CELLULOSE, LIGNIN AND OTHER NATURAL POLYMERS AS SUSTAINABLE PESTICIDE DELIVERY PLATFORMS: A REVIEW

NARCIS ANGHEL

"Petru Poni" Institute of Macromolecular Chemistry, Grigore Ghica Voda 41A, 700487 Iasi, 40 Romania
✉ *Corresponding author: N. Anghel, anghel.narcis@icmpp.ro*

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Synthetic pesticides remain indispensable for crop protection, yet their long-term sustainability is challenged by resistance development, residue concerns, off-target toxicity and regulatory pressure. This review synthesizes the main directions through which pesticide use is being redesigned: biodegradable carriers, bio-based formulations, microbial and botanical biopesticides, semiochemical tools and nano-enabled delivery systems. Particular attention is given to formulation-dependent performance, because field efficacy is strongly shaped by solubility, stability, adhesion, release kinetics and placement rather than by the active ingredient alone. Biodegradable polymers, such as chitosan, cellulose, starch and poly(lactic acid), together with controlled-release capsules, nanoemulsions and stimuli-responsive matrices, may improve persistence at the target site, while reducing leaching, volatilization and repeated application. However, the environmental benefits of these systems cannot be assumed; they require field-realistic testing of degradation products, carrier fate, non-target effects and farmer adoption. The review highlights that safer pesticide innovation depends on integrating green chemistry, ecotoxicology, regulatory adaptation and integrated pest management rather than replacing one input with another.

Keywords: biopesticides, biodegradable agrochemicals, nano-enabled delivery systems, green chemistry, ecotoxicology, regulation, integrated pest management

INTRODUCTION

Crop protection remains a central component of food security, particularly under climate variability, changing pest pressure and the need to increase yields without expanding agricultural land. Synthetic pesticides contributed substantially to the intensification of agricultural production, and their use remains widespread in herbicide, fungicide and insecticide programs.[1-3] However, the same properties that make many conventional pesticides effective – chemical stability, systemic action, broad biological activity and persistence – can also generate environmental and public-health concerns when exposure extends beyond the target organism or the intended application window.[4,5] Current discussions therefore no longer focus only on replacing hazardous active substances, but also on redesigning how agrochemicals are formulated, delivered, degraded and regulated. Representative conventional and alternative pesticide examples are summarized in Table 1, while the main structural pesticide classes are illustrated in Figure1. This convergence makes the review timely for both regulators and formulation scientists.

This review synthesizes evidence from conventional pesticide use, green chemistry, biodegradable carriers, biopesticides, nanotechnology, regulatory science and sustainable agriculture. The central premise is that pesticide sustainability depends on the interaction between active ingredient, carrier, formulation, delivery route and management context. Biopesticides and biodegradable formulations can reduce specific risks, but they are not automatically risk-free; their field performance and environmental profile depend on formulation stability, release behavior, degradation products, exposure pathways and compatibility with Integrated Pest Management (IPM). Nano-enabled and biodegradable delivery systems have attracted particular attention as they can address common weaknesses of both synthetic pesticides and biological products. Encapsulation may protect sensitive compounds from ultraviolet radiation,

oxidation or rapid wash-off; nanoemulsions may improve the dispersion of hydrophobic botanical actives; and polymeric carriers may reduce leaching, while maintaining biologically effective concentrations at the target site.[7-9]

Table 1
Major commercialized agrochemicals and their applications

Pesticide class	Application domain	Type	Active substance	Commercial name	Manufacturer	Notes/restrictions
Herbicide	field crops (corn, wheat, soy)	systemic	Glyphosate	Roundup	Bayer	widely detected in soil and water; resistant weeds emerging
Herbicide	corn, cereals	selective	Atrazine	Aatrex	Syngenta	restricted in eu due to groundwater contamination
Herbicide	cereals, maize	selective, systemic	2,4-D	2,4-D Ester/Amine formulations	Multiple	linked to water contamination, endocrine disruption concerns
Herbicide	soy, corn	systemic	Dicamba	Xtendimax	Bayer	concerns about drift damage to neighboring crops
Insecticide	multiple crops	neonicotinoid	Imidacloprid	Confidor	Bayer	partially banned in EU; harmful to pollinators
Insecticide	maize, oilseed rape	neonicotinoid	Clothianidin	Poncho	Bayer	detected in surface water; pollinator toxicity
Insecticide	sugar beet, cereals	neonicotinoid	Thiamethoxam	Cruiser	Syngenta	restricted in EU due to bee decline
Insecticide	cotton, vegetables	pyrethroid	Cypermethrin	Arrivo	BASF, FMC	effective but resistance issues widespread
Insecticide	cotton, maize	pyrethroid	Lambda-cyhalothrin	Karate	Syngenta	high toxicity to aquatic organisms
Insecticide	vegetables, fruit trees	organo-phosphate	Chlorpyrifos	Lorsban	Corteva Agriscience	banned in EU and US for neurotoxicity
Insecticide	vegetables, ornamentals	carbamate	Carbaryl	Sevin	Bayer	toxic to pollinators; reduced use
Fungicide	wheat, barley	triazole	Tebuconazole	Folicur	Bayer	linked to resistance development
Fungicide	vineyards	strobilurin	Azoxystrobin	Amistar	Syngenta	widespread resistance reported in pathogens
Fungicide	wheat, maize	benzimidazole	Carbendazim	Bavistin	BASF	resistance issues; banned in EU
Fungicide	vineyards, vegetables	copper-based	Copper oxychloride	Cuprofix	UPL, others	concerns over soil accumulation
Biopesticide (bacterial)	vegetables, orchards	microbial insecticide	*Bacillus thuringiensis* (Bt)	Dipel, XenTari	Valent BioSciences, Certis	safe for vertebrates; selective for lepidoptera
Biopesticide (fungal)	vegetables, cereals	entomo-pathogenic fungus	*Beauveria bassiana*	Botanigard	Certis	Effective against resistant insects
Biopesticide (fungal)	soil pests	entomo-pathogenic fungus	*Metarhizium anisopliae*	Met52	BASF	soil-applied; controls coleopteran larvae
Biopesticide (botanical)	vegetables, ornamentals	plant extract	Azadirachtin (from neem)	NeemAzal	Trifolio-M	interferes with insect molting; biodegradable
Biopesticide (semio-chemical)	orchards, cotton	sex pheromone	Codling moth pheromone (*Cydia pomonella*)	Isomate-C	Shin-Etsu	used for mating disruption in IPM
Biopesticide (semio-chemical)	cotton fields	sex pheromone	Pink bollworm pheromone (*Pectinophora gossypiella*)	PB-Rope L	Suterra	widely adopted for pheromone-based pest control

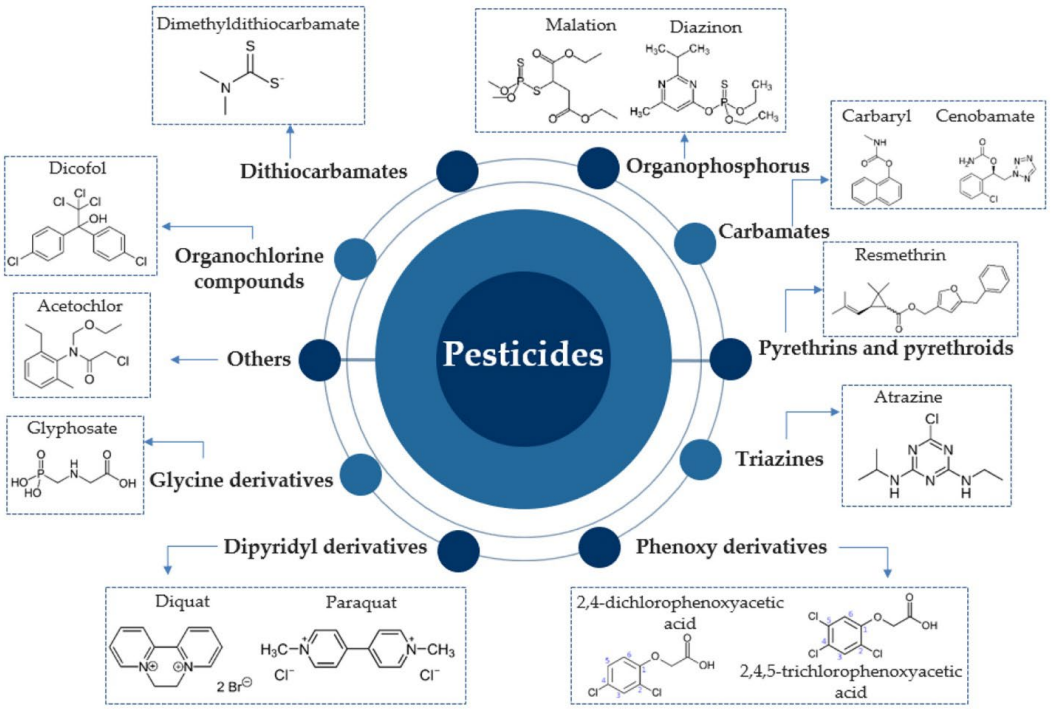


Figure 1: Diagram showing the main classes of pesticides along with the chemical structures of their representative compounds (reproduced from Daraban *et al*.[6] under the terms of the Creative Commons Attribution License (CC BY))

At the same time, new materials introduce new questions for risk assessment. Particle size, surface charge, dissolution, biodegradation and interactions with soil or aquatic microbiota are not adequately captured by conventional pesticide testing alone.[10] This review therefore frames innovation in pesticide delivery as a combined agronomic, environmental and regulatory challenge

CONVENTIONAL PESTICIDES AND THE NEED FOR REDESIGN

Conventional pesticides have historically provided rapid, scalable and economically attractive control of weeds, insects and pathogens. Their continued use is understandable: many cropping systems still rely on reliable chemical tools to prevent yield loss, maintain product quality and respond to unpredictable outbreaks. Nevertheless, repeated and broad use creates three persistent problems. The first is ecological exposure. Pesticides can migrate from treated fields into soil, groundwater, surface water and sediments through runoff, leaching, spray drift and erosion.[11,12] Monitoring studies have repeatedly reported herbicides and insecticides, including glyphosate-related residues and neonicotinoids, in water compartments, indicating that intended field use can translate into wider environmental distribution.[13,14] Selected environmental footprints of conventional pesticides are summarized in Table 2.

The second problem is biological disruption beyond the target pest. Aquatic invertebrates, pollinators, soil microorganisms and natural enemies may be affected by direct toxicity, sublethal stress or changes in community structure. These effects are difficult to predict when organisms are exposed to mixtures rather than to isolated active substances, or when exposure occurs repeatedly at low concentrations.[17,32] Human exposure also occurs through occupational handling, contaminated food, water and proximity to treated environments. Although acute poisoning is most visible in contexts with limited protective equipment, chronic exposure remains a concern because it may involve endocrine, neurological, reproductive and developmental endpoints.[4,33,34] Figure 2 outlines the major routes through which pesticide exposure may affect human and environmental health, and Figure 3 illustrates typical environmental transport pathways using neonicotinoids as an example.

Table 2
Examples of conventional pesticides and their environmental footprint

Pesticide type	Environmental footprint	References
DDT (organochlorine)	highly persistent, bioaccumulates, long-term soil and water contamination, toxic to wildlife	5,15
Atrazine (herbicide)	water contamination, persists in soil, disrupts aquatic ecosystems	16,17
Glyphosate (herbicide)	widespread contamination, potential effects on soil microbes and water quality	18,19
Endrin (organochlorine)	persistent, bioaccumulates, toxic to higher trophic levels	20,21
Chlorpyrifos (organophosphate)	acute toxicity to non-target organisms, water and soil contamination	22,23
Imidacloprid (neonicotinoid)	harmful to pollinators (bees), water contamination, persistence in soil	24,25
Carbendazim (fungicide)	detected in soils long after use, potential soil and water contamination	6,26
Linuron (herbicide)	persistent in soil, detected years after application	27,28
Pyrethroids (insecticide)	toxic to aquatic organisms, less persistent than organochlorines but still ecologically impactful	29,30

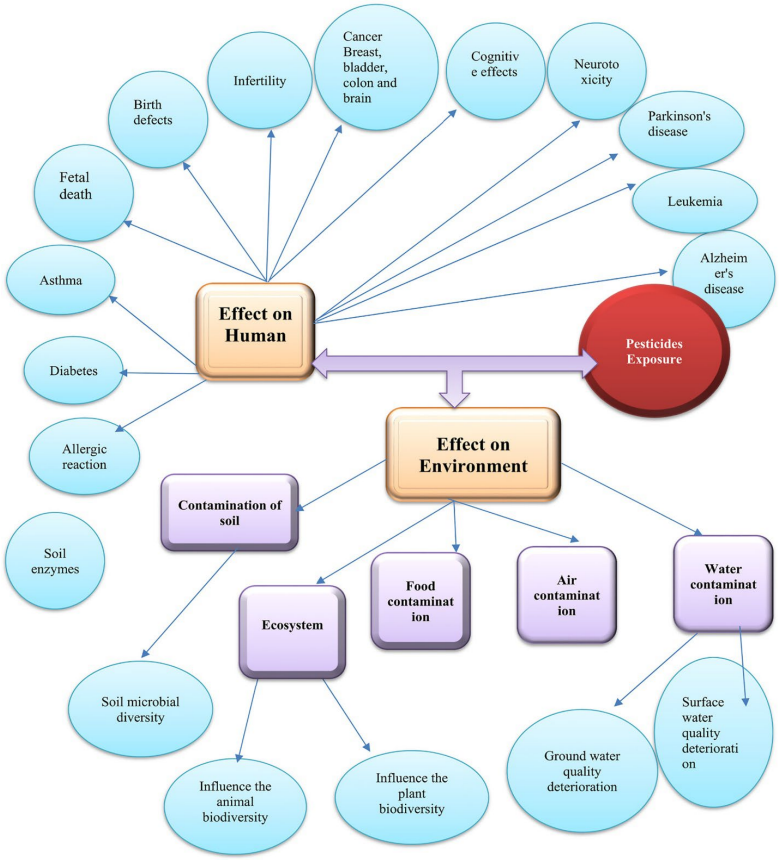


Figure 2: Pesticides effects on human and environment (reproduced from Ahmad *et al.*[4] under the terms of the Creative Commons Attribution License (CC BY))

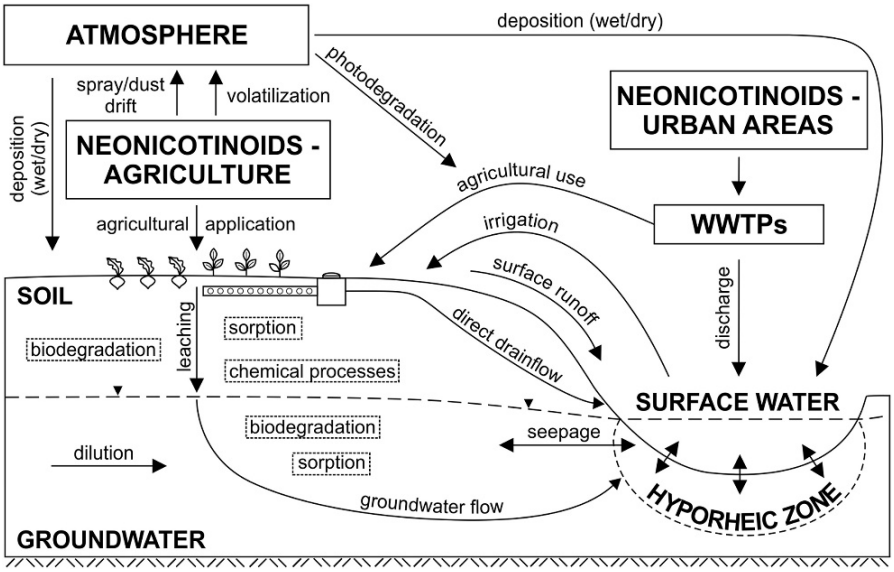


Figure 3: Environmental dissemination and accumulation in non-target organisms of neonicotinoid insecticides (reprinted with permission from Pietrzak *et al*.[31] under the terms of the Creative Commons Attribution License (CC BY))

The third problem is resistance. Repeated use of the same mode of action selects resistant pest populations and reduces the effective lifetime of available products. This is not only a technical problem for farmers; it can also increase environmental pressure when higher application frequency or alternative broad-spectrum products are used to compensate for declining efficacy. In this context, safer pesticide design must be broader than lower toxicity. It should include specificity, degradability, improved placement, controlled release, reduced dose, resistance management and integration with nonchemical tactics.[1,35] The most promising innovations are therefore those that maintain agronomic performance while lowering unnecessary exposure.

GREEN CHEMISTRY AND BIODEGRADABLE FORMULATION CONCEPTS

Green chemistry provides a useful design logic for agrochemicals as it shifts attention from end-of-pipe mitigation to prevention of hazard and waste at the molecular and formulation levels. Principles such as safer solvents, renewable feedstocks, catalysis, design for degradation and lower-energy production are directly relevant to pesticide development.[36,37] For crop protection, this means designing active substances, carriers and auxiliaries that perform their protective role and then degrade into less harmful products, without leaving persistent residues or creating avoidable manufacturing burdens. The translation of green chemistry principles into agrochemical design is summarized in Table 3.

Biodegradable and bio-based carriers are one practical expression of this approach. Chitosan, cellulose, starch, alginate, lignin-derived materials, poly(lactic acid) and related polymers have been investigated as matrices, capsules, films or nanocarriers for controlled pesticide delivery.[7,45,46] These materials may improve formulation performance in several ways: by stabilizing sensitive active ingredients, improving dispersibility, increasing adhesion to leaves, slowing release, protecting against photodegradation or reducing leaching. For example, chitosan-based systems have been studied for their dual role as biodegradable carriers and biologically active materials, while cellulose-based platforms offer renewable and modifiable structures for controlled releas.[47,48] Representative biodegradable and bio-based carriers are listed in Table 4 and schematically grouped in Figure 4.

Table 3
Green chemistry principles applied to agrochemicals

Green chemistry principle	Application in agrochemicals	Concrete examples (compounds, technologies)	Ecological benefits	Refs.
Prevention	designing processes to minimize waste generation	controlled-release formulations	reduces environmental contamination	36,38
Atom economy	maximizing incorporation of materials into the final product	one-pot syntheses of herbicides	less waste, efficient resource use	39,40
Less hazardous chemical syntheses	avoiding toxic reagents and intermediates	use of biocatalysts in pesticide synthesis	safer for workers and environment	41,42
Designing safer chemicals	creating agrochemicals with reduced toxicity	selective insecticides targeting pests only	minimizes harm to non-target species	36,43
Safer solvents and auxiliaries	using water or benign solvents in formulations	water-based pesticide formulations	reduces volatile organic compound emissions	37,40
Energy efficiency	conducting reactions at ambient temperature and pressure	microwave-assisted synthesis of fungicides	lowers energy consumption and emissions	42
Use of renewable feedstocks	sourcing from biomass or agricultural waste	biopesticides from plant extracts	reduces fossil resource use	41
Reduce derivatives	minimizing use of protecting groups and unnecessary modifications	direct functionalization in synthesis	fewer by-products and less waste	39,43
Catalysis	employing catalysts to improve efficiency and selectivity	enzyme-catalyzed synthesis of active ingredients	reduces energy and material use	36,40
Design for degradation	ensuring agrochemicals break down into harmless products	readily biodegradable herbicides	prevents environmental persistence	37,38
Real-time analysis for pollution prevention	monitoring processes to avoid by-product formation	in-line sensors for process control	prevents accidental releases	42,44
Inherently safer chemistry for accident prevention	designing processes to minimize risk of accidents	use of non-flammable solvents in manufacturing	improves safety for workers and environment	43,44

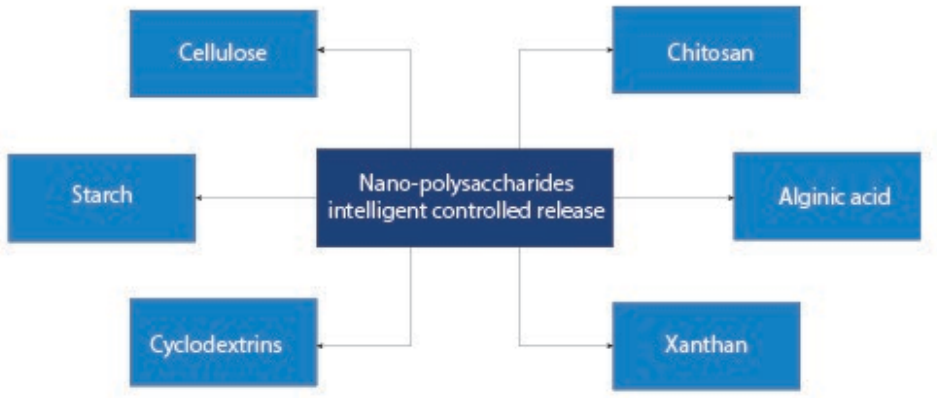


Figure 4: Types of nano intelligent controlled-release carriers made from polysaccharides

Table 4
Types of biodegradable and bio-based formulations for agrochemicals

Type of material/carrier	Role/function in formulation	Examples of use in pesticides	Advantages and limitations	Refs.
Cellulose	controlled release matrix, carrier	encapsulation of pesticides and fertilizers	biodegradable, abundant, modifiable; may have poor mechanical strength, fast release rate	7,46
Chitosan	nanocarrier, encapsulation, film former	pesticide and fertilizer delivery systems	biocompatible, biodegradable, enhances uptake; limited by cost and scalability	7,52
Starch	nanocarrier, slow-release matrix	encapsulation of agrochemicals	renewable, biodegradable, low toxicity; may require modification for stability	7,53
Poly(lactic acid) (PLA)	biopolymer matrix for nano/microcarriers	controlled release of pesticides	biodegradable, renewable; cost and slow degradation in some soils	7,52
Dextrin-based microgels	slow-release carrier for fertilizers	dual fertilizer (urea, phosphate) delivery	biodegradable, improves plant growth; synthesis complexity, specific to fertilizer use	53,54
Poly(vinyl alcohol) (PVA)	hydrogel matrix for controlled release	phosphate fertilizer delivery	biodegradable, good swelling; may need blending with other materials for strength	55,56
Agar	biodegradable film for volatile release	semiochemical (e.g., garlic extract) films	biodegradable, slow release; mechanical properties affected by additives	55,56
Biochar	sorbent, carrier for remediation	remediation of agrochemicals in soil/water	high sorption, renewable; mainly for remediation, not direct delivery	57,58
Natural deep eutectic solvents (NADES)	green solvent, extraction medium	extraction of bioactive compounds	biodegradable, low toxicity; industrial scale-up and toxicity data limited	56,59

Recent advances in biodegradable pesticide delivery include layer-by-layer modification of cellulose-nanofibril Pickering emulsions to control release and improve formulation stability,[49] lignin–zein co-assembly for sustained abamectin delivery and enhanced photostability,[50] and one-step assembly of lignin-based micro- and nanospheres for photoprotection and sustained release of photosensitive pesticides.[51]

Controlled-release systems are especially relevant when conventional formulations lose activity too quickly or produce an early concentration peak followed by subeffective exposure. Microcapsules, hydrogels and polymeric matrices can smooth the release profile and reduce the need for repeated application.[9,60,61] In practical terms, this may improve efficacy against pests with extended emergence or diseases that require sustained protection. However, biodegradable does not mean automatically benign. Degradation products, local pH changes, microbial effects and carrier persistence must be evaluated under realistic soil and water conditions. A biodegradable carrier that reduces leaching, but disrupts soil functions at high local concentrations would not meet the broader sustainability goal.

Formulation auxiliaries also deserve attention. Water-based systems and safer solvent choices can reduce volatile organic compound emissions and operator exposure, whereas adjuvants can improve spreading, rainfastness or penetration. Yet, adjuvants may also increase phytotoxicity or non-target uptake if selected without considering crop surface, active substance, water quality and compatibility with biological agents. Thus, formulation development should be treated as a risk-management tool, not merely as an industrial step after active ingredient discovery.

BIOPESTICIDES AND NATURE-INSPIRED PEST SOLUTIONS

Biopesticides are frequently presented as alternatives to conventional chemicals as they often show higher specificity, lower mammalian toxicity and faster environmental degradation. They include microbial pesticides, botanical products, biochemical pesticides, semiochemicals and plant-incorporated protectants.[62,63] Their

importance is increasing as regulatory pressure on hazardous synthetics grows and farmers seek tools compatible with residue reduction, organic production and IPM. However, the field performance of biopesticides remains highly dependent on formulation, application timing and environmental conditions.[64,65] Major biopesticide categories, modes of action and practical limitations are summarized in Table 5.

Nano-enabled delivery systems are designed to improve the transport, retention and release of pesticide actives at scales where surface area, particle size and interfacial behavior become decisive. They include nanoemulsions, nanocapsules, polymeric nanoparticles, mesoporous silica, nanoclays, lipid carriers, cellulose nanocarriers and other engineered structures. Their promise lies in addressing formulation bottlenecks: poor water solubility, low stability, rapid photodegradation, volatilization, wash-off, leaching and inefficient uptake.[7,8,10] The main nanocarrier platforms, advantages and uncertainties are summarized in Table 6.

Nanoemulsions are particularly relevant for hydrophobic botanical compounds and essential oils. By creating stable dispersions with small droplet sizes, they can improve coverage, apparent solubility and bioavailability while slowing evaporation.[77] Polymeric nanoparticles based on biodegradable materials may encapsulate fungicides, insecticides or plant growth regulators and release them gradually in response to moisture, pH, enzymes or redox conditions.[48,60] Cellulose-based nanocarriers are attractive because cellulose is renewable, modifiable and compatible with plant systems, while MOF and other porous materials can offer high loading capacity and tunable release profiles.[8,85]

The potential benefits are substantial: lower applied doses, reduced number of applications, improved rainfastness, less leaching, better protection of labile actives and more precise exposure at the target site. However, these advantages remain conditional. A nanoformulation should be considered valuable only when it solves a specific agronomic delivery problem and demonstrates benefits under realistic field conditions. Laboratory evidence of controlled release is not enough if the carrier is expensive, unstable in tank mixtures, difficult to scale or poorly understood after release into soil and water. PLP-crosslinked chitosan nanogels have recently been investigated for pH-responsive thiamethoxam release and improved foliar deposition.[90]

Table 5
Categories and examples of biopesticides/nature-inspired alternatives

Type of biopesticide	Representative example	Mode of action	Benefits and challenges	Refs.
Microbial	*Bacillus thuringiensis* (Bt)	produces toxins that disrupt insect gut, causing death	high specificity, eco-friendly; limited spectrum, short shelf-life	62
Plant-based (botanical)	Neem (Azadirachtin)	inhibits feeding, growth, and reproduction in insects	biodegradable, low mammalian toxicity; instability, rapid degradation, higher cost	66
Plant-based (essential oil)	Thymol (from thyme oil)	disrupts cell membranes, inhibits enzymes in pests	multiple targets, low resistance risk; volatility, variable efficacy in field conditions	66,67
Microbial (fungal)	*Beauveria bassiana*	infects and kills insects via spore germination	effective against resistant pests, safe for non-targets; sensitive to uv, humidity-dependent	68
Semiochemical	Pheromone traps	alters pest behavior (*e.g.*, mating disruption, attraction)	non-toxic, species-specific, reduces pesticide use; requires monitoring, not lethal to pests	6,62
Microbial (viral)	Baculovirus (NPV, GV)	infects and lyses insect larvae	host-specific, minimal non-target effects; slow action, sensitive to sunlight	69
Nanobiopesticide	Silver nanoparticles (bio-derived)	disrupts cellular processes in pests	enhanced activity, controlled release; regulatory and safety concerns, production cost	62,70

Table 6
Types of nanocarriers and their applications in agrochemicals

Type of nanocarrier	Type of active ingredient delivered	Key advantages	Risks/uncertainties	Refs.
Chitosan-based nanoparticles	pesticides, plant growth regulators	biodegradable, controlled release, reduced toxicity	limited data on long-term environmental fate, potential for bioaccumulation	7,82
Nanoemulsions	essential oils, pesticides	enhanced solubility, improved stability, increased efficacy	environmental persistence, unknown effects on non-target organisms	77,83
Mesoporous silica	fertilizers, pesticides	high loading capacity, controlled release, photostability	potential toxicity, regulatory uncertainties	83,84
Cellulose nanocarriers	fungicides, herbicides, plant growth regulators	biocompatible, stimuli-responsive release, sustainable	limited knowledge on plant and soil interactions	85,86
Metal-organic frameworks (MOFs)	fertilizers, pesticides	biodegradable, tunable release profiles	soil contamination, bioaccumulation concerns	87
Polymeric nanoparticles	plant hormones, pesticides	targeted delivery, improved uptake, reduced leaching	unclear long-term plant and food safety	88,89
Lipid-based nanocarriers	pesticides, essential oils	enhanced bioavailability, reduced volatilization	potential allergenicity, stability in field conditions	77,83
Tar polymers	model agrochemicals, dyes	efficient foliar uptake, organ targeting	limited biodegradability, possible accumulation	88,89

Risk assessment for nanopesticides is also more complex than for conventional formulations. The active ingredient may be familiar, but nanoscale delivery can change bioavailability, persistence, organism uptake and distribution among environmental compartments. Particle size distribution, surface charge, coating composition, dissolution rate and degradation behavior may influence both efficacy and hazard.[91] For this reason, regulatory science must evaluate not only the active substance, but also the formulation architecture. Standard acute toxicity endpoints should be complemented by chronic, sublethal and ecosystem-function endpoints, particularly for pollinators, aquatic organisms and soil microbiota. Without such data, nano-enabled delivery may be either over-restricted because of uncertainty or over-adopted on the assumption that reduced dose equals reduced risk.

Recent safe-and-sustainable-by-design discussions likewise emphasize non-target impacts and environmental behavior when assessing nano-enabled agrochemicals.[92]

ECOTOXICOLOGICAL AND REGULATORY BARRIERS

The transition from conventional pesticides to bio-based, biodegradable and nano-enabled systems exposes weaknesses in existing risk-assessment frameworks. Many regulatory procedures were developed for single-molecule synthetic chemicals with relatively defined composition and predictable analytical characterization. Microbial agents, botanical mixtures and nanostructured carriers are more complex. They may contain living organisms, multiple bioactive compounds, variable metabolites or carrier materials whose behavior changes with particle size and environmental conditions.[10,93] The main regulatory and ecotoxicological challenges are organized in Table 7, while Figure 5 highlights desirable features of adaptable testing methods for mesocosm-scale evaluation. For biopesticides, the most important questions are not limited to acute toxicity. Microbial products may persist, reproduce or interact with native microbiomes; botanical products may generate metabolites with different toxicity from the parent mixture; and semiochemical systems may alter ecological interactions in ways not captured by conventional dose-response tests. For biodegradable carriers, it is necessary to evaluate degradation products and their effect on soil functions, microbial communities and aquatic organisms.

Table 7
Ecotoxicological and regulatory challenges for eco-friendly agrochemicals

Type of agrochemical	Ecotoxicological limitation	Current regulatory limitation	Recommendation for future evaluation	Refs.
Biodegradable	lack of standardized ecotoxicological tests for complex matrices; unknown long-term impacts	no harmonized rules for ecotoxicity assessment; inconsistent legal definitions	develop tiered, standardized ecotoxicological protocols; harmonize legal definitions and safety standards	94,95
Biopesticide	variable efficacy in field vs. lab; potential for gene transfer or microbiome disruption	complex, lengthy registration; lack of global regulatory coordination; high costs	streamline registration, promote global harmonization, invest in public awareness and strain improvement	95,96
Nanopesticide	scarce data on fate, behavior, and unintended effects on non-target species	stringent, fragmented regulations; lack of specific nano-focused risk assessment frameworks	develop nano-specific risk assessment tools; require pre-market notification, post-market monitoring, and labeling	10,97

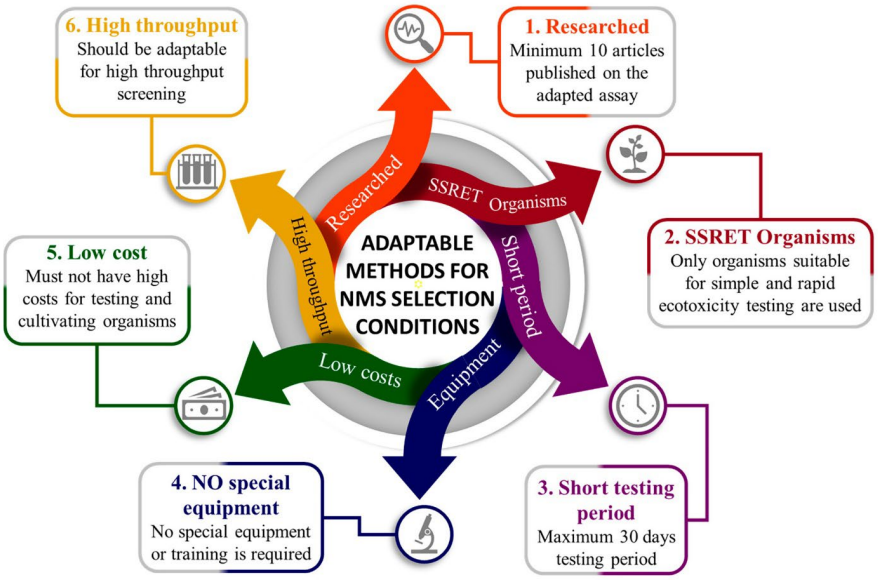


Figure 5: Conditions guiding the selection of standard ecotoxicity assessment methods suitable for adaptation to nanomaterials (reproduced from Boros & Ostafe[98] under the terms of the Creative Commons Attribution License (CC BY))

For nanopesticides, testing must consider agglomeration, dissolution, transformation and possible food-chain transfer.[91,99]

Regulatory fragmentation further slows adoption. Different jurisdictions may classify biopesticides, nanomaterials or plant-incorporated protectants differently, creating uncertainty for developers and delays for farmers. At the same time, faster approval cannot mean weaker safety evaluation. A balanced approach would use tiered testing: initial characterization and exposure assessment, followed by targeted ecotoxicological tests triggered by formulation properties and intended use. Guidance developed for nanomaterials in the food and feed chain illustrates the need for adapted protocols that address particle-specific behavior and exposure routes.

Economic barriers also matter. Many biological and nano-enabled products are more expensive than conventional pesticides and may require better storage, training, timing or monitoring. Farmers are unlikely to adopt them only because they are described as green; they must be reliable, affordable and compatible with existing equipment

and advisory systems. Regulatory approval, field validation and extension services should therefore be considered part of the innovation pathway rather than separate downstream processes.

INTEGRATED PEST MANAGEMENT AND PRACTICAL DEPLOYMENT

Advanced formulations will have limited impact if they are used within the same prophylactic logic that created many pesticide-related problems. Their value is highest when embedded in IPM, where interventions are guided by pest identification, monitoring, thresholds, forecasting and compatibility with biological control.[35,100] In this context, biodegradable and nano-enabled systems should be used to improve the precision and durability of necessary interventions, not to justify unnecessary applications. Integrated deployment pathways are summarized in Table 8 and Figure 6.

Table 8
Integrative strategies for sustainable agriculture

Approach	Role of eco-friendly agrochemicals	Expected benefits	Examples of application	Refs.
Precision agriculture	minimizes chemical input through targeted use and data-driven decisions	reduces environmental impact, increases input efficiency, and improves yields	GPS-guided fertilizer application, remote sensing for pest detection	101,102
Soil microbiome	utilizes biofertilizers and plant growth-promoting microorganisms to replace synthetics	enhances soil health, nutrient cycling, and plant resilience	application of PGPms, compost teas, microbial inoculants	103,104
Circular economy	promotes recycling of organic waste, reducing reliance on synthetic chemicals	closes nutrient loops, reduces waste, and improves resource efficiency	composting, manure management, crop residue incorporation	104,105
Integrated Pest Management (IPM)	employs biopesticides and natural predators, reducing synthetic pesticide use	maintains pest control, preserves beneficial species, and lowers resistance risk	use of pheromone traps, biological control agents	1,106

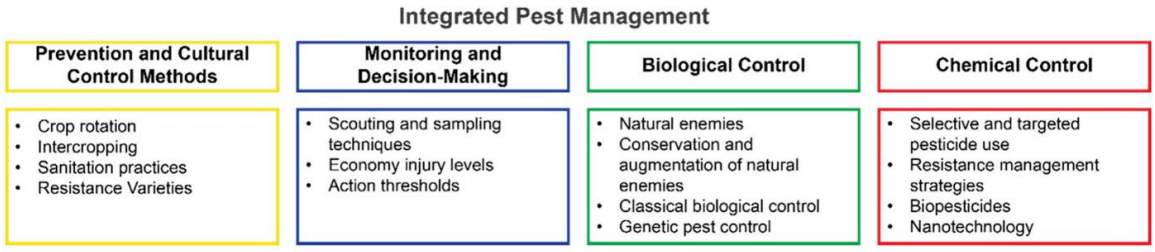


Figure 6: Core components of an Integrated Pest Management (IPM) program (reproduced from Zhou *et al.*[100] under the terms of the Creative Commons Attribution License (CC BY))

Practical deployment begins with prevention: crop rotation, resistant varieties, sanitation, habitat management, balanced fertilization and irrigation practices that reduce pest establishment or disease pressure.[101] Monitoring and decision-support tools can then determine whether intervention is needed. Precision agriculture, remote sensing, automated traps and site-specific application technologies can reduce blanket treatment and improve dose placement.[102,107] When chemical or biological intervention is justified, formulation selection should match the pest, crop, environment and risk pathway. Seed coatings may be appropriate for early soil-borne threats; pheromone systems for behaviorally mediated pests; encapsulated botanicals for volatile actives; and controlled-release carriers for long pressure windows.

Future research should prioritize field-realistic comparison rather than isolated laboratory novelty. The key questions are whether new formulations maintain control at lower total active ingredient, reduce exposure in vulnerable compartments, remain compatible with natural enemies and biological products, and delay resistance. Life-

cycle thinking is also needed, because a product that degrades rapidly in the field may still carry a high manufacturing footprint if synthesis, purification or carrier production is energy-intensive.[108] Circular-economy strategies, including the use of agricultural residues as carriers or sources of bioactive compounds, may improve sustainability when supported by quality control and safety assessment. Priority research domains for safer pesticide delivery are summarized in Table 9.

Table 9
Future research directions in eco-friendly agrochemicals

Research domain	Main objective	Current challenges	Anticipated opportunities	Refs.
Molecular design	develop efficient, selective, and low-toxicity agrochemicals	resistance development, environmental persistence, off-target effects	novel compounds with high selectivity and rapid degradation	109,110
Biopesticides	enhance efficacy and field applicability of microbial/plant-based products	lower effectiveness, limited persistence, delivery and formulation issues	advanced bioformulations, improved delivery systems, integration with nanotechnology	111,112
Nanotechnology	improve delivery, efficacy, and sustainability of agrochemicals	safety concerns, regulatory uncertainty, potential toxicity, high production costs	controlled release, reduced doses, targeted delivery, enhanced crop yields	113
Regulation	establish safety standards and guidelines for new eco-friendly agrochemicals	lack of harmonized regulations, insufficient risk assessment frameworks	comprehensive policies, improved risk assessment, support for commercialization	109,114
Socio-economics	promote adoption and commercialization of eco-friendly agrochemicals	farmer awareness, cost barriers, public perception, market access	economic incentives, education, increased investment, sustainable agriculture and food security	7

The most defensible future direction is therefore not the replacement of synthetic pesticides by a single preferred alternative, but the diversification of pest management tools. Biodegradable formulations, biopesticides, semiochemicals and nano-enabled delivery systems can all contribute, provided they are evaluated by performance, exposure reduction, environmental fate and adoption feasibility.

CONCLUSIONS

Pesticide innovation is moving from active-ingredient substitution toward delivery-centered design. Biodegradable carriers, bio-based formulations, microbial and botanical products, semiochemical systems and nanotechnology can improve pest control while reducing some environmental burdens. Their sustainability, however, depends on evidence rather than assumption. Controlled release, improved stability and lower dose are beneficial only when they reduce real exposure and maintain field efficacy without generating new risks through carriers, degradation products or altered bioavailability. Regulatory frameworks must therefore adapt to complex formulations while remaining scientifically rigorous. For farmers, these technologies will be adopted only if they are reliable, affordable and compatible with IPM. The safest path forward is integrated: greener chemistry, better delivery, ecotoxicological validation, resistance management and practical advisory support. Future progress will depend on field evidence and harmonized testing.

REFERENCES

[1] J. Pretty, *Science*, **362** (2018), https://doi.org/10.1126/science.aav0294
[2] A. Sharma, V. Kumar, B. Shahzad, M. Tanveer, G. P. S. Sidhu *et al*., *SN Appl. Sci*., **1**, 11 (2019), https://doi.org/10.1007/s42452-019-1485-1
[3] N. Umetsu and Y. Shirai, *J. Pestic. Sci*., **45**, (2020), https://doi.org/10.1584/jpestics.d20-201
[4] M. F. Ahmad, F. Ahmad, A. Alsayegh, M. Zeyaullah, A. AlShahrani *et al*., *Heliyon*, **10**, 7 (2024), https://doi.org/10.1016/j.heliyon.2024.e29128

[5] M. Tudi, H. D. Ruan, L. Wang, J. Lyu, R. Sadler *et al*., *Int. J. Environ. Res. Public Health*, **18**, 3 (2021), https://doi.org/10.3390/ijerph18031112
[6] G. Daraban, R. Hlihor and D. Șuteu, *Toxics*, **11**, 12 (2023), https://doi.org/10.3390/toxics11120983
[7] T. Machado, J. Grabow, C. Sayer, P. Araújo, M. Ehrenhard *et al*., *Adv. Colloid. Interface Sci*., **303**, (2022), https://doi.org/10.1016/j.cis.2022.102645
[8] R. D. Reis, L. Mahmoud, E. Ivanovska, R. Telford, M. Addicoat *et al*., *Adv. Sustain. Sys*., **7**, 12 (2023), https://doi.org/10.1002/adsu.202300269
[9] A. Zanino, F. Pizzetti, M. Masi and F. Rossi, *Eur. Polym. J*., **203**, (2024), https://doi.org/10.1016/j.eurpolymj.2023.112665
[10] R. Grillo, L. Fraceto, M. Amorim, J. Scott-Fordsmand, R. Schoonjans *et al*., *J. Hazard. Mater*., **404**, (2020), https://doi.org/10.1016/j.jhazmat.2020.124148
[11] M. Syafrudin, R. Kristanti, A. Yuniarto, T. Hadibarata, J. Rhee *et al*., *Int. J. Environ. Res. Public Health*, **18**, 2 (2021), https://doi.org/10.3390/ijerph18020468
[12] Z. Vryzas, *Curr. Opin. Environ. Sci. Health*, **4**, (2018), https://doi.org/10.1016/J.COESH.2018.03.001
[13] L. Carretta, R. Masin and G. Zanin, *Environ. Rev*., **30**, 1 (2021), https://doi.org/10.1139/ER-2020-0106
[14] S. Rajan, M. Parween and N. J. Raju, *Environ. Geochem. Health*, **45**, 8 (2023), https://doi.org/10.1007/s10653-023-01608-6
[15] J. Riedo, F. Wettstein, A. Rösch, C. Herzog, S. Banerjee *et al*., *Environ. Sci. Technol*., **55**, 5 (2021), https://doi.org/10.1021/acs.est.0c06405
[16] B. Ridoutt, D. Baird, J. Navarro and G. Hendrie, *Nutrients*, **13**, 12 (2021), https://doi.org/10.3390/nu13124314
[17] W. Zhou, M. Li and V. Achal, *Emerging Contaminants*, **11** (2024), https://doi.org/10.1016/j.emcon.2024.100410
[18] T. Sarkar, S. Ram and P. Verma, *J. Agric. Biotech. Appl. Sci*., **3**, 1 (2025), https://doi.org/10.63143/jabaas312025
[19] F. Tang, A. Malik, M. Li, M. Lenzen and F. Maggi, *Commun. Earth Environ*., **3** (2022), https://doi.org/10.1038/s43247-022-00601-8
[20] L. Goritschnig, H. Burtscher-Schaden, T. Durstberger and J. Zaller, *Environments*, **11**, 7 (2024), https://doi.org/10.3390/environments11070137
[21] V. Pathak, V. Verma, B. Rawat, B. Kaur, N. Babu *et al*., *Front. Microbiol*., **13** (2022), https://doi.org/10.3389/fmicb.2022.962619
[22] H. Burtscher-Schaden, T. Durstberger and J. Zaller, *Toxics*, **10**, 2 (2022), https://doi.org/10.3390/toxics10120753
[23] R. Majumder, *Ecotoxicology*, **33** (2024), https://doi.org/10.1007/s10646-024-02806-3
[24] C. Benbrook, S. Kegley and B. Baker, *Agronomy*, **11**, 7 (2021), https://doi.org/10.3390/agronomy11071266
[25] N. Joshi, T. Leslie, E. Rajotte and D. Biddinger, *Chemosphere*, **240**, 124926 (2020), https://doi.org/10.1016/j.chemosphere.2019.124926
[26] A. Larsen, F. Noack and L. Powers, *Science*, **383** (2024), https://doi.org/10.1126/science.adf2572
[27] A. Larsen, C. Powers and S. McComb, *Nat. Commun*., **12** (2021), https://doi.org/10.1038/s41467-021-25502-w
[28] M. Marimuthu, K. Xu, W. Song, Q. Chen and H. Wen, *Food Chem*., **463**, 141288 (2025), https://doi.org/10.1016/j.foodchem.2024.141288
[29] A. Khursheed, M. Rather, V. Jain, A. Wani, S. Rasool *et al*., *Microb. Pathob*., **173**, 105854 (2022), https://doi.org/10.1016/j.micpath.2022.105854
[30] L. Muneret, M. Mitchell, V. Seufert, S. Aviron, E.A. Djoudi *et al*., *Nat. Sustain*., **1** (2018), https://doi.org/10.1038/s41893-018-0102-4
[31] D. Pietrzak, J. Kania, E. Kmiecik, G. Malina and K. Wątor, *Chemosphere*, **255**, 126981 (2020), https://doi.org/https://doi.org/10.1016/j.chemosphere.2020.126981
[32] F. Sánchez-Bayo, *Toxics*, **9**, 8 (2021), https://doi.org/10.3390/toxics9080177
[33] M. Eddleston, *Medicine*, **48**, 3 (2020), https://doi.org/10.1016/j.mpmed.2019.12.019
[34] M. Tudi, H. Li, L. Wang, J. Lyu, L. Yang *et al*., *Toxics*, **10**, 6 (2022), https://doi.org/10.3390/toxics10060335
[35] S. Dara, *J. Integr. Pest Manag*., **10**, 1 (2019), https://doi.org/10.1093/JIPM/PMZ010
[36] G. Whiteker, *Org. Process. Res. Dev*., **23**, 10 (2019), https://doi.org/10.1021/acs.oprd.9b00305
[37] J. Zimmerman, P. Anastas, H. Erythropel and W. Leitner, *Science*, **367** (2020), https://doi.org/10.1126/science.aay3060
[38] T. Savitskaya, I. Kimlenka, Y. Lu, D. Hrynshpan, V. Sarkisov *et al*., "Green Chemistry: Process Technology and Sustainable Development", Springer, Singapore, 2021, pp. 31–92
[39] W. Abdussalam-Mohammed, A. Ali and A. O. Errayes, *Chem. Methodol*., **4** (2020), https://doi.org/10.33945/SAMI/CHEMM.2020.4.4
[40] O. Kharissova, B. Kharisov, C. O. González, Y. Méndez and I. López, *R. Soc. Open Sci*., **6**, 191378 (2019), https://doi.org/10.1098/rsos.191378
[41] S. Bhandari, *Green Chem. Technol. Lett*., **4**, 2 (2018), https://doi.org/10.18510/GCTL.2018.422
[42] P.K. Sharma, *Found. Chem*., **24** (2022), https://doi.org/10.1007/s10698-022-09442-x
[43] B. Omran and K. Baek, *J. Environ. Manage*., **311** (2022), https://doi.org/10.1016/j.jenvman.2022.114806
[44] S. Dutta, *ACS Omega*, **9** (2024), https://doi.org/10.1021/acsomega.4c01960
[45] M. Del Prado-Audelo, S. Bernal-Chávez, S. Gutiérrez-Ruíz, H. Hernández-Parra, I. Kerdan *et al*., *Oxidat. Med. Cell. Longev*., **2022** (2022), https://doi.org/10.1155/2022/5766199

[46] L. Pang, Z. Gao, H. Feng, S. Wang and Q. Wang, *J. Control. Release.*, **316** (2019), https://doi.org/10.1016/j.jconrel.2019.11.004
[47] G. Mahai, Y. Wan, A. Wang, W. Xia, L. Shi *et al.*, *Env. Pollut.*, **291** (2021), https://doi.org/10.1016/j.envpol.2021.118225
[48] Z. Xia, Q. Zhou, Y. Zhang, T. Zhang and W. Xue, *J. Adv. Res.*, **71** (2024), https://doi.org/10.1016/j.jare.2024.05.029
[49] R. Fan, C. Liu, L. Yang, P. Liu and F. Kong, *Eur. Polym. J.*, **255** (2026), https://doi.org/10.1016/j.eurpolymj.2026.114860
[50] Z. Liang, Z. Zhou, L. Chen and X. Qiu, *Int. J. Biol. Macromol.*, **382** (2026), https://doi.org/10.1016/j.ijbiomac.2026.154326
[51] H.-Z. Sun, H.-X. Bai, Y.-H. Shang, X.-Y. Ye, M. Wang *et al.*, *Green Chem.*, **28**, 24 (2026), https://doi.org/10.1039/d6gc01679k
[52] F. Mohan and P. Praseetha, *J. Inorg. Organomet. Polym.*, **33** (2023), https://doi.org/10.1007/s10904-023-02695-9
[53] A. Dhiman, P. Thaper, D. Bhardwaj and G. Agrawal, *ACS Appl. Mater. Interfaces*, **16**, 9 (2024), https://doi.org/10.1021/acsami.3c16670
[54] N. Sharma, A.K. Singh and R. Dutta, *Polym. Bull.*, **78**, (2020), https://doi.org/10.1007/s00289-020-03252-x
[55] P. Campa-Siqueiros, I. Vargas-Arispuro, P. Quintana-Owen, Y. Freile-Pelegrín, J. Azamar-Barrios *et al.*, *Int. J. Biol. Macromol.*, **151** (2020), https://doi.org/10.1016/j.ijbiomac.2020.02.158
[56] M. Sharma, R. Bhat, Z. Usmani, D. McClements, P. Shukla *et al.*, *Biomolecules*, **11**, 5 (2021), https://doi.org/10.3390/biom11050768
[57] R. Gautam, M. Goswami, R. Mishra, P. Chaturvedi, M. K. Awashthi *et al.*, *Chemosphere*, **272** (2021), https://doi.org/10.1016/J.CHEMOSPHERE.2021.129917
[58] S. Mishra, L. Cheng and A. Maiti, *J. Environ. Chem. Eng.*, **9**, 1 (2020), https://doi.org/10.1016/j.jece.2020.104901
[59] A. Mišan, J. Nađpal, A. Stupar, M. Pojic, A. Mandic *et al.*, *Crit. Rev. Food Sci. Nutr.*, **60** (2019), https://doi.org/10.1080/10408398.2019.1650717
[60] Y. Xiang, X. Lu, J. Yue, Y. Zhang, X. Sun *et al.*, *Sci. Total Environ.*, **722**, 137811 (2020), https://doi.org/10.1016/j.scitotenv.2020.137811
[61] S. Zhou, Y. Pan, L. Zhang, B. Xue, A. Zhang *et al.*, *Mar. Pollut. Bull.*, **131** (2018), https://doi.org/10.1016/j.marpolbul.2018.04.055
[62] M. Ayilara, B. Adeleke, S. Akinola, C. Fayose, U. Adeyemi *et al.*, *Front. Microbiol.*, **14**, 1040901 (2023), https://doi.org/10.3389/fmicb.2023.1040901
[63] L. H. Samada and U. Tambunan, *J. Biol. Sci.*, **20**, (2020), https://doi.org/10.3844/ojbsci.2020.66.76
[64] P. Kumar, S. Pandhi, D. Mahato, M. Kamle and A. Mishra, *Egypt. J. Biol. Pest Control*, **31** (2021), https://doi.org/10.1186/s41938-021-00475-6
[65] L. Ruiu, *Agronomy*, **8**, 11 (2018), https://doi.org/10.3390/AGRONOMY8110235
[66] I. Gupta, R. Singh, S. Muthusamy, M. Sharma, K. Grewal *et al.*, *Plants*, **12**, 16 (2023), https://doi.org/10.3390/plants12162916
[67] F. Acheuk, S. Basiouni, A. Shehata, K. Dick, H. Hajri *et al.*, *Biomolecules*, **12**, 2 (2022), https://doi.org/10.3390/biom12020311
[68] G. Lengai and J. Muthomi, *J. Biosci. Med.*, **6** (2018), https://doi.org/10.4236/JBM.2018.66002
[69] P. Kumar, M. Kamle, R. Borah, D. Mahato and B. Sharma, *Egypt. J. Biol. Pest Control*, **31** (2021), https://doi.org/10.1186/s41938-021-00440-3
[70] D. Šunjka and Š. Mechora, *Plants*, **11**, 22 (2022), https://doi.org/10.3390/plants11223172
[71] B. M. Sangeetha, K. S. V. P. Chandrika, R. D. Prasad, N. B. Bharati, K. V. Dinesh *et al.*, *Chem. Biol. Technol. Agric.*, **13**, 1 (2026), https://doi.org/10.1186/s40538-026-00998-w
[72] G. Mendoza-Almanza, E. Esparza-Ibarra, J. Ayala-Luján, M. Mercado-Reyes, S. Godina-González *et al.*, *Toxins*, **12**, 5 (2020), https://doi.org/10.3390/toxins12050301
[73] S. Wang, W. Kain and P. Wang, *Insect Biochem. Mol. Biol.*, **102** (2018), https://doi.org/10.1016/j.ibmb.2018.09.013
[74] M. Mannino, C. Huarte-Bonnet, B. Davyt-Colo and N. Pedrini, *J. Fungi*, **5**, 2 (2019), https://doi.org/10.3390/jof5020033
[75] M. Ferrelli and R. Salvador, *Viruses*, **15**, 9 (2023), https://doi.org/10.3390/v15091838
[76] N. Hasheminejad, F. Khodaiyan and M. Safari, *Food Chem.*, **275** (2019), https://doi.org/10.1016/j.foodchem.2018.09.085
[77] A. Kumar, R. Kanwar and S. Mehta, *ACS Agric. Sci. Technol.*, **2**, 5 (2022), https://doi.org/10.1021/acsagscitech.2c00100
[78] N. Kannan and N. Chandrasekaran, *RSC Adv.*, **16**, 26 (2026), https://doi.org/10.1039/d6ra02377k
[79] P. F. A. Rodrigues, F. S. Maia, I. Z. Sarti, J. A. Ventura, A. G. G. Amaral *et al.*, *Sci. Rep.*, (2026), https://doi.org/10.1038/s41598-026-67933-9
[80] P. Mishra, N. Singh, S. K. Chandraker, G. K. Ahirwar, R. Shukla *et al.*, *BioSM*, **3**, 1 (2026), https://doi.org/10.1186/s44316-026-00059-0
[81] C. Hellmann, A. Greiner and A. Vilcinskas, *Adv. Sci.*, **11**, (2023), https://doi.org/10.1002/advs.202304098
[82] A. Pereira, H. Oliveira and L. Fraceto, *Sci. Rep.*, **9** (2019), https://doi.org/10.1038/s41598-019-43494-y
[83] P. Fincheira, N. Hoffmann, G. Tortella, A. Ruíz, P. Cornejo *et al.*, *Nanomaterials*, **13**, 13 (2023), https://doi.org/10.3390/nano13131978
[84] A. Ali, T. Hussain, N. Tantashutikun, N. Hussain and G. Cocetta, *Agriculture*, **13**, 2 (2023), https://doi.org/10.3390/agriculture13020397
[85] T. Machado, S. Beckers, J. Fischer, C. Sayer, P. Araújo *et al.*, *J. Colloid. Interface Sci.*, **601**, (2021), https://doi.org/10.1016/j.jcis.2021.05.030

[86] K. Vinzant, D. Clouse, S. Amit, I. Ivanov, V. Davis *et al*., *Adv. Sustain. Sys*., **8**, (2023), https://doi.org/10.1002/adsu.202300511
[87] S. Basak, P. Bhattacharyya, R. Pudake, P. Lokhande, U. Rednam *et al*., *Front. Nanotechnol*., **6** (2024), https://doi.org/10.3389/fnano.2024.1385981
[88] Y. Zhang, L. Fu, S. Li, J. Yan, M. Sun *et al*., *Environ. Sci. Technol*., **55**, 15 (2021), https://doi.org/10.1021/acs.est.1c01065
[89] Y. Zhang, M. Martinez, H. Sun, M. Sun, R. Yin *et al*., *Environ. Sci. Technol*., **57**, 8269 (2023), https://doi.org/10.1021/acs.est.3c01154
[90] P. Liang, B. Li, G. Liu, J. Xu, Q. Zhang *et al*., *Int. J. Biol. Macromol*., **383**, 154395 (2026), https://doi.org/https://doi.org/10.1016/j.ijbiomac.2026.154395
[91] E. Petersen, G. Goss, F. Kammer and A. Kennedy, *Nat. Nanotechnol*., **16** (2021), https://doi.org/10.1038/s41565-021-00889-1
[92] Y. Ma, Z. Li, Y. Zhu, J. Li, Z. Qu *et al*., *Environ. Res*., **308**, 125660 (2026), https://doi.org/https://doi.org/10.1016/j.envres.2026.125660
[93] R. Kumari, K. Suman, S. Karmakar, V. Mishra, S. G. Lakra *et al*., *Front. Genom. Ed*., **5**, 1200987 (2023), https://doi.org/10.3389/fgeed.2023.1200987
[94] S. Albert and E. Bloem, *Sci. Total Environ*., **879**, 163076 (2023), https://doi.org/10.1016/j.scitotenv.2023.163076
[95] M. Vassileva, S. Mocali, L. Canfora, E. Malusá, L. G. Del Moral *et al*., *Front. Plant. Sci*., **13** (2022), https://doi.org/10.3389/fpls.2022.862875
[96] A. Basu, P. Prasad, S. Das, S. Kalam, R. Sayyed *et al*., *Sustainability*, **13**, 3 (2021), https://doi.org/10.3390/SU13031140
[97] M. Usman, M. Farooq, A. Wakeel, A. Nawaz, S. Cheema *et al*., *Sci. Total Environ*., **721** (2020), https://doi.org/10.1016/j.scitotenv.2020.137778
[98] B. V. Boros and V. Ostafe, *Nanomaterials*, **10**, 4 (2020), https://doi.org/10.3390/nano10040610
[99] K. Rasmussen, H. Rauscher, P. Kearns, M. González and J. R. Sintes, *Regul. Toxicol. Pharmacol*., **104** (2019), https://doi.org/10.1016/j.yrtph.2019.02.008
[100] W. Zhou, Y. Arcot, R. Medina, J. Bernal, L. Cisneros-Zevallos *et al*., *ACS Omega*, **9** (2024), https://doi.org/10.1021/acsomega.4c06628
[101] F. Shah and W. Wu, *Sustainability*, **11**, 5 (2019), https://doi.org/10.3390/SU11051485
[102] K. Sharma and S. K. Shivandu, *Sens. Int*., **5** (2024), https://doi.org/10.1016/j.sintl.2024.100292
[103] N. Chandel, A. Kumar and R. Kumar, *Int. J. Plant Soil Sci*., **36**, 6 (2024), https://doi.org/10.9734/ijpss/2024/v36i64651
[104] Y. Kamakaula, *West Science Nature and Technology*, **2**, 2 (2024), https://doi.org/10.58812/wsnt.v2i02.964
[105] V. Martínez-García, J. Martínez-Paz and F. Alcon, *Ecosyst. Serv*., **72**, 101698 (2025), https://doi.org/10.1016/j.ecoser.2025.101698
[106] S. Muhie, *J. Agric. Food Res*., **10**, 100446 (2022), https://doi.org/10.1016/j.jafr.2022.100446
[107] A. Zanin, D. Neves, L. Teodoro, C. Silva, S. P. Silva *et al*., *Sci. Rep*., **12** (2022), https://doi.org/10.1038/s41598-022-09607-w
[108] C. Marques, S. Güneş, A. Vilela and R. Gomes, *Foods*, **14**, 9 (2025), https://doi.org/10.3390/foods14091553
[109] S. Guo, F. He, B. Song and J. Wu, *Food Energy Secur*., **10**, e293 (2021), https://doi.org/10.1002/FES3.293
[110] Y. Xiao, C. Wu, P. Cui, L. Zhou and Q. Yin, *J. Agric. Food Chem*., **71**, 28 (2023), https://doi.org/10.1021/acs.jafc.3c01084
[111] A. Bhattacharjee, S. Dubey and S. Sharma, *J. Plant Growth Regul*., **42**, 6741 (2023), https://doi.org/10.1007/s00344-023-10996-z
[112] A. Khan, A. V. Singh, S. Gautam, A. Agarwal, A. Punetha *et al*., *Front. Plant. Sci*., **14**, 1270039 (2023), https://doi.org/10.3389/fpls.2023.1270039
[113] P. Li, Y. Huang, C. Fu, S. Jiang, W. Peng *et al*., *EcoMat*, **3**, 5 (2021), https://doi.org/10.1002/eom2.12132
[114] H. Singh, A. Sharma, S. Bhardwaj, S. Arya, N. Bhardwaj *et al*., *Environ. Sci. Processes Impacts*, **23**, 213 (2021), https://doi.org/10.1039/d0em00404a