral and soil colloids, specifically iron and clay-based minerals, are viewed as efficient sinks for nanomaterials. Table 1 shows various polymer-based nanocarriers and explains the properties and applications of the resulting nanopesticides. In addition, biopolymers are excellent materials derived from natural resources and can be broadly employed as nanocarriers. They have beneficial properties such as excellent stability, biocompatibility, biodegradability nontoxicity and semi-crystallinity.^{73,74} The essential biopolymer is chitosan, a natural polysaccharide originating from the exoskeletons of insects or the cell walls of fungi. Chitosan-based nanocarriers have a broad range of applications in agriculture, for instance in crop protection, the growth of plants, *etc.* It is well understood that weeds are a significant threat to modern agriculture. Therefore, the formation of nanoherbicides using biopolymeric materials could enhance the efficiency of herbicides.

Current biomimetic routes for the mitigation of soil contamination

Nano based formulations for utilization in agriculture have been synthesized using physical, biological, and chemical pathways, which lead to enhancements in the environmental toxicity, cost, cytotoxicity, *etc.* Therefore, concerns have been raised about the need to fabricate such formulations without using noxious compounds during synthesis. Fig. 3 illustrates the balance between concentration, size and biodegradability which affect the toxicity of nanopesticides. Green chemistry, a magic bullet in the present scenario, has resulted in many innovations and has been used in the agricultural sector. Lately, microwave irradiation and sonochemistry have gained attention as clean, green and environmentally benign strategies for the synthesis of greener nanoparticles. Anastas *et al.* designed a Green ChemisTREE which outlines the principles of green chemistry: atom economy, utilization of benign solvents, economic viability, waste prevention, time-saving approaches and simple instrumentation, in contrary to other techniques highlighted as improving energy efficiency.⁹¹ The production of nanomaterials using microorganisms and plants has achieved the consideration of researchers worldwide due to their environmentally friendly properties. Several plants and bacteria have been employed to develop various nanoparticles for the protection of crops. Several natural substances are well known to display pesticidal characteristics, but most of them



Table 1 Comparison of a range of nanoformulations as delivery systems of nanopesticides, delineating the characteristics and outcomes

Polymer	Material	Characteristics	Outcome	Ref.
Chitosan	Zinc nanoparticles	Inhibitory activity against pathogenic bacteria	Bio-reduction of silver nitrate by <i>Pleurotus ostreatus</i>	75
Chitosan	Copper nanoparticles	Increased antioxidant activity, enhanced growth parameters, enzyme defense	A biodegradable nanocomposite has been fabricated against <i>Curvularia</i> leaf spots in maize	76
Chitosan	Copper(II) ion nanogel	Nanogels were produced to adsorb Cu(II) ions, which were found to be more stable	Appropriate substrate for inhibiting the growth of <i>Fusarium graminearum</i> , suitable for applications in biopesticides and a pH-sensitive delivery system.	77
Chitosan/Cashew gum	<i>Lippia sidoides</i>	Nanogel loaded with <i>Lippia sidoides</i> oil	<i>In vitro</i> release profiles exhibit sustained and slower release	78
Chitosan	Copper and zinc nanoparticles	Nanoparticles have been tested against amylase and protease enzymes correlated with the immobilization of food	Defense enzymes of the plant which protects them for diseases	79
Polyamide 6 cellulose acetate	Nanofibers	Pheromones were incorporated in high concentration via electrospinning	Release of pheromones from polymer carriers	80
Chitosan-co-poly(lactic acid)	Imidacloprid	Imidacloprid loaded particles exhibited a sustained release process	Lipophilic pesticide delivery for imidacloprid systems	81
Chitosan	Spinosad and permethrin	Agrochemical loaded chitosan nanoparticles analyzed on <i>Drosophila melanogaster</i> under several conditions	An excellent residual effect, used for insect pest management	82
Chitosan	Gum arabic nanoparticles	Encapsulated geraniol was fabricated and tested for biological activity against <i>Bemisia tabaci</i> . Protection against UV degradation was observed	Potential system for utilization in insect pest management	83
Polyethylene glycol	Essential oil (peppermint and palmarosa)	Enhanced lethal and sub-lethal impacts of essential oil against <i>Blattella germanica</i> L.	Developed to control German cockroaches	84
Poly(<i>N</i> -isopropyl acrylamide-co-methacrylic acid)-methacrylic acid	Hollow mesoporous silica nanoparticles	Sustained protection in rice plants against <i>Nilaparvata lugens</i> . Effectively protects the model pesticide thiamethoxam against UV irradiation and displayed strong adhesion.	Temperature coefficient of pesticides	85
	Zein nanoparticles/neem oil	No phytotoxicity toward <i>Phaseolus vulgaris</i> . Nanoencapsulated neem oil was effective against <i>Tetranychus urticae</i> and <i>Bemisia tabaci</i>	The nanobiopesticide has the potential to regulate agricultural pests	86
Poly(lactic-co-glycolic acid)	Nanoparticles	The encapsulated nanoparticles had thermodynamically favorable characteristics to control disease by <i>Phytophthora infestans</i> employing cyzofamid.	Suppression of infection in tomato leaves and useful in breakthrough load reduction techniques	87
Starch with disulfide bridged bond	Mesoporous silica nanoparticles	Fabricated nano vehicles could prevent the premature release of avermectin and the degradation of active ingredients	Superior insecticidal activity and non-toxic organic solvent employed in stimuli-responsive nanocarriers	88
Poly ϵ -caprolactone	Chitosan nanoparticles	Encapsulation of <i>thiamethoxam</i> in polymeric nanoparticles by the solvent evaporation technique. Protection from premature degradation. The microalgae and microcrustaceans were examined to evaluate the toxicity	Low ecotoxicity and can prevent huanglongbing disease on citrus plants	89
Chitosan	β -Cyclodextrin containing linalool and carvacrol	The decrease in toxicity is observed upon nanoencapsulation and demonstrated insecticidal activity against <i>Tetranychus urticae</i> and <i>Helicoverpa armigera</i>	Repellent activity and decrease in oviposition was demonstrated for mites	90

usually require protection against premature degradation and are unstable. Several polymer-based formulations using greener strategies have already been discussed in Table 1 in various forms such as nanoparticles, nanofibers, nanogels, nano-emulsions, nanospheres, etc.

In a study on the synthesis of Ag nanoparticles, cell-free extracts of *Trichoderma viride* were utilized for *in vivo* and *in vitro* screening against a causative agent *i.e.*, *Alternaria solani* to treat infection with blight disease in tomato plants. The antifungal results demonstrated that there was a 100% reduction in the spore count after treatment for three days. In addition, a 74% reduction in the fungal biomass was found after treatment for seven days. The effects on the foliage of the prepared nanoparticles were to facilitate a 48.57% reduction in the fungal spore count, while the pristine weight and content of

the total chlorophyll of the plants increased by 32.58% and 23.52%, respectively, in comparison with those of the untreated infected plants.⁹² Nevertheless, although micro-organisms have been considerably studied to generate biogenic nanoparticles, there are still some gaps which need to be addressed. The reduction mechanisms that micro-organisms employ to fabricate nanoparticles are not completely understood, which makes it difficult to regulate the processes. Additionally, it is important to maintain the stability of the culture media because the reaction processes in the media can be influenced by the salinity, pH and temperature, which impede the scaling up of this to the industrial level. Moreover, the employment of plants to fabricate biogenic nanoparticles has difficulties, for instance, changes in the shape and size and less recovery results in the reduced synthetic rate of the nanoparticles.



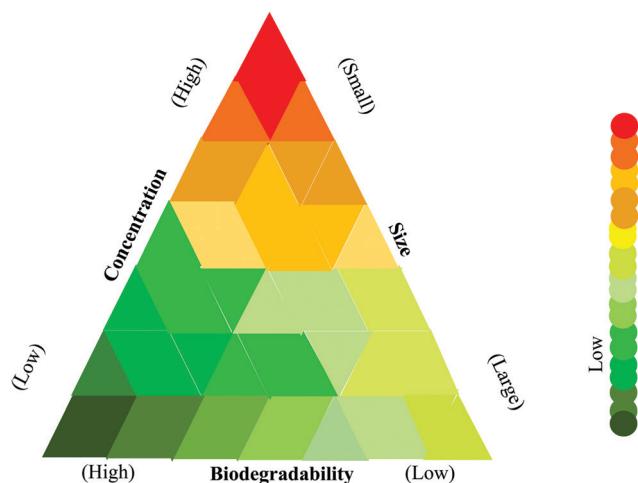


Fig. 3 Balance between concentration, size and biodegradability affecting the toxicity of nanopesticides.

Therefore, it is required to refine the understanding of the appropriate selection of plant extracts to be used as reducing agents with a knowledge of the reduction mechanisms. To recap, it is necessary to achieve a total comprehension of the mechanisms regulating the fabrication of nanoparticles through live organisms to develop economically viable strategies for the innovation of industrially fabricated nanoparticles with

suitable physicochemical characteristics, low toxicity and high biological activity.⁹³ The aforementioned nanoformulations display inherent potential for agricultural applications and can be used to examine the maturity of crops and health conditions, discern and tune the amount of fertilizers and pesticides and sense the humidity of the soil to tailor irrigation, which eradicates the misuse of water.

Additional benefits provided by the computational modeling of nanopesticides

There has been a proliferation in endeavours to understand the release mechanisms or to evaluate whether they are regulated by desorption from the surface, erosion of the polymer structure or diffusion *via* the polymer matrix through computational modeling. Computational methods are in the foreground of the investigation of developed nanopesticides, which is attributed to their colossal potential to improve the understanding and innovation in environmental and (eco)toxicological analyses. Computational tools aid in reducing the time and cost required to attain authentic information to perform risk assessments and can be used alongside experimental data by delivering the necessary evidence to avoid futile experimental studies. Fig. 4 depicts how experimental data is utilized in conjunction with the outputs of

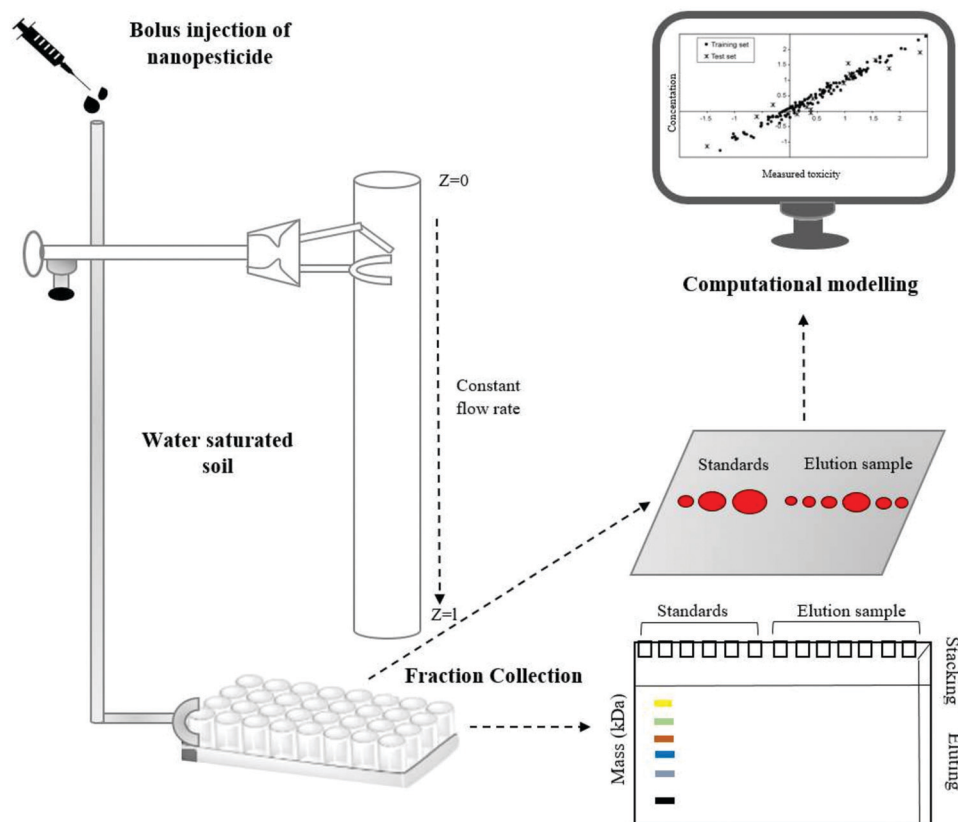


Fig. 4 Computational approaches to assessing nanopesticides.¹¹⁶



computational models to assess nanopesticides. Xiang and co-workers conducted a series of experiments employing nanofibers focussed on differentiating between the degradation and diffusion controlled release mechanisms by utilizing the Higuchi equation, which has been applied in cases where the swelling of polymers and dissolution is negligible. For the in-active ingredients, the diffusion-controlled release was remarkably controlled by the nanocomposites' hydrophobicity, which followed Fickian kinetics, although the consequent mechanism of degradation followed time-independent, zero-order kinetics. The study revealed that increasing the content of cellulose nanocrystals also increases the rate of the degradation of the fibers and the release of the active ingredients.⁹⁴ Other landmark research has employed the strategy of fitting release curves utilizing mathematical models developed for the pharmaceutical industry.⁹⁵ In another study, Fickian and non Fickian models have been employed for the release profiles of nanopesticides in water,^{96,97} which have been also employed for the estimation of genotoxicity. Ritger and Peppas designed the power model of semi-empirical power that has been extensively utilized to distinguish the type of mechanisms involved in the release of pharmaceuticals from nanosystems, which has been latterly applied for nanopesticides.⁹⁸ When more than one mechanism is involved, this model has become inappropriate in conditions such as Fickian transport (diffusion combination) and non-Fickian transport (Type II, regulated by polymer chain relaxation). The exponent value gives the type of release mechanism: (a) $n < 0.43$ means that the mechanism is Fickian diffusion, (b) $n > 0.85$ means that release is regulated by the process of relaxation and (c) $0.43 < n < 0.85$ reflects anomalous characteristics with the kinetics of non-Fickian release and an amalgamation of the relaxation and diffusion of polymeric chains.^{99,100} Some other linear models, such as first and second-order kinetic models, have also been employed. The aforementioned results demonstrated that the release of pesticide active ingredients is influenced by diffusion *via* the polymeric matrix, the surface desorption and the degradation of the polymeric structure. Therefore, a prodigious number of components are anticipated to exert a potential influence on the release profiles of nanopesticides in the agricultural field.

There has been a substantial upsurge of interest in quantitative structure–activity/toxicity/property relationship (QSAR/QSTR/QSPR) models lately. Viallaverde and co-workers analysed QSAR and QSPR tools for the evaluation of the biological and physiochemical effects of nanopesticides. Some of the potential modelling methods suggested for development of nano QSAR and QSPR tools include artificial neural networks, Gaussian processes, multiple linear regression and partial least squares for quantitative problems, knowledge-based expert systems, k-nearest neighbour and linear discriminant analysis for qualitative problems and principle component analysis, support vector machines and decision trees for both types of problems. The authors reported that nanopesticides have not been evaluated utilizing nano-QSAR and QSPR models so far and emphasized the inclusion of trailblazing nanodescriptors with the capacity to combine both the size-dependent and chemical attributes of nanopesticides. They further suggested the

correlation of biological and physiochemical end-points from theoretical and experimental nanodescriptors.¹¹² Molecular modelling techniques, density functional theory calculations, kinetic mean field models and molecular dynamic simulations have been employed to achieve an understanding of the dynamics and interaction of nanoparticles within biological systems.¹¹³ Recently, Mishra *et al.* utilized molecular docking to analyse the interactions between silver nanoparticles and the digestive enzymes of termites and gut-associated microbes. The study revealed the potential prospects of fabricated nanopesticides for pest management in the agricultural and forestry sectors.¹¹⁴

Machine learning and artificial intelligence allow the determination of the most basic boundaries that decide and predict the behaviour of nanoparticles in soil and plant environments from enormous datasets. The utilization of mechanized information recovery from public data sets, data pre-processing and gap filling, and robotized parting of the information into test and approval sets for modelling can work with the *in silico* investigation of nanomaterials that can be applied to plants effectively. Nanomaterial changes in various soil conditions and distinctive rhizosphere syntheses under changing environmental conditions could likewise be predicted by incorporating prescient models, empowering the improvement of nanomaterials for horticultural applications in a range of climatic and local conditions. More extensive environment impacts and the forecasting of nanomaterials–soil–plant practices under future environmental situations can likewise be predicted utilizing, for instance, deep learning approaches and Bayesian networks. Such models are particularly significant as they can work under information shortages, yet can effectively consolidate new information as it arises. The use of these models to develop the full understanding and advancement of sustainable farming will provide significant new multifaceted bits of knowledge and ideas for ways forward.¹¹⁷

Toxicity: the stumbling block for nanopesticides

With the rapid expansion of nanotechnology, there is trepidation concerning their plausible entry into the food chain and the ensuing bioaccumulation of manufactured nanomaterials. However, the dangerous impacts caused by the toxicity of pesticides and nanomaterials on living organisms are still poorly understood. Therefore, we have to investigate these concerns because the inherent aftermath on humans and biota is life-changing. Toxicity is the crucial element in the efficacy of pesticides and is correlated to their action against the target organisms. Toxicity is a consequence of the stabilizers, reducing agents and organic solvents employed to circumvent the agglomeration of undesirable colloids. The employment of nanomaterials is not innately risky, for example, traditional foods harbor innumerable nanoscale materials including proteins in milk, fat globules in mayonnaise, carbohydrates, DNA, *etc.* However, the use of some designed nanoscale



materials in agriculture, water and food may prove to be detrimental to human health and the environment.¹¹⁵ Hence, there is an urgent need to innovate and develop techniques for the non-hazardous, efficient and economically viable production of nano-scale compounds to accelerate their utilization in agriculture.

Some studies have reported increased pesticidal toxicity at extremely low concentrations of nanopesticides, in contrary to traditional formulations. It has been suggested that the toxicity of nanopesticides was much higher, close to nearly an order of magnitude higher, when compared to conventional formulations, although analysis could not be compared across several pests or host organisms.^{101,102} Sasson *et al.* reported that nanopesticides exhibited higher toxicity toward target organisms compared to those of commercial products, which focussed on the need for the accurate comparison of nanopesticides with authentic existing conventional equivalents.¹⁰³ The variability in toxicity among conventional formulations is not peculiar, but it ordinarily

remains enigmatic, attributed to the formulations and ingredient processes being confidential and proprietary. In another study, the activity of nanopesticides was compared with those of the pristine active ingredients with commercial formulations. Such investigations are required to distinguish the effect of nanoformulations in opposition to classical formulations by considering the toxicity of fungicides and insecticides. Therefore, the products fabricated to regulate the release behaviour of the active ingredients require study over an adequate time frame as the time period of the investigation was shown to influence their activity.¹⁰⁴ Fig. 5 illustrates the life cycle of nanopesticides.

Environmental repercussions

The behavior and fate of nanopesticides during their application in the environment are the pivotal determinants of their impact

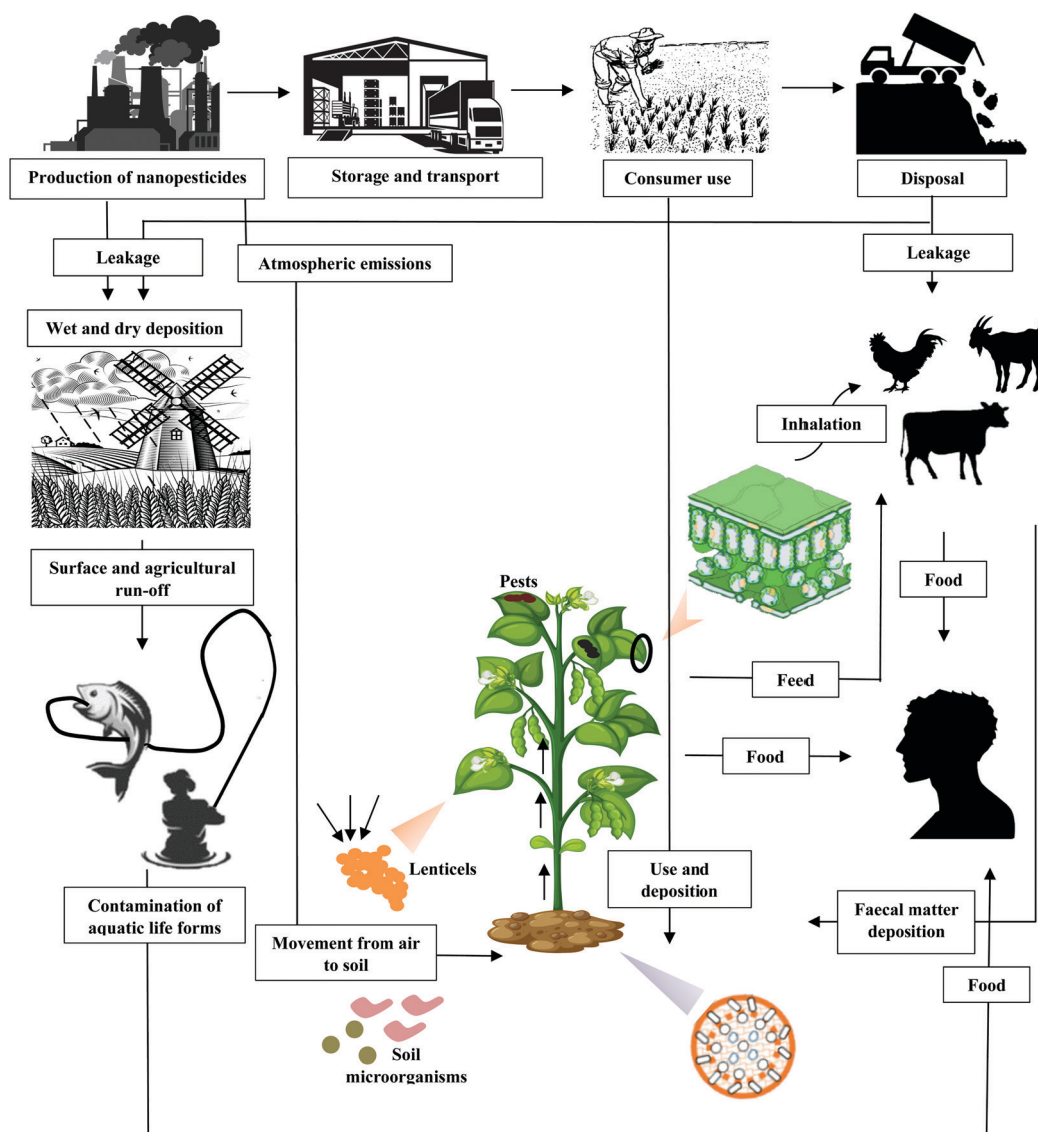


Fig. 5 The life cycle of nanopesticides.



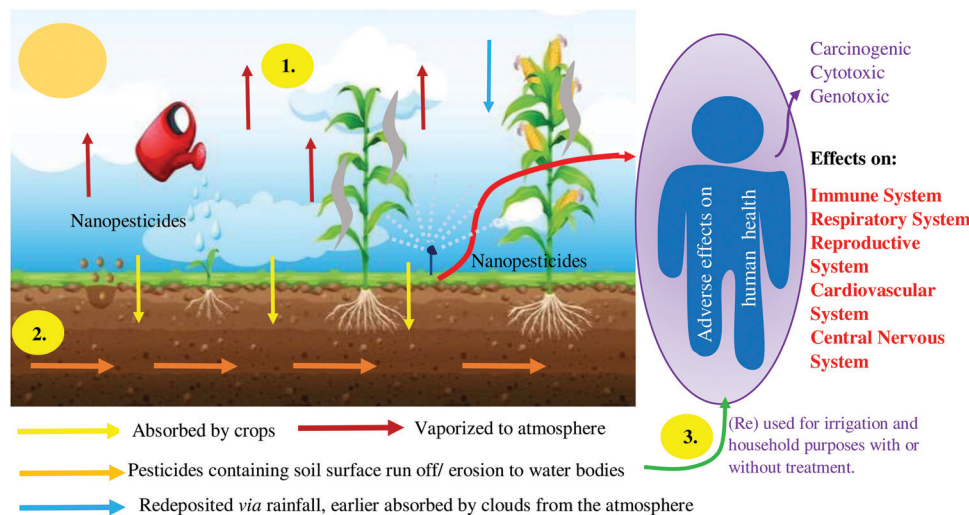


Fig. 6 Nanopesticide drift and the adverse consequences that could lead to contamination of (1) the air, (2) land and (3) water.

on human health and the ecosystem. The perennial objective of nanoformulations is to steadily release the active ingredients or else they can become too unstable and mobile in the agricultural field. In the aforementioned conditions, the release of active ingredients from nanocarrier systems is an essential process that controls the environmental fate of nanopesticides. The inefficiency of the application and delivery of pesticides is also a Gordian knot. It has been observed that 10 to 75% of pesticides do not reach the selected target. The issues related to the employment of pesticides include their toxicity to non-target organisms, their persistence, the development of resistance and their accumulation in environmental spaces (Fig. 6).

If nanotechnology could enhance crop nutrition, fertilization and the efficiency of irrigation, there would be huge related benefits triggered by the reduced environmental pressure associated with the production of crops. The quantification of unbound dissolved ions of dormant noxious micronutrients is necessary to appropriately analyze the impact of nanopesticides in contrast with the effects conventional products. Such investigations these days are thought to be crucial for the environmental assessment risk of nanomaterials. Agriculture is in dire need of a revolution to meet the expanding demand for food while eradicating its impact on biota. It is paramount that essential research efforts are imparted for the innovation of new products that are highly competitive and can make future agriculture more sustainable. The responsible implementation of nanotechnology can optimistically play a pertinent role in attaining this objective.

Current consumption patterns and health impacts

The consumption of pesticides does have a socio-economic impact on the economy as a whole. They are certainly helpful in improving overall crop productivity; the demand for pesticides is continuously on the rise and currently stands at 4.19 million tonnes annually, as per the data collected by the FAO

(Food and Agriculture Organisation of the United Nations). However, the associated health hazards associated with their consumption cannot be ignored. In a global comparative analysis[†] of the consumption of pesticides over the years *vis-à-vis* their gradual impact on the health of the population, it could be deduced that for the world overall (Fig. 7(g)), the growth in the consumption of pesticides has contributed to the deterioration of health, with the share of the population with cancer or the presence of neoplasms rising over the years. Country-wise, it could be deduced that in countries like China (Fig. 7(b)) and Russia (Fig. 7(c)), the consumption of pesticides has certainly taken a toll on the health of the population. In other words, the percentage of the population suffering from cancer or the presence of neoplasms in the population has been rising over the years in these regions. In such situations, the deployment of smart nanotechnology could be useful in mitigating the adverse healthcare hazards associated with the use of pesticides. In the case of advanced regions like the European Union (Fig. 7(e)) and the USA (Fig. 7(d)) as well, the rising consumption of pesticides over this time has led to a significant adverse impact on the health of the population. In the case of the former region, the share of its population with cancer has been rising consistently since 2005 onwards and has flattened since 2015. In the case of the latter country, the percentage of the population suffering with cancer shows a steadily rising trend from 2003 onwards. However, in a country like Australia (Fig. 7(a)), the growing consumption of pesticides is unlikely to have harmed the health of the population in this country. In the case of an emerging economy like the primarily agrarian India, the consumption of pesticides was the highest during the structural transformation period of the 1990s and gradually reduced during the millennium decade starting in the year 2000. Eventually, the consumption

[†] The pictorial representation (Fig. 7) is based on data collected by the Food and Agriculture Organisation of the United Nations and the Institute of Health Metrics and Evaluation, USA.



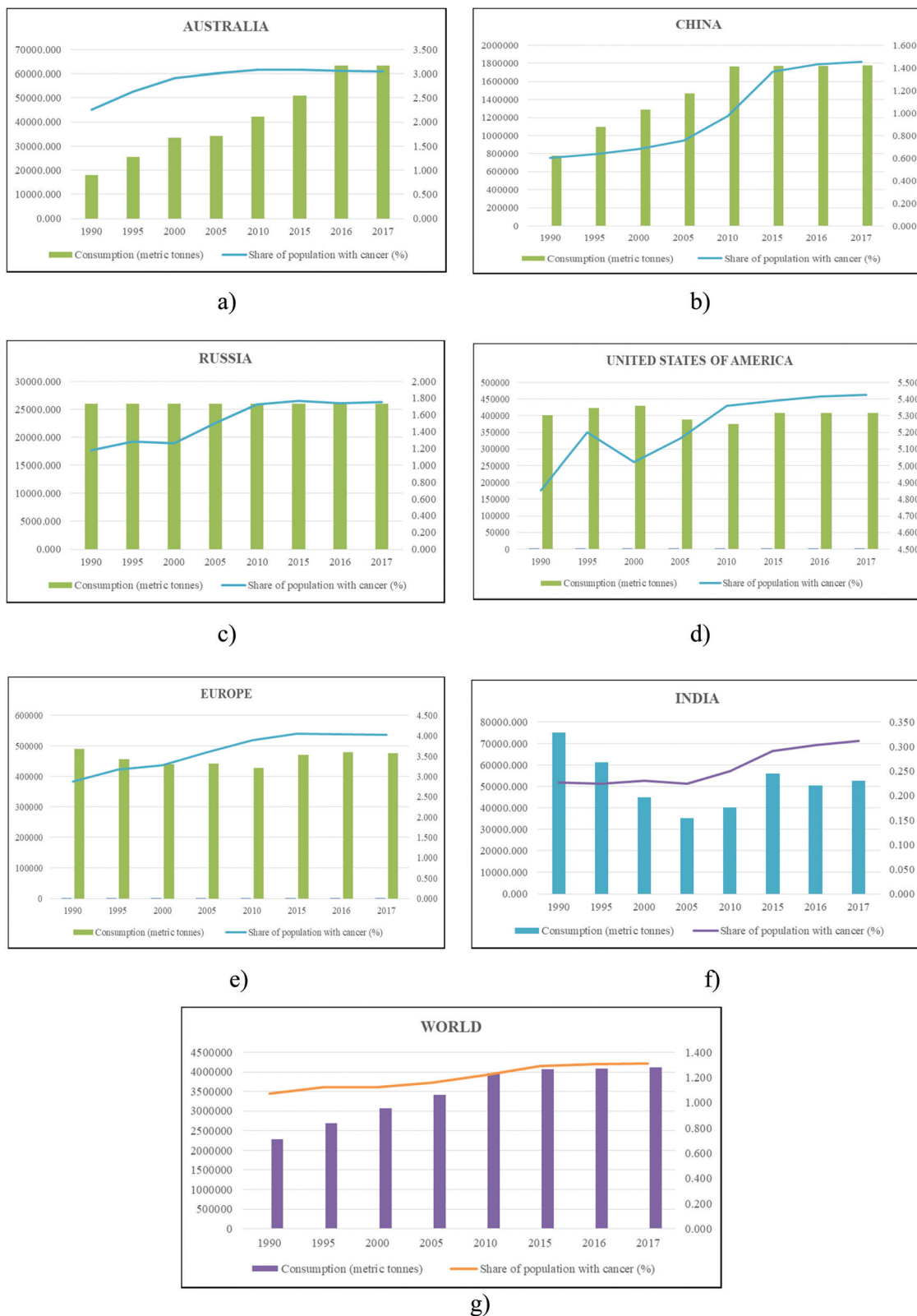


Fig. 7 Country-wise and world trends (pesticide consumption and health impact). Source: authors' analysis of data collected from ref. 105 and 106.

pattern has risen from the year 2013 onwards and has stabilized eventually. However, the correlation between the consumption trend and the adverse impact on health is not

quite evident from the data, although the share of the population with cancer has been rising over the years in the country.



The positive effects of nanoscience or nanotechnology in such countries could be a possibility. Nanotechnology has emerged as one of the most promising technologies of recent times. At nano-dimensions, the quantum confinement of electronic states results in unusually exceptional properties and thus ameliorates the issues of conventional bulk materials.¹⁰⁵ Globally, it is estimated that the nanotechnology market is expected to exceed US\$ 125 billion¹⁰⁶ as it continues to have an impact on nearly all sectors of the globalized world, such as information and communication technology, electronics, energy, cosmetics, automotives, agriculture, *etc.* As an agrarian country, India, operating at a much larger agricultural scale, is set to become a country with a larger share of demand for such technologically advanced products related to farming.

In the case of India's agricultural sector specifically, productivity and food security could be directly linked to the application of nanopesticides. Fig. 8 demonstrates the various applications of nanotechnology in the agricultural sector.

The excessive use of pesticides and their impact on health and the environment has resulted in demand for technologically advanced and safe solutions to the current agricultural formulations. In such situations, the deployment of smart nanotechnology solutions could be useful in mitigating the adverse health hazards associated with the excessive use of conventional pesticides. At present, nanopesticides are designed either as nano-sized particles of organic and inorganic constituent species as the active ingredients (AIs) in nanopesticide formulations or in the form of small engineered nanostructures having the pesticide as the active ingredient. Nanoscale formations are seen as potential candidates for bringing about a change in addressing the problems associated with bulk pesticides, especially in terms of their high efficacy and the reduction in the use of huge quantities of pesticides, however, the field is still in its infancy. Toxicity to humans and other non-target organisms, along with possible environment impacts, are the major challenges for the potential large scale applications of these nanopesticides. Thus, a word of caution is needed when it comes to the consideration of large scale

applications of nanopesticides. More importantly, developing a robust regulatory framework for designing application protocols by analysing the potential risks associated with these products requires much more research effort from the scientific community because otherwise it may prove to be a major threat to food security globally. Thus, in order to overcome the challenges and major stumbling blocks in the way of large scale applications, we need various safer-by-design technologically advanced agrochemical systems with global applicability.

Natural compounds and biological systems are also viewed as interesting alternatives to conventional pesticides. Natural compounds and other biologically derived species have immense potential for use as safe and environmentally friendly agrochemicals, requiring only low doses, and they are obtainable from living systems as renewable resources, thus, they do not require much screening and have immense societal acceptability, which has attracted enormous interest. The subject has been reviewed at length in a recent study.¹¹⁸ Pascoli and co-workers evaluated the toxicity of neem-oil based nanopesticides towards non-target organisms, utilizing *Allium cepa*, soil nitrogen cycle microbiota and *Caenorhabditis elegans* in order to develop a safer-by-design strategy. Propitious results in the toxicity studies opened up perspectives for the use of nanobiopesticides to contribute to sustainable agriculture and improved food safety.¹¹⁹ Recently, Zhao and co-workers utilized carboxymethyl cellulose and rosin, two cheap and widely available biodegradable natural resources, for the synthesis of amphiphilic nanocarriers for the encapsulation of hydrophobic pesticides. It was inferred that the use of natural materials improved the long-term insecticidal effect of the pesticide, as well as reducing the harm to aquatic animals endangered by the immoderate utilization of organic solvents in conventional pesticides.¹²⁰ These naturally derived agrochemical systems are, however, constrained by many limitations as compared to their synthetic counterparts in terms of their low effectiveness, complex matrix chemical structures, low persistence, higher extraction cost, inability to penetrate the applied plant forms, inherent instability and much higher biodegradability. Nanotechnology, with special reference to

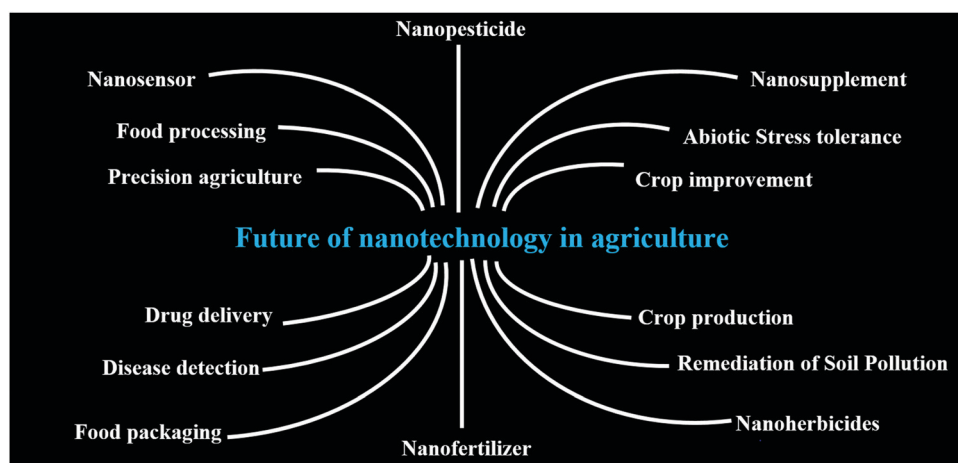


Fig. 8 Application of nanotechnology in agriculture. Source: Islam (2019).¹⁰⁷



engineered nanoscale devices, can effectively be used to address the limitations of these natural compounds based pesticide formulations by enhancing their efficacy and stability while still maintaining their safety aspects in relation to the environment and other non-target organisms. The success of such technologies will be inherently dependent upon the safety of these designed systems in relation to the environment and other organisms.

RNA interference (RNAi) technology has been explored for the last two decades and provides another very interesting and novel mechanism for effective crop disease control and the field of pest management. The application of this technology is based on introducing double stranded RNA (dsRNA) or small interfering RNA (siRNA) with the objective of silencing target genes in plants or plant dwelling organisms by way of their direct application as pesticides. Progress in this area is expected to bring a new generation of plant protection agrochemical systems in addition to creating new plant varieties. The RNA interference mechanism is present in all eukaryotic organisms and is triggered by the cellular uptake of dsRNA molecules which are homologous to a target gene in the pest or pathogen. These dsRNAs are then processed by the RNAi pathway within the cell, which eventually leads to a depletion of messenger RNAs (mRNAs) and proteins which are encoded by that particular target gene. As in the case of other prevailing technologies, the RNAi technique requires comprehensive evaluation in relation to risk assessment frameworks and application protocols.^{121,122} The COST Action iPlanta, one of the largest network of European scientists, has published the outcomes of very important study aimed to discuss the risk assessment of RNAi plants and crops in relation to target and non-target organisms and the environment.¹²³ Bioinformatics may prove to be of immense help in carrying out such assessments of these RNAi plants by way of comparing the genomes of target and non-target organisms upon exposure to interfering RNA. Although RNAi technology has enormous potential to present the next generation of agrochemical solutions in crop protection and pest management, the instability or rapid degradation of bare assayed dsRNA is a major challenge in the way of its practical utility in farming.

Nanotechnology, as a fundamental core platform, can be put to use to help design innovative nanoscale carriers for dsRNA while simultaneously preventing dsRNA degradation, especially technology that would not generate environmental damage. A number of recent studies have been dedicated to designing potentially viable nano carriers in this area.^{124–126} It may be noted here that, in contrast to other techniques, dsRNA technology brings specific solutions to specific problems in relation to pest management as the silencing of a particular gene is needed for a specific pest related problem.

Thus, we need to employ a complex mix of strategies in terms of nanotechnology and biotechnology for safer-by-design agrochemical solution systems, preferably based on natural products.¹⁰⁸ In this way, we can actively contribute to transforming scientific and technological excellence into high economic returns in the form of new sustainable, eco-friendly and cost effective products, production processes and technological advancements to

address the needs of the agricultural industry. Hence, it is important to maintain a concerted focus and efforts towards the development and application of technologically advanced agrochemicals through active investment and funding, coupled with government initiatives.

Conclusion and the way forward

Sustainable agriculture is a pivotal part of the move to address the proliferation in the demand for food for a swiftly growing global population. The work of researchers has increased to develop nanopesticides that are less threatening to the biota, in contrast with traditional formulations, and subsequent investigations will be needed to evaluate whether any potential developed materials can keep pace with existing formulations, in terms of their performance and cost. Therefore, innovative pathways and strategies that prevent damage to plants and ameliorate the efficiency of agrochemicals employed to attain food must proceed cautiously and sustainably. A huge amount of research will therefore be required in the near future and will entail (a) the assessment of the durability and bioavailability of nanopesticides, (b) the innovation of avant-garde protocols to foster properties for their reliable fate and (c) analysis of the current assessment of environmental risk strategies and their rectification where required. Additionally, there is an epoch-making need for a better conception of the mechanisms regulating the adverse, as well as the favourable, responses affecting the employment of nanoformulations under biotic and abiotic stressors. The behaviour of nanomaterials should also be examined in bioremediation to develop integrated remediation approaches. As an industry with a focus on profits, agricultural merchandising has intrinsic limitations that must be prudently contemplated to allow their future use, as well as public understanding and acceptance.

Conflicts of interest

The authors declare that there are no conflicts of interest.

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