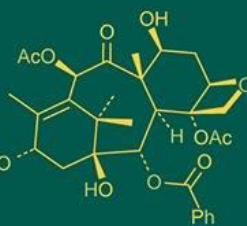
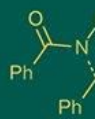
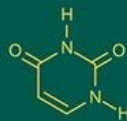
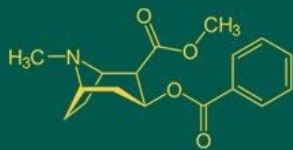


International Journal of Advanced Biochemistry Research



ISSN Print: 2617-4693
ISSN Online: 2617-4707
NAAS Rating (2025): 5.29
IJABR 2025; SP-9(9): 289-299
www.biochemjournal.com
Received: 15-07-2025
Accepted: 18-08-2025

Mahima Tobi

Ph.D Scholar, Department of Entomology, College of Agriculture, Vellanikkara, Kerala Agricultural University, Thrissur, Kerala, India

Amrith Raj

Ph.D Scholar, Department of Plant Pathology, College of Agriculture, Vellayani, Kerala Agricultural University, Thrissur, Kerala, India

Fida Banu MR

Postgraduate (MSc. (Ag.) Soil Science and Agricultural Chemistry), Kerala Agricultural University, University, Thrissur, Kerala, India

Sreelekshmi M

Ph.D Scholar, Department of Soil science and Agricultural Chemistry, College of Agriculture, Vellayani, Kerala Agricultural University, Thrissur, Kerala, India

Bhavana Sajeev

Department of Agricultural Extension, College of Agriculture, Vellanikkara, Kerala Agricultural University, Thrissur, Kerala, India

Corresponding Author:**Mahima Tobi**

Ph.D Scholar, Department of Entomology, College of Agriculture, Vellanikkara, Kerala Agricultural University, Thrissur, Kerala, India

Chemical drivers of crop development: A review on agrochemical interventions

Mahima Tobi, Amrith Raj, Fida Banu MR, Sreelekshmi M and Bhavana Sajeev

DOI: <https://www.doi.org/10.33545/26174693.2025.v9.i9Sd.5508>

Abstract

Agrochemicals such as fertilizers, pesticides, herbicides, fungicides, and plant growth regulators are central to modern agriculture, enhancing yields, improving nutrient availability, and protecting crops from biotic and abiotic stresses. This review summarizes their classification, mechanisms of action, and influence on crop growth and phenology, while also addressing soil-plant interactions and stress mitigation. Despite their benefits, excessive use contributes to soil degradation, water contamination, biodiversity decline, and health risks. Advances in nanotechnology-based formulations, smart delivery systems, and precision agriculture are emerging as sustainable alternatives that improve efficiency and reduce environmental impacts. Regulatory frameworks and resistance management strategies remain crucial for balancing productivity with ecological preservation. By integrating conventional and innovative approaches, agrochemicals can continue to support food security while moving toward more sustainable farming systems.

Keywords: Agrochemicals, crop productivity, stress management, soil-plant interaction, precision agriculture; sustainability

Introduction

Agricultural productivity has always been dependant on the judicious use of inputs that enhance soil fertility, protect crops, and ensure food security for a growing population. Agrochemicals, comprising fertilizers, pesticides, herbicides, fungicides, and plant growth regulators remain central to modern farming practices due to their capacity to boost yields, mitigate biotic and abiotic stresses, and sustain crop development under diverse environments. Their role extends beyond immediate yield improvements, influencing molecular, biochemical, and physiological processes that shape plant growth and phenology (Singh & Prasad, 2018) ^[64].

Despite these advantages, the overuse and mismanagement of agrochemicals have raised concerns regarding soil degradation, biodiversity loss, water pollution, and potential human health hazards (Meena *et al.*, 2020; Anjaria & Vaghela, 2024) ^[48, 51]. Balancing the duality of their benefits and risks is therefore a pressing global challenge. Recent advancements in classification systems by organizations such as IRAC, HRAC, and FRAC have improved resistance management strategies, while innovations in nanotechnology and precision delivery have sought to minimize environmental footprints (Kah *et al.*, 2019; Noman *et al.*, 2024) ^[34, 49].

This review synthesizes current knowledge on the classification, mechanisms of action, and crop-level impacts of agrochemicals, while also addressing their role in stress alleviation, soil-plant interactions, and emerging sustainable delivery systems. By highlighting both the positive contributions and the ecological concerns, it provides a comprehensive perspective on agrochemical interventions in crop development and identifies pathways for future research and policy refinement.

Agrochemicals

According to the Organisation for Economic Cooperation and Development (OECD), agrochemicals are defined as: “commercially produced, usually synthetic, chemical compounds used in farming, such as a fertilizer, a pesticide or a soil conditioner”.

However, agrochemicals may also include additional categories that are currently in use in the agro-food chain (Prasad, 2020) ^[64]. Agrochemicals are chemical products indispensable to modern agriculture, employed to enhance crop yields, safeguard crops from pests and diseases, and maintain soil health (Matthews, 2015) ^[45]. Agrochemicals are pivotal for sustainable agriculture, enhancing productivity and protecting crops from myriad threats. Understanding their classification and precise mode of action (MoA) is crucial for effective application, minimizing environmental impact, and, particularly for pesticides, managing resistance development (Russell, 2005) ^[60]. Recent advancements continue to refine these classifications and uncover novel modes of action, especially in the context of combating increasing pest resistance.

Classification of Agrochemicals and their mode of action (MoA)

The MoA refers to the specific biochemical or physiological pathway through which an agrochemical exerts its effect on the target organism or plant. Understanding MoA is fundamental for designing effective and sustainable pest management strategies, particularly for preventing or delaying the evolution of resistance (Russell, 2005) ^[60].

Fertilizers: These agrochemicals are designed to supply essential nutrients (macro and micronutrients) to the soil, thereby promoting robust plant growth and development (Epstein and Bloom, 2005) ^[19]. Macronutrients (e.g., Nitrogen (N), Phosphorus (P), Potassium (K)) are integral for chlorophyll and protein synthesis, promoting vegetative growth (Marschner, 2012) ^[44], critical for energy transfer (ATP), root development, and reproductive processes like flowering and fruiting (Mengel *et al.*, 2001) ^[46]. Micronutrients are required in smaller amounts, nonetheless act as co-factors for numerous enzymatic reactions and specific metabolic pathways (Marschner, 2012) ^[44].

Pesticides: This broad category encompasses chemicals formulated to control or eradicate pests that pose a threat to agricultural crops (Roberts *et al.*, 1999). Pesticides are categorized by the target pest and, crucially, by their MoA, which is systematically classified by expert committees to guide resistance management. Pesticides are further subdivided based on the specific pest group they target (Worthing and Hance, 1991) ^[69].

Herbicides (Weed Control)

Herbicides target unwanted plants and exhibit a wide range of MoAs. The Herbicide Resistance Action Committee (HRAC) provides a global classification system for herbicides based on their MoA. This system uses letters and numbers to group herbicides with the same target site, enabling rotation strategies to combat herbicide resistance. The 2024 HRAC Global Herbicide MoA Classification poster and master list are the most recent updates.

HRAC Group A (Group 1): Include ACCase Inhibitors (Acetyl-CoA Carboxylase Inhibitors) inhibit a key enzyme in lipid biosynthesis, primarily affecting grasses by preventing the formation of new cell membranes. Examples: Haloxypol, Quizalofop.

HRAC Group B (Group 2): Includes ALS Inhibitors (Acetolactate Synthase Inhibitors) prevent the synthesis of branched-chain amino acids (valine, leucine, isoleucine), essential for plant growth (Duke and Powles, 2008) ^[17]. Examples: Sulfonylureas (e.g., Chlorimuron), Imidazolinones (e.g., Imazethapyr).

HRAC Group C (includes Groups 5, 6, 7): Includes photosynthesis inhibitors which disrupt the electron transport chain in photosystem II, leading to the production of reactive oxygen species and cell damage. Examples: Atrazine (Group 5), Bromoxynil (Group 6), Diuron (Group 7)

HRAC Group G (include Group 9): Comprises of EPSPS Inhibitors (Enolpyruvylshikimate-3-phosphate Synthase Inhibitors) which inhibit an enzyme in the shikimate pathway, blocking the synthesis of aromatic amino acids (phenylalanine, tyrosine, tryptophan) (Duke and Powles, 2008) ^[17]. Example: Glyphosate

HRAC Group H (Group 10) Glutamine Synthetase Inhibitors: These inhibit the enzyme glutamine synthetase, leading to ammonia accumulation and disruption of amino acid synthesis. Example: Glufosinate

HRAC Group O (Group 4) Synthetic Auxins: Includes compounds mimic natural plant auxins but cause uncontrolled and abnormal growth due to hormonal imbalance, leading to plant death (Grossmann, 2010) ^[25]. Examples: 2,4-D, Dicamba.

HRAC Group F (Group 13, 14, 27, 28): Pigment Inhibitors and Cell Membrane Disruptors: This group includes various mechanisms leading to bleaching or rapid cell membrane destruction. Examples: Isoxaflutole (Group 27, HPPD inhibitor), Flumioxazin (Group 14, PPO inhibitor), Paraquat (Group 22, Photosystem I electron diversion).

Newer compounds: Recent research continues to identify novel herbicide targets to combat resistance, such as Solanyl Diphosphate Synthase (SPS) and Homogentisate Solanesyltransferase (HST) (He *et al.*, 2022) ^[28].

Insecticides

The Insecticide Resistance Action Committee (IRAC) provides a comprehensive classification system for insecticides and acaricides based on their mode of action. The latest updates to its classification now include biologics and nematicides, highlighting their commitment to evolving resistance management strategies (Basarab *et al.*, 2020) ^[7]. The key groups and their actions are:

Group 1: Acetylcholinesterase (AChE) Inhibitors: These block the breakdown of the neurotransmitter acetylcholine, leading to continuous nerve impulse transmission, overstimulation, and paralysis. Subgroups: Carbamates (e.g., Carbaryl), Organophosphates (e.g., Malathion)

Group 2: GABA-gated Chloride Channel Blockers: These prevent chloride ions from entering nerve cells by blocking GABA receptors, leading to hyperexcitation and convulsions. Examples: Cyclopyridol organochlorines, Phenylpyrazoles (Fiproles, e.g., Fipronil)

Group 3: Sodium Channel Modulators: These affect the flow of sodium ions across nerve cell membranes, causing repetitive firing of neurons and ultimately paralysis. Examples: Pyrethroids (e.g., Permethrin), DDT

Group 4: Nicotinic Acetylcholine Receptor (nAChR) Competitive Modulators: These bind to and activate nAChRs, mimicking acetylcholine and causing overstimulation of the nervous system. Examples: Neonicotinoids (e.g., Imidacloprid, Thiamethoxam)

Group 5: Nicotinic Acetylcholine Receptor (nAChR) Allosteric Modulators-Site I: These allosterically activate nAChRs, leading to nervous system hyperexcitation. Examples: Spinosyns (e.g., Spinosad)

Group 6: Glutamate-gated Chloride Channel (GluCl) Allosteric Modulators: These activate glutamate-gated chloride channels, leading to an influx of chloride ions and subsequent paralysis. Examples: Avermectins/Milbemycins (e.g., Abamectin)

Group 7: Juvenile Hormone Receptor Modulators: These disrupt and prevent metamorphosis when applied to pre-metamorphic insect instars. Examples: Juvenile hormone mimics (e.g., Methoprene)

Group 15: Inhibitors of Chitin Biosynthesis, Type 0: These interfere with the synthesis of chitin, a crucial component of the insect exoskeleton, thus disrupting molting. Examples: Benzoylureas (e.g., Lufenuron)

Group 28: Ryanodine Receptor Modulators: These activate insect ryanodine receptors, leading to uncontrolled calcium release from muscle stores, causing muscle contraction followed by paralysis. This is a significant class of new chemistry in recent years. Examples: Diamides (e.g., Chlorantraniliprole)

Group 30: GABA-gated Chloride Channel Allosteric Modulators (New Class): This relatively newer group acts on a distinct site within the GABA-gated chloride channel, causing hyperexcitation. Examples: Broflanilide, Fluxametamide

Fungicides (Fungal Disease Control)

Fungicides target fungal pathogens by inhibiting their growth or directly killing them. The Fungicide Resistance Action Committee (FRAC) provides a comprehensive MoA classification to aid in resistance management. FRAC codes, consisting of numbers and letters, are displayed on fungicide labels to help users rotate between different MoA groups. The key groups and their mode of action as per FRAC (2005) are:

Group 1: MBC Fungicides (Methyl Benimidazole Carbamates): These inhibit mitosis and cell division by disrupting beta-tubulin assembly in the fungal cytoskeleton. Examples: Carbendazim, Thiabendazole.

Group 3: (includes DMI fungicides-Demethylation inhibitors): inhibit ergosterol biosynthesis (a key component of fungal cell membranes) by targeting the C14-demethylase

enzyme. A notable example is Triazoles (e.g., Tebuconazole, Difenconazole).

Invariably, SDHI Fungicides (Succinate Dehydrogenase Inhibitors included in Group 7): inhibit complex II (succinate dehydrogenase) in the mitochondrial respiration chain, disrupting fungal energy production (FRAC, 2025). Examples: Boscalid, Fluxapyroxad, Pydiflumetofen.

QoI Fungicides (Quinone Outside Inhibitors classified into Group 11): commonly known as strobilurins inhibit complex III (cytochrome bc1 at the Qo site) in the mitochondrial respiration chain, blocking electron transport. Examples: Azoxystrobin, Pyraclostrobin.

Group 12: Phenylpyrroles (PP Fungicides): These fungicides interfere with signal transduction pathways related to osmotic regulation. Example: Fludioxonil.

Group M (Groups M1-M12): also known as Multi-site Contact Protectants act on multiple biochemical pathways, preventing spore germination and inhibiting fungal growth on the plant surface. They are considered to have a low resistance risk. Examples: Copper (M01), Mancozeb (M03), Chlorothalonil (M05).

Group 40 (includes CAA fungicides-carboxylic acid amides): disrupt cell wall biosynthesis by inhibiting cellulose synthase. Examples: Dimethomorph, Mandipropamid.

Effect of agrochemicals on crop production

The use of agrochemicals significantly influences crop production, primarily through the enhancement of yields and pest management. However, their application raises concerns regarding environmental and health impacts (Kosoe *et al.*, 2023) ^[37]. This duality necessitates a comprehensive understanding of both the benefits and drawbacks associated with agrochemical use. In developed countries, such as those in Europe, where use of agrochemicals was high, the yields and per capita production were also high and increasing over time (Kelly *et al.*, 2007) ^[35]. Per capita cereal production in most African countries was low; fertilizer and pesticide use in these countries was also low. The use of agrochemicals as fertilisers and pesticides has been strongly recommended as a means of increasing the crop yield. Among the common pesticides that farmers use is DDT, fluvalinate, coumaphos, chlorothalonil and chlorpyrifos (Zhu *et al.*, 2014) ^[71]. All of these chemical's impact on the environment and living beings in different ways, making it very difficult to list them all in one article that is primarily focused on legal and practical control issues. A farmer who seeks to maximise yield focuses on a single type of crop and uses fertilisers that attempt to favour the growth of the desired crop while creating a micro-environment that is unfavourable for other plants. In both conventional and integrated farming, the use of chemical and inorganic fertilisers to achieve this goal is very common (Bengtsson *et al.*, 2005) ^[9]. In Europe, for example, it was reported that cereal yield had tripled from 1960 to 2000, due to fertilizer application (Tschamtkke *et al.*, 2005) ^[66]. On the other hand, the use of fertilisers for a longer period of time affects soil fertility which in return decreases the crop yield. In China, maize and wheat production was reduced by 50 percent and 32 percent due to the continuous use of potassium fertilizer (Huang *et al.*, 2003) ^[29]. Soil fertility is negatively affected by the use of agrochemicals. In the long run, these chemicals decrease the

fertility of the soil. They can change the soil pH, causing acidification or alkalisation. Nitrogenous fertilisers can cause acidification by lowering the soil pH from 5.8 to 4.7 (Subehia *et al.*, 2005) ^[65].

Molecular and biochemical mechanism influenced by agrochemicals

Agrochemicals influence plant molecular mechanisms primarily by interfering with key biochemical pathways, gene expression, and signalling processes essential for plant growth and development (Singh and Prasad, 2018) ^[64]. For instance, certain herbicides target vital enzymatic activities in plants; glyphosate inhibits the enzyme 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS) in the shikimate pathway, preventing the synthesis of aromatic amino acids like phenylalanine, tyrosine, and tryptophan. Chlorpyrifos dramatically alters amino acid pathways in *Oryza sativa* (rice) and led to a significant degradation of soluble proteins (Liu and Zhu, 2020) ^[40]. This disruption hampers protein synthesis and secondary metabolite production, ultimately leading to plant death. Similarly, organophosphorus insecticides such as fenamiphos can inhibit acetylcholinesterase activity in plants, which affects neurotransmitter regulation and cellular signalling pathways, impairing growth processes. These chemicals can also induce oxidative stress by generating reactive oxygen species (ROS), which damage cellular components such as lipids, proteins, and DNA, disrupting normal cellular functions (Khorshid *et al.*, 2015) ^[36]. Furthermore, agrochemicals can alter gene expression by affecting transcription factors and signalling molecules that regulate plant responses to environmental stimuli. For example, exposure to certain pesticides induces the upregulation of stress-responsive genes, including those involved in antioxidant production (like superoxide dismutase and catalase) and detoxification processes (such as cytochrome P450 enzymes). However, prolonged or high-dose exposure can suppress essential genes involved in photosynthesis, nutrient uptake, and cell division, impairing plant growth and yield (Jia *et al.*, 2023) ^[33]. In crops like wheat and maize, pesticides can interfere with hormonal signalling pathways, such as auxin and cytokinin, which regulate cell elongation, division, and differentiation. Disruption of these pathways leads to abnormal development, reduced biomass, and compromised reproductive success. Overall, agrochemicals affect plant molecular mechanisms by inhibiting critical enzymes, inducing oxidative damage, modulating gene expression, and disturbing hormone signalling, which collectively impair plant vitality and productivity.

Mitochondrial and Cellular Disruption: Agrochemicals can induce oxidative stress by generating ROS, which disrupts cellular functions and activates defense mechanisms. Pesticides disturb cellular homeostasis by deteriorating nuclear components and dissipating the mitochondrial membrane potential ($\Delta\Psi_m$). Reactive oxygen species (ROS) deposited in plant tissues impair membrane integrity, causing electrolytes to flow out of the cell.

Agrochemicals can induce oxidative stress by generating ROS, which disrupts cellular functions and activates defense mechanisms. Pesticides like malathion and chlorpyrifos have been shown to decrease mitotic frequency and increase chromosome abnormalities, such as lagging chromosomes and micronuclei (Arya *et al.*, 2017; Shabbir *et al.*, 2021) ^[6, 62].

Proteomic analysis of maize showed that the herbicide amiprofos methyl (APM) affected the expression of numerous proteins, which could serve as biochemical markers for toxicity.

Foliar pesticide applications enhance the tricarboxylic acid cycle (TCA) by 1.1-fold in cucumber fruits. Pesticides are reported to cause oxidative stress in plants by producing reactive oxygen species (ROS) such as superoxide anions (O_2^-) and hydrogen peroxide (H_2O_2). For example, the pesticide chlorothalonil enhanced H_2O_2 levels in tomato plants. Pesticides can upsurge lipid peroxidation and the production of ROS (O_2^- , OH , and H_2O_2), which is the ultimate cause of mitochondrial membrane potential disruption.

Impact of Agrochemicals on crop phenology and growth stages

The growth and phenological development of crop plants are governed by genetic, environmental, and hormonal factors. Adequate availability of essential mineral nutrients, both macro and micronutrients, and plant growth regulators is critical for optimal crop yield. Deficiencies in these essential inputs can lead to impaired physiological functions, resulting in stunted growth, delayed phenological transitions, and reduced productivity. Agrochemicals, including fertilizers and plant growth regulators, directly modulate these processes by influencing nutrient availability and hormonal balance, thereby affecting developmental stages of crop growth. Begum *et al.* (2018) ^[8] reported that yield and yield attributes of rice variety GNV10-89 differed by foliar and soil application of different agrochemicals at 65 and 85 days after transplanting. Agrochemicals used were 25% extra nitrogen (N) soil application, NPK (19:19:19) @ 1.0%, triacontanol (2.0 ml l⁻¹), GA3 (50 ppm), nitrobenzene (20 ppm), salicylic acid (500 ppm), 6-BAP (20 ppm), borax (0.2%), and triacontanol (2.0 ml l⁻¹) and borax (0.2%) foliar applications. Foliar spray of NPK-19:19:19 @ 1.0% recorded significantly higher number of filled spikelet per panicle (232.9), percent increase of filled spikelet (33.6), least number of unfilled spikelets per panicle (61.3), less percent of chaffyness (20.9%), 1000 grain weight (23.6 g), the highest grain yield (8709.8 kg ha⁻¹) and percent increase of grain yield compared to control.

Soil-plant interaction in response to chemical inputs

Soil-plant interactions are dynamic processes influenced by chemical inputs such as fertilizers, pesticides, herbicides, liming materials and other soil amendments which modify physical, chemical and biological properties of soil, thereby affecting nutrient availability, microbial activity, and ultimately plant growth (Fig. 1).

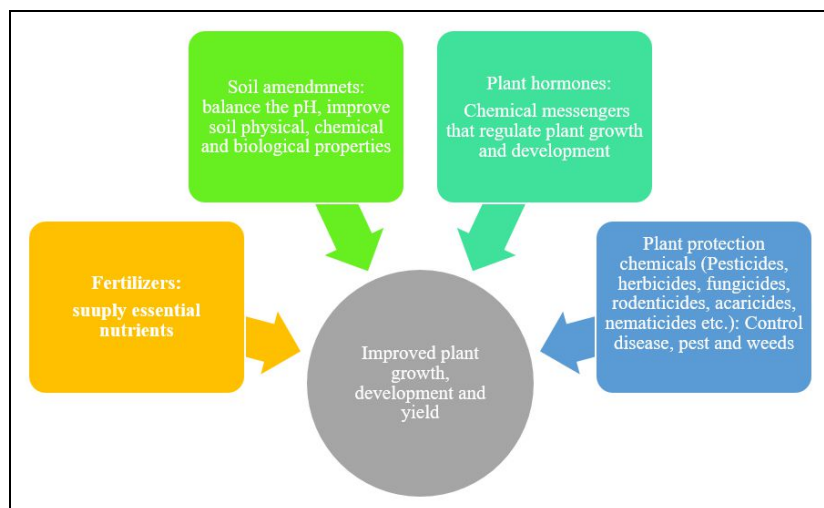


Fig 1: Soil plant interaction in response to chemical inputs

Role of agrochemicals in alleviating abiotic and biotic stress

Agrochemicals play a crucial role in mitigating abiotic and biotic stresses in crop production thereby improving plant resilience, growth, and productivity. Supply of nutrients into soil can alleviate abiotic stress (Table 1). Antioxidant enzymes such as superoxide dismutase, peroxidase and catalase were increased by the nutrients such as nitrogen, potassium, calcium and magnesium. Improvement in water uptake can be achieved with osmotic adjustments and stomatal regulation by potassium and calcium. Micronutrients such as iron, boron and zinc help in activating various physiological changes in plants, activate defence mechanisms and improve the metabolic process by which the plants adapt to various adverse stresses (Kumari *et al.*, 2022) ^[39]. Application of potassium fertilizer in arid environment improves plant water status and growth and yield of soybean under water stress (Mageed *et al.*, 2016) ^[18].

Plant nutrition significantly influences their susceptibility to pest and disease attacks. By altering growth patterns, anatomical and morphological traits, and especially chemical composition, nutrient availability can either enhance or reduce a plant's resistance and tolerance to various pests and diseases. Application of potassium

fertilizers decreased the incidence of fungal diseases by 70% bacteria by 69%, insects and mites by 63% and viruses by 41% (Perrenoud, 1990) ^[54]. High silicon accumulation in the leaves affected by *Magnaporthe grisea* helps reduce lesion development (Sakr, 2016) ^[61] and enhances the tolerance of the stem, stalk, and shoot in crops such as *Triticum*, *Oryza*, *Zea*, and *Saccharum* species against biotic stress (Debona *et al.*, 2017) ^[13].

Plant growth regulators played a key role in controlling abiotic (Table 2) and biotic stress responses. Foliar application of 1% pink-pigmented facultative methylotrophs (PPFM) during the panicle initiation and flowering stages under moisture stress conditions resulted in improved crop performance compared to the untreated control. Additionally, it significantly reduced the population of brown planthopper (BPH) in the experimental plots (Ajaykumar *et al.*, 2023) ^[1]. This might be due to the change in physiology of plant systems, i.e., the production of flavonoids, which repel sucking and chewing insects.

Chemical interventions such as insecticides, pesticides, herbicides, and fungicides play a vital role in safeguarding crops against pests, diseases, and weeds. By targeting specific biotic stress, these agrochemicals help farmers preserve plant health and reduce yield losses caused by it.

Table 1: Effect of primary nutrients on abiotic stress management (Kumari *et al.*, 2022) ^[39]

Nutrient	Effect on Abiotic Stress
Nitrogen (N)	Enhances chlorophyll biosynthesis, photosynthesis, water use efficiency, ROS scavenging, proline accumulation; improves root plasticity and osmotic regulation; reduces stress-related yield losses
Phosphorus (P)	Improves root architecture, water uptake, photosynthesis, cell membrane stability, and antioxidant enzyme activity; alleviates drought and salinity-induced oxidative stress
Potassium (K)	Regulates stomatal movement, osmotic balance, water use efficiency, ROS detoxification, and proline accumulation; enhances tolerance to drought, salinity, and waterlogging
Calcium (Ca)	Acts as a secondary messenger, stabilizes membranes, competes with Na ⁺ under salinity, enhances drought and chilling tolerance, supports antioxidant defences and nutrient uptake
Magnesium (Mg)	Maintains photosynthesis, enzyme activation, osmoregulation, and structural stability; improves water retention under drought and is affected by salinity and heat
Sulphur (S)	Forms glutathione and related compounds, enhances antioxidant defence, regulates ROS and stress signalling, improves heat, salinity, metal toxicity tolerance

Table 2: Effect of plant growth hormones on abiotic stress management (Rasool, 2022) ^[58]

Hormone	Key Role in Abiotic Stress Management
Abscisic Acid (ABA)	Regulates stomatal closure, enhances antioxidant defense, promotes Osmo protectant synthesis.
Jasmonic Acid (JA)	Activates antioxidant enzymes, accumulates osmolytes, regulates stomata, modulates stress gene expression.
Salicylic Acid (SA)	Enhances heat and salt tolerance, induces systemic acquired resistance (SAR), regulates ROS balance.
Ethylene (ET)	Modulates root and shoot growth, enhances defense overgrowth, synergizes with JA during stress.
Cytokinins (CK)	Delays senescence, promotes stress priming, modulates SA and JA signaling pathways.
Auxins (IAA)	Alters root architecture, modulates stress-related gene expression, interacts with JA and SA.
Gibberellins (GA)	Balances growth and defense, degraded under stress, interact antagonistically with JA.
Brassinosteroids (BR)	Stabilizes membranes, enhances tolerance to salinity and heat, regulates JA signaling.

Advances in Smart and Sustainable Agrochemical Delivery Systems

Recent innovations in agrochemical delivery systems have focused on improving efficiency, reducing waste, and minimizing environmental harm. Nanotechnology has played a pivotal role in this advancement, enabling the development of nanoformulations such as nanoencapsulation and nanocarriers, which enhance the controlled release of pesticides and fertilizers (Kah *et al.*, 2019) ^[34]. These systems improve bioavailability while reducing leaching and volatilization, thereby optimizing agrochemical efficacy. Additionally, nanomaterials and nanocomposites have been employed to enhance the stability, dispersion, and targeted delivery of agrochemicals while minimizing residual pollution (An *et al.*, 2022) ^[4].

Another significant advancement is stimuli-responsive delivery, where agrochemicals are released in response to environmental triggers such as pH, temperature, or enzymatic activity (Lowry *et al.*, 2019) ^[41]. Hydrogel-based delivery systems, for example, can release nutrients in sync with crop demand, significantly improving nutrient use efficiency. Similarly, clay-nanocomposites have emerged as biocompatible and environmentally friendly vehicles for delivering micronutrients and pesticides, addressing critical issues such as non-target effects and leaching (Pal *et al.*, 2022) ^[51].

Recent developments in bioinspired smart microcarriers have further refined precision delivery, ensuring that agrochemicals are efficiently absorbed by plants while minimizing runoff (Noman *et al.*, 2024) ^[49]. These innovations complement precision agriculture tools, including drone-assisted spraying and sensor-based application systems, which optimize agrochemical use by ensuring site-specific and demand-driven delivery (Zhang *et al.*, 2015) ^[70].

The integration of smart nanomaterials and nanocomposites has also improved interactions with soil microbiomes, enhancing both crop protection and production (Kumar *et al.*, 2022) ^[39]. Collectively, these advancements in agrochemical delivery systems contribute to sustainable farming practices, improved crop yields, and enhanced food security while reducing the ecological footprint of conventional agrochemical use.

Environmental and Residual Impacts of Agrochemical Use

The widespread application of agrochemicals, while boosting agricultural productivity, has led to significant environmental consequences, including soil degradation, water pollution, and biodiversity loss. These impacts stem from both direct chemical toxicity and long-term residual effects, necessitating urgent mitigation strategies.

- **Soil Environment Degradation:** Agrochemical use profoundly alters soil microbial communities and physicochemical properties. Studies indicate that pesticides and synthetic fertilizers reduce microbial diversity, disrupt nutrient cycling, and increase plant disease susceptibility (Meena *et al.*, 2020) ^[48]. Persistent residues, such as glyphosate, accumulate in soil, harming non-target organisms and reducing beneficial microbial populations (Van Bruggen *et al.*, 2018) ^[68]. Additionally, intensive agrochemical use contributes to soil structure deterioration, including organic matter depletion, increased erosion risk, and reduced water retention (Wang *et al.*, 2004) ^[27]. In contrast, organic farming systems enhance microbial activity, improve soil fertility, and maintain higher organic carbon levels, demonstrating greater long-term sustainability (Gomiero *et al.*, 2011) ^[23].
- **Water Pollution and Aquatic Ecosystem Disruption:** Agrochemical runoff poses severe risks to water quality and aquatic life. Nitrogen and phosphorus leaching from fertilizers cause eutrophication, leading to algal blooms and oxygen depletion in freshwater systems (Glibert *et al.*, 2006) ^[22]. Pesticide contamination in groundwater and surface waters has been widely documented, with residues detected in drinking water sources in West Africa and Southeast Asia (Fianko *et al.*, 2011) ^[20]. These pollutants adversely affect aquatic organisms, causing fish mortality, bioaccumulation in food chains, and reproductive failures in birds. Regulatory measures, such as nitrate limits in New Zealand (Wang *et al.*, 2004) ^[27], highlight the growing recognition of agrochemical-induced water pollution.
- **Biodiversity Loss and Ecosystem Disruption:** The ecological footprint of agrochemicals extends to terrestrial and aquatic biodiversity decline. Pesticides, particularly neonicotinoids, have been implicated in pollinator population collapse, threatening ecosystem stability and crop pollination services (Goulson *et al.*, 2015) ^[24]. Conventional farming systems are associated with reduced species richness, including declines in beneficial arthropods, soil fauna, and rare flora (Gomiero *et al.*, 2011) ^[23]. Conversely, organic and integrated pest management (IPM) systems support higher biodiversity, improved ecosystem resilience, and enhanced carbon sequestration.

Mitigation Strategies Emerging solutions aim to counteract agrochemical impacts

- Bioremediation and phytoremediation leverage microbes and plants to degrade or absorb contaminants (Rani *et al.*, 2021) ^[57].

- Organic amendments and reduced-chemical farming restore soil health and reduce pollution (Meena *et al.*, 2020) ^[48].
- Precision agriculture and regulated agrochemical use minimize over-application and environmental leakage (Wang *et al.*, 2004) ^[27].

While agrochemicals remain integral to modern agriculture, their environmental costs necessitate a shift toward sustainable practices that balance productivity with ecological preservation. Future strategies should prioritize soil regeneration, water protection, and biodiversity conservation to ensure long-term agricultural resilience.

Regulatory Frameworks and Policy Guidelines for Agrochemical Use

Global Regulatory Landscape

The use of agrochemicals is governed by diverse regulatory frameworks aimed at balancing agricultural productivity with environmental and human health protection. In developed regions, stringent regulations such as the European Union's REACH and the U.S. EPA's FIFRA mandate comprehensive toxicity testing and risk assessments before agrochemical approval (Damalas & Eleftherohorinos, 2011) ^[11]. These frameworks prioritize the Precautionary Principle, restricting chemicals with uncertain long-term effects. However, developing nations often face enforcement challenges, leading to misuse and inadequate safety measures.

International efforts, including the FAO/WHO International Code of Conduct on Pesticide Management, promote sustainable agrochemical use through guidelines on labeling, storage, and application. Emerging regulatory trends incorporate digital traceability systems for monitoring agrochemical distribution and eco-labeling schemes to guide farmers toward safer practices (Pretty & Bharucha, 2015) ^[55]. Despite these measures, disparities persist in regulatory stringency, particularly between industrialized and developing economies (Kudsk & Mathiassen, 2020; Marchand, 2023) ^[38, 42].

Controversies and Knowledge Gaps

While agrochemicals have been instrumental in supporting global food security for a population exceeding eight billion (Odewale *et al.*, 2023) ^[50], their overuse has led to soil degradation, water pollution, and biodiversity loss (Anjaria & Vaghela, 2024) ^[5]. Chronic health risks, including cancer and neurological disorders, further complicate regulatory decision-making.

Key controversies include

- **Divergent Regulatory Approaches:** The EU's hazard-based restrictions contrast with the U.S. risk-based assessments, creating trade conflicts and uneven safety standards (Grossman, 2009) ^[26].
- **Enforcement Challenges:** Many developing countries lack the infrastructure for effective monitoring, leading to illegal agrochemical use and environmental harm.
- **Economic vs. Ecological Trade-offs:** Some argue for **stricter bans** to protect ecosystems, while others emphasize agrochemicals' economic necessity, advocating for incentive-based policies.

Toward Integrated Regulatory Strategies

Addressing these challenges requires

1. **Harmonizing International Standards:** Strengthening global cooperation to align risk assessment protocols.
2. **Capacity Building in Developing Nations:** Enhancing technical and regulatory infrastructure for enforcement (Devi *et al.*, 2022) ^[15].
3. **Promoting Sustainable Alternatives:** Incentivizing precision agriculture, biopesticides, and organic farming to reduce reliance on synthetic agrochemicals (Anjaria & Vaghela, 2024) ^[5].

Effective agrochemical regulation must reconcile food security demands with ecological and public health preservation. Future policies should prioritize science-based risk assessment, global equity in enforcement, and investment in sustainable alternatives to mitigate long-term agrochemical impacts.

Crop-Specific Case Studies of Agrochemicals: Comprehensive analysis

The widespread use of agrochemicals in intensive crop production systems poses a significant threat to the functionality and sustainability of agroecosystems. Metabolomics, the quantitative assessment of small molecules, metabolites, and their intermediates, has emerged as a crucial technique for detecting metabolic alterations in plants exposed to various stresses, including pesticides (Shahid *et al.*, 2023) ^[63]. Agrochemicals contribute to soil compaction, erosion, and loss of fertility, which undermine soil health and its ability to support crops (Pereira *et al.*, 2023) ^[53]. Continuous application of fertilizers and pesticides can lead to soil acidification and reduced microbial diversity, essential for nutrient cycling (Odewale *et al.*, 2023) ^[50]. The comprehensive analysis presents crop-specific case studies on agrochemical applications, drawing from recent research across multiple agricultural systems. The studies demonstrate significant variability in agrochemical efficacy based on crop type, geographic location, and application methods. Numerous studies have used advanced metabolomic approaches, such as GC-MS, LC-MS/MS, and NMR, to investigate the effects of agricultural pesticides on specific crops.

- **Maize (*Zea mays*):** A study on maize roots exposed to the organochlorine pesticides lindane and chlordecone used 1H-HR-MAS NMR-based metabolomics. Lindane and chlordecone exposure in maize roots increased the amount of fatty acids (FA) and oxidized FAs, which led to protein and lipid catabolism. The analysis identified approximately 26 altered metabolites and mapped them to eight metabolic pathways. Findings revealed that sucrose was downregulated, and changes were observed in the TCA cycle metabolites succinate and fumarate, suggesting reduced respiration. Additionally, there were significant changes in amino acids like gamma-aminobutyric acid, asparagine, and isoleucine, pointing to an imbalance between carbon and nitrogen. The presence of oxidized fatty acids suggested a degraded state of cell wall integrity (Pascal-Lorber *et al.*, 2016) ^[52].
- **Lettuce (*Lactuca sativa*):** The effects of the fungicide mancozeb on lettuce were studied using HR-MAS NMR (Dias *et al.*, 2014) ^[16]. Mancozeb exposure caused oxidative stress by inducing variations in

phenylalanine and polyphenols and led to the upregulation of the Krebs cycle. Abnormalities in sucrose, phospholipid, nucleotide, and nicotinamide metabolism were also observed. In another study, UHPLC was used to analyze the metabolic changes in lettuce leaves exposed to the insecticides imidacloprid (IMD) and fenvalerate (FVE). FVE significantly reduced leaf flavonoid content, while IMD altered the metabolism of amino acids and carbohydrates. Residue analysis showed that lettuce retained higher levels of mancozeb compared to other crops like tomatoes and apples, with decay rates and half-lives were found to be similar across different dithiocarbamate fungicides (Hughes and Tate, 1982) ^[31].

- **Rice (*Oryza sativa*):** Metabolomics research has been conducted on rice, an agronomically important crop. GC-MS analysis of rice plants exposed to insecticides like diazinon and chlorpyrifos revealed time-dependent metabolic changes across multiple pathways. These included alterations in sugar, amino acid, and organic acid biosynthesis, as well as oxidative stress responses. Another study used GC-LRMS-targeted metabolomics technique to investigate the effects of pesticides on rice leaves and seeds. The results showed that while amino acid levels were up-regulated in both leaves and seeds, levels of phenols, antioxidants, and carbohydrates were downregulated in the seeds (Mahdavi *et al.*, 2015). Similarly, three typical pesticides, including herbicide butachlor, insecticide chlorpyrifos and fungicide tricyclazole, induced the expression regulation of different key genes, exhibiting considerable distinction on metabolic responses in rice (Liu and Zhu, 2020) ^[40].
- **Cucumber (*Cucumis sativus*):** Copper-based pesticides revealed their significant impact on cucumber plant metabolism and defense mechanisms. Cu-based pesticides caused a depletion of antioxidants in cucumber, which in turn increased the levels of benzoic acid, gallic acid hydrate, and p-coumaric acid, suggesting the activation of a defense mechanism (Zhao *et al.*, 2016) ^[53]. Similar responses were observed with other pesticides, such as imidacloprid and dichlorvos, which also activated antioxidant defense systems and increased levels of proteins, proline, carbohydrates, and phenolic compounds in cucumber seedlings (Homayoonzadeh *et al.*, 2020) ^[30]. In another study, UHPLC-Q-Orbitrap-HRMS was used to analyze the metabolomics of pesticide-treated cucumber leaves. The study found that antioxidants alleviated pesticide stress by up-regulating the shikimate-phenylpropanoid pathway.
- **Radish (*Raphanus sativus* var. *longipinnatus*):** A study using LC-MS/MS analyzed radish plants exposed to various pesticides, including deltamethrin, thiamethoxam, metalaxyl, and cyhalothrin (Danek *et al.*, 2021) ^[12]. Non-targeted analysis revealed the presence of metabolites of thiamethoxam, cyhalothrin, and deltamethrin, even when the parent pesticide concentrations were below the limit of detection. This demonstrated the importance of non-targeted analysis for assessing pesticide exposure even after the parent compound has been metabolized.
- **Potato:** Neonicotinoid insecticides are a vital tool for controlling arthropods in potato crops. They're usually applied to seeds or directly into the furrow during

planting. Once applied, the insecticides are absorbed by the plant, making them mobile throughout its system and effective against important early-season pests. Application of soil insecticide in crop plants with neonicotinoid contamination of water leaching from the application zone (Huseth and Groves, 2014) ^[32].

Challenges

The use of agrochemicals presents several challenges, particularly concerning their environmental and toxicological impacts. While pesticides are crucial for intensive crop production, their widespread use and accumulation in the soil pose a serious threat to the functionality and sustainability of agroecosystems. Pesticide residues frequently contaminate soil, water, and air, affecting non-target species and entire ecosystems. For example, a significant portion of applied pesticides can be lost to the environment through runoff, leaching into groundwater, and drift, impacting aquatic life, beneficial insects, and wildlife (Tudi *et al.*, 2021) ^[67]. The phytotoxic effects of pesticides on non-target organisms have also garnered significant attention due to their persistent presence in the environment. A major challenge in metabolomics, is the comprehensive investigation of all metabolites influenced by various stressors, a task complicated by the physiochemical diversity of the entire metabolome. Identifying metabolites is a significant hurdle for untargeted metabolomics. Furthermore, selecting appropriate LC columns to effectively separate highly polar metabolites without losing the separation of less polar ones remains a difficulty. The health risks associated with agrochemical use are a critical concern, especially for farmworkers and consumers. Many studies have linked chronic exposure to certain pesticides with a range of health issues, including neurological disorders and an elevated risk of cancer. The situation is often more dire in developing countries, where farmers frequently lack access to or knowledge of proper personal protective equipment (PPE). A study on smallholder farmers in Ghana and Uganda, for instance, found that a vast majority of farmers applied pesticides without wearing PPE and often mixed chemicals with their bare hands, leading to an increased risk of chemical poisoning (Demi and Sicchia, 2021) ^[14]. A major biological challenge is the development of resistance in pest populations. When a pesticide is used repeatedly, it creates a strong selection pressure that favors pests with a natural genetic ability to survive the chemical. The agrochemical industry and farmers also face significant regulatory and economic challenges. In many countries, the process for registering new and safer molecules is described as lengthy and expensive, which can stifle innovation and delay the introduction of more advanced products.

Future directions in agrochemical use

Looking to the future, there is a push to further the application of metabolomics and transcriptomics within the framework of the OECD's chemical safety program. The combination of various analytical methodologies, such as mixed-mode column technologies with UHPLC, is anticipated to increase the coverage of metabolome change detection and aid in environmental science. The analysis of thousands of metabolites at the cellular level will enable the creation of extensive computational models, leading to a deeper understanding of molecular mechanisms in

ecotoxicological research. These advancements are expected to facilitate the discovery of biomarkers for early exposure to agrochemicals. Metabolomics and transcriptomics are poised to play a significant role in toxicology laboratories for evaluating the molecular effects of pollutants, including chemical pesticides, provided their use is approved for chemical safety regulation. This would provide a wealth of useful information for ecotoxicological studies. Lipidomics, a technique that identifies changes in the lipid content of plant tissues after they've been exposed to pesticides, offers significant potential. It can help us understand how pesticides work (their modes of action), clarify the ways they cause harm (toxicity mechanisms), and reveal how plants are exposure pathways.

Conclusion

Agrochemicals remain indispensable tools for global agriculture, significantly enhancing crop yields, nutrient availability, and resilience against diverse stresses. As detailed in this review, their influence spans molecular to ecosystem levels, shaping plant physiology, phenology, and productivity. At the same time, persistent challenges, including soil degradation, water contamination, biodiversity decline, and the evolution of pest resistance underscore the need for more sustainable approaches. Emerging technologies such as nanocarrier-based formulations, stimuli-responsive delivery systems, and precision agriculture hold promise for improving efficiency while minimizing ecological impacts. Robust regulatory frameworks, integrated pest management practices, and capacity building are equally important in developing nations to ensure responsible usage and equitable benefits. Ultimately, the future of agrochemicals lies not in their wholesale replacement but in their integration into holistic, sustainable farming systems that balance productivity with environmental stewardship. Advancing this balance will be key to meeting the twin goals of global food security and ecological resilience in the decades ahead.

References

1. Ajaykumar R, Krishnasamy SM, Dhanapal R, Ramkumar G, Megaladevi P, Manjubala M, *et al.* Mitigation of abiotic and biotic stress using plant growth regulators in rice. *Agronomy*. 2023;13(9):2226.
2. Alam MJ, Al-Mahmud A, Islam MA, Hossain MF, Ali MA, Dessoky ES, *et al.* Crop diversification in rice-based cropping systems improves the system productivity, profitability and sustainability. *Sustainability*. 2021;13(11):6288.
3. Alfoeldi T, Fliessbach A, Geier U, Kilcher L, Niggli U. Organic agriculture and the environment. Frick, Switzerland: Research Institute of Organic Agriculture (FiBL); 2002.
4. An C, Sun C, Li N, Li W. Nanomaterials and nanotechnology for the delivery of agrochemicals: strategies towards sustainable agriculture. *J Nanobiotechnology*. 2022;20(1):11.
5. Anjaria P, Vaghela S. Toxicity of agrochemicals: impact on environment and human health. *Deleted Journal*. 2024;2(1).
6. Arya SK, Ghosh I, Banerjee R, Mukherjee A. Malathion and dithane induce DNA damage in *Vicia faba*. *Toxicol Ind Health*. 2017;33(11):843-854.
7. Basarab GS, Doig P, Eyermann CJ, Galullo V, Kern G, Kimzey A, *et al.* Antibacterial spiropyrimidinetriones with N-linked azole substituents on a benzisoxazole scaffold targeting DNA gyrase. *J Med Chem*. 2020;63(20):11882-11901.
8. Begum Y, Patil R, Meena M, Amaregouda A. Effect of foliar and soil application of different agrochemicals on phenology, physiological parameters and productivity of rice (*Oryza sativa* L.). *J Pharmacogn Phytochem*. 2018;7:2947-2952.
9. Bengtsson J, Ahnström J, Weibull AC. The effects of organic agriculture on biodiversity and abundance: a meta-analysis. *J Appl Ecol*. 2005;42(2):261-269.
10. Buch K, Saikanth DRK, Singh BV, Mallick B, Pandey SK, Prabhavathi N, *et al.* Impact of agrochemicals on beneficial microorganisms and human health. *Int J Environ Clim Change*. 2023;13(10):1135-1145.
11. Damalas CA, Eleftherohorinos IG. Pesticide exposure, safety issues, and risk assessment indicators. *Int J Environ Res Public Health*. 2011;8(5):1402-1419.
12. Danek M, Plonka J, Barchanska H. Metabolic profiles and non-targeted LC-MS/MS approach as a complementary tool to targeted analysis in assessment of plant exposure to pesticides. *Food Chem*. 2021;356:129680.
13. Debona D, Rodrigues FA, Datnoff LE. Silicon's role in abiotic and biotic plant stresses. *Annu Rev Phytopathol*. 2017;55:85-107.
14. Demi SM, Sicchia SR. Agrochemicals use practices and health challenges of smallholder farmers in Ghana. *Environ Health Insights*. 2021;15:11786302211043033.
15. Devi PI, Manjula M, Bhavani RV. Agrochemicals, environment, and human health. *Annu Rev Environ Resour*. 2022;47(1):399-421.
16. Dias MC, Figueiredo P, Duarte IF, Gil AM, Santos C. Different responses of young and expanded lettuce leaves to fungicide Mancozeb: chlorophyll fluorescence, lipid peroxidation, pigments and proline content. *Photosynthetica*. 2014;52(1):148-151.
17. Duke SO, Powles SB. Glyphosate-resistant weeds and crops. *Pest Manag Sci*. 2008;64(4):317-318.
18. El-Mageed TAA, El-Sherif AM, Ali MM, El-Wahed MHA. Combined effect of deficit irrigation and potassium fertilizer on physiological response, plant water status and yield of soybean in calcareous soil. *Arch Agron Soil Sci*. 2016;63:827-840.
19. Epstein E, Bloom AJ. Mineral nutrition of plants: principles and perspectives. 2nd ed. Sunderland (MA): Sinauer Associates, Inc.; 2005.
20. Fianko JR, Donkor A, Lowor S, Yeboah P. Agrochemicals and the Ghanaian environment: a review. *Rev Environ Contam Toxicol*. 2011;215:1-25.
21. Geisseler D, Scow KM. Long-term effects of mineral fertilizers on soil microorganisms—a review. *Soil Biol Biochem*. 2014;75:54-63.
22. Glibert PM, Harrison J, Heil C, Seitzinger S. Escalating worldwide use of urea—a global change contributing to coastal eutrophication. *Biogeochemistry*. 2006;77(3):441-463.
23. Gomiero T, Pimentel D, Paoletti M. Environmental impact of different agricultural management practices: conventional vs. organic agriculture. *Crit Rev Plant Sci*. 2011;30(1-2):95-121.

24. Goulson D, Nicholls E, Botías C, Rotheray EL. Bee declines driven by combined stress from parasites, pesticides, and lack of flowers. *Science*. 2015;347(6229):1255-57.
25. Grossman K. Auxin herbicides: current status of mechanism and mode of action. *Pest Manag Sci*. 2010;66(2):113-120.
26. Grossman MR. Protecting health, environment and agriculture: authorisation of genetically modified crops and food in the United States and the European Union. *Deakin Law Rev*. 2009;14(2):257-304.
27. Hailong W, Magesan G, Bolan N. An overview of the environmental effects of land application of farm effluents. In: *Proceedings of the SuperSoil 2004: 3rd Australian New Zealand Soils Conference*; 2004 Dec 5-9; Sydney, Australia.
28. He B, Hu Y, Wang W, Yan W, Ye Y. The progress towards novel herbicide modes of action and targeted herbicide development. *Agronomy*. 2022;12(11):2792.
29. Huang J, Hu R, Pray C, Qiao F, Rozelle S. Biotechnology as an alternative to chemical pesticides: a case study of Bt cotton in China. *Agric Econ*. 2003;29(1):55-67.
30. Homayoonzadeh M, Moeini P, Talebi K, Roessner U, Hosseiniaveh V. Antioxidant system status of cucumber plants under pesticides treatment. *Acta Physiol Plant*. 2020;42(11):161.
31. Hughes JT, Tate KG. Dithiocarbamate spray residues on lettuces, tomatoes, berryfruits, and apples. *N Z J Exp Agric*. 1982;10(3):301-304.
32. Huseh AS, Groves RL. Environmental fate of soil applied neonicotinoid insecticides in an irrigated potato agroecosystem. *PLoS One*. 2014;9(5):e97081.
33. Jia Y, Kang L, Wu Y, Zhou C, Li D, Li J, *et al*. Review on pesticide abiotic stress over crop health and intervention by various biostimulants. *J Agric Food Chem*. 2023;71(37):13595-13611.
34. Kah M, Kookana RS, Gogos A, Bucheli TD. A critical evaluation of nanopesticides and nanofertilizers against their conventional analogues. *Nat Nanotechnol*. 2018;13(8):677-684.
35. Kelly VA, Morris M, Kopicki RJ, Byerlee D. Fertilizer use in African agriculture: lessons learned and good practice guidelines. Washington (DC): World Bank; 2007.
36. Khorshid MA, Hassan AF, Abd El-Gawad M, Enab AK. Effect of some plants and pesticides on acetylcholinesterase. *Am J Food Technol*. 2015;10:93-99.
37. Kosoe EA, Achana GT, Ogwu MC. Meta-evaluation of the one health implication on food systems of agrochemical use. In: Ogwu MC, Opute AP, Adekunle CO, editors. *One health implications of agrochemicals and their sustainable alternatives*. Singapore: Springer Nature Singapore; 2023. p. 387-409.
38. Kudsk P, Mathiassen SK. Pesticide regulation in the European Union and the glyphosate controversy. *Weed Sci*. 2020;68(3):214-222.
39. Kumari VV, Banerjee P, Verma VC, Sukumaran S, Chandran MAS, Gopinath KA, *et al*. Plant nutrition: an effective way to alleviate abiotic stress in agricultural crops. *Int J Mol Sci*. 2022;23(15):8519.
40. Liu N, Zhu L. Metabolomic and transcriptomic investigation of metabolic perturbations in *Oryza sativa* L. triggered by three pesticides. *Environ Sci Technol*. 2020;54(10):6115-6124.
41. Lowry GV, Avellan A, Gilbertson LM. Opportunities and challenges for nanotechnology in the agri-tech revolution. *Nat Nanotechnol*. 2019;14(6):517-522.
42. Marchand P. EU chemical plant protection products in 2023: current state and perspectives. *Agrochemicals*. 2023;2(1):106-117.
43. Mariyono J, Kuntariningsih A, Suswati E, Kompas T. Quantity and monetary value of agrochemical pollution from intensive farming in Indonesia. *Manag Environ Qual*. 2018.
44. Marschner H. Marschner's mineral nutrition of higher plants. London: Academic Press; 2012.
45. Matthews GA. Pesticides: health, safety and the environment. Chichester, UK: Wiley-Blackwell; 2015.
46. Mengel K, Kirkby EA, Kosegarten H, Appel T. The soil as a plant nutrient medium. In: Mengel K, Kirkby EA, editors. *Principles of plant nutrition*. Dordrecht: Springer Netherlands; 2001. p. 15-110.
47. Mengel K, Kirkby EA. *Principles of plant nutrition*. Dordrecht: Springer Netherlands; 2001.
48. Meena RS, Kumar S, Datta R, Lal R, Vijayakumar V, Brtnicky M, *et al*. Impact of agrochemicals on soil microbiota and management: a review. *Land*. 2020;9(2):34.
49. Noman M, Ahmed T, White JC, Wang J. Bioinspired smart microcarriers precisely deliver agrochemicals in plants. *Trends Plant Sci*. 2024.
50. Odewale SA, Odekanle EL, Fakinle BS. Global environmental sustainability and agrochemical use. In: Ogwu MC, Opute AP, Adekunle CO, editors. *One health implications of agrochemicals and their sustainable alternatives*. Singapore: Springer Nature Singapore; 2023. p. 735-764.
51. Pal A, Kaur P, Dwivedi N, Rookes J, Bohidar HB, Yang W, *et al*. Clay-nanocomposite based smart delivery systems: a promising tool for sustainable farming. *ACS Agric Sci Technol*. 2022;3(1):3-16.
52. Pascal-Lorber S, Letondor C, Liber Y, Jamin EL, Laurent F. Chlordecone transfer and distribution in maize shoots. *J Agric Food Chem*. 2016;64(2):409-415.
53. Pereira P, Bogunovic I, Inacio M, Zhao W, Barcelo D. Agriculture intensification impacts on soil and water ecosystem services. In: *EGU General Assembly Conference Abstracts*; 2023. p. EGU-1423.
54. Perrenoud S. Potassium and plant health. 2nd rev. ed. Basel, Switzerland: International Potash Institute; 1990.
55. Pretty J, Pervez Bharucha Z. Integrated pest management for sustainable intensification of agriculture in Asia and Africa. *Insects*. 2015;6(1):152-182.
56. Prasad MNV. Agrochemicals detection, treatment and remediation: pesticides and chemical fertilizers. Amsterdam: Elsevier; 2020.
57. Rani L, Thapa K, Kanojia N, Sharma N, Singh S, Grewal AS, *et al*. An extensive review on the consequences of chemical pesticides on human health and environment. *J Clean Prod*. 2021;283:124657.
58. Rasool N. Alleviating biotic stress. In: Hakeem KR, editor. *Plant hormones: recent advances, new perspectives and applications*. Amsterdam: Elsevier; 2022. p. 17.

59. Roberts TR, Hutson DH, Jewess PJ, Lee P, Nicholls PH. Metabolic pathways of agrochemicals, volume 2: insecticides and fungicides. Cambridge: Royal Society of Chemistry; 1999.
60. Russell PE. A century of fungicide evolution. *J Agric Sci.* 2005;143(1):11-25.
61. Sakr N. The role of silicon (Si) in increasing plant resistance against fungal diseases. *Hell Plant Prot J.* 2016;9:1-15.
62. Shabbir M, Singh M, Maiti S, Saha SK. Organophosphate pesticide (Chlorpyrifos): environmental menace; study reveals genotoxicity on plant and animal cells. *Environ Chall.* 2021;5:100313.
63. Shahid M, Singh UB, Khan MS. Metabolomics-based mechanistic insights into revealing the adverse effects of pesticides on plants: an interactive review. *Metabolites.* 2023;13(2):246.
64. Singh P, Prasad SM. Antioxidant enzyme responses to oxidative stress due to chlorpyrifos, dimethoate and dieldrin stress in palak (*Spinacia oleracea* L.) and their toxicity alleviation by soil amendments in tropical croplands. *Sci Total Environ.* 2018;630:839-848.
65. Subehia SK, Verma S, Sharma SP. Effect of long-term use of chemical fertilisers with and without organics on forms of soil acidity, phosphorus adsorption and crop yields in an acid soil. *J Indian Soc Soil Sci.* 2005;53(3):308-314.
66. Tschardtke T, Klein AM, Krüss A, Steffan-Dewenter I, Thies C. Landscape perspectives on agricultural intensification and biodiversity ecosystem service management. *Ecol Lett.* 2005;8(8):857-874.
67. Tudi M, Daniel Ruan H, Wang L, Lyu J, Sadler R, Connell D, *et al.* Agriculture development, pesticide application and its impact on the environment. *Int J Environ Res Public Health.* 2021;18(3):1112.
68. Van Bruggen AH, He MM, Shin K, Mai V, Jeong KC, Finckh MR, *et al.* Environmental and health effects of the herbicide glyphosate. *Sci Total Environ.* 2018;616:255-268.
69. Worthing CA, Hance RJ. The pesticide manual. 9th ed. Farnham, UK: British Crop Protection Council; 1991.
70. Zhang X, Davidson EA, Mauzerall DL, Searchinger TD, Dumas P, Shen Y. Managing nitrogen for sustainable development. *Nature.* 2015;528(7580):51-59.
71. Zhu W, Schmehl DR, Mullin CA, Frazier JL. Four common pesticides, their mixtures and a formulation solvent in the hive environment have high oral toxicity to honey bee larvae. *PLoS One.* 2014;9(1):e77547.