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Challenges and solutions of the mutual impacts between climate change and pesticides

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Abstract

This review article is presented under the major heading—Pesticides-Environment Mutual Impacts. It examines the bidirectional interactions between climate change and pesticide use in agricultural and environmental systems. Climate change has emerged as one of the most pressing global challenges, affecting ecosystems and disrupting weather patterns worldwide. Its impacts are global in scale and not confined to specific regions, often disproportionately affecting developing countries despite being largely driven by anthropogenic activities in developed nations. Pesticides contribute to climate change through greenhouse gas (GHG) emissions associated with their production, transport, application, degradation, and disposal. These contributions occur both directly and indirectly. Direct emissions arise from energy-intensive manufacturing processes and fumigant applications, which release considerable amounts of CO_2 and other GHGs into the atmosphere. Indirect effects occur through soil degradation that reduces carbon sequestration capacity and through environmental contamination that weakens natural climate-regulation services. Conversely, climate change strongly influences pesticide performance and environmental behavior. Temperature, precipitation patterns, and atmospheric CO_2 concentrations can influence pesticide degradation, reduce application efficiency, and enhance volatilization, runoff, and leaching under changing climate conditions. Furthermore, these conditions may promote the development of resistance in insects, weeds, and plant pathogens. In general, a reinforcing feedback loop exists in which pesticide use contributes to climate change, while climate change increases dependence on pesticides. To address these interconnected challenges, three complementary strategies, minimization, mitigation, and adaptation, must be implemented simultaneously at both national and international levels.

Keywords: Climate change, Pesticides, Agriculture, Environment, Challenges and solutions

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Introduction

Overview of climate change and pesticide use

Climate can be defined as the long-term pattern of average weather conditions that characterize local, regional, and global environments[1]. According to the United Nations Framework Convention on Climate Change (UNFCCC), climate change refers to long-term alterations in the climate system that are attributed directly or indirectly to human activities that modify the composition of the global atmosphere, in addition to natural climate variability[2,3]. These alterations are often manifested through increasing frequency and intensity of extreme weather events, such as droughts, floods, and heatwaves[4−6].

Developed countries are primarily responsible for greenhouse gas emissions driving climate change; however, their adverse impacts are disproportionately experienced by developing nations[7]. Climate change is not confined to specific regions, as its effects on agriculture in exporting countries influence global food security[8]. It directly and indirectly affects humans, plants, animals, and entire environmental systems[9].

Since the 1940s, the use of synthetic agrochemicals, including pesticides, has significantly increased to address food shortages and famines worldwide. Pesticide production grew from 0.2 million tons in the 1950s to approximately five million tons by 2000, with an annual growth rate of about 11%[10,11]. Consequently, there has been sustained pressure on the intensive use of pesticides. Pesticides encompass various chemical groups such as organophosphates, carbamates, pyrethroids, neonicotinoids, as well as fungicides and herbicides, each with different modes of action targeting specific organisms. However, their toxic effects are not limited to pests; they also impact non-target organisms, posing risks to biodiversity and ecosystems[10]. Pesticides control emerging pest pressures but also contribute to environmental contamination, human health risks, and, in some cases, the release of greenhouse gases during production and application[12−15]. This creates a complex feedback loop in which climate change influences pesticide dynamics and, conversely, pesticide use can exacerbate climate-related pressures.

Importance of studying the mutual impacts between climate change and pesticides

Despite extensive research on climate change and pesticide use individually, the bidirectional interactions between these two factors remain insufficiently synthesized in the literature. Climate change affects pesticide efficacy, environmental fate, and usage patterns, while pesticide production, formulation, and application contribute to greenhouse gas emissions and ecosystem disruption. This mutual relationship highlights the need for an integrated understanding of how climate change and pesticides influence each other within agricultural and environmental systems.

Understanding these interactions is essential for developing climate-resilient and sustainable pest management strategies, minimizing risks to human health, and protecting environmental quality. Furthermore, synthesizing current knowledge on this topic can provide valuable guidance for researchers, policymakers, and practitioners to address emerging challenges and implement effective mitigation and adaptation strategies.

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General climate change effects on agriculture and pests

Climate change influences agriculture, pests, and pesticide dynamics through multiple interacting factors. Rising temperatures, altered precipitation patterns, and elevated CO_2 concentrations directly affect crop productivity, pest abundance, and pesticide use[16,17].

Changes in temperature and rainfall can degrade arable land, reduce water availability, and affect crop growth cycles, impacting yields and food security[14,18−20]. Warmer temperatures and elevated CO_2 levels accelerate insect development, expand pest ranges, increase weed growth, and promote crop diseases, which often necessitate higher pesticide inputs[12,21,22].

Climate-driven changes in soil properties, pest dynamics, and crop distribution influence pesticide efficiency, environmental behavior, and overall usage[16]. Higher temperatures and rainfall variability increase volatilization, runoff, leaching, and microbial degradation, while elevated CO_2 can reduce uptake and effectiveness in plants[13,23]. However, increased atmospheric CO_2 levels can positively impact ecosystems by stimulating plant growth[24].

In general, climate change and pesticide use are closely interconnected, creating a feedback loop that impacts agriculture, ecosystems, and human health. This review aims to clarify these mutual interactions, highlighting key challenges, environmental risks, and potential strategies for sustainable management.

This review synthesizes the current knowledge on the bidirectional relationship between climate change and pesticide use, with a focus on how changing climatic conditions influence pesticide efficacy, environmental fate, and associated ecological and human health risks, as well as how pesticide production and application contribute to climate change. It is based on a comprehensive analysis of peer-reviewed scientific literature, international reports, and regulatory documents covering pesticide behavior, climate drivers, agricultural impacts, and environmental consequences. This review integrates evidence from multiple disciplines and highlights key knowledge gaps, emerging challenges, and practical strategies for minimization, mitigation, and adaptation. The findings provide valuable guidance for researchers, policymakers, and agricultural practitioners seeking to develop climate-resilient pest management systems, protect environmental quality, and safeguard public health under changing climatic conditions.

Method

This review examines the effects of climate change on pesticide dynamics and efficacy, contributing to the growing awareness of climate-related risks within the pesticide-environment system. A systematic literature search was conducted using Google Scholar, Web of Science, Scopus, ScienceDirect, and the Egyptian Knowledge Bank (EKB). The search covered publications from January 2001 to June 2025, and the final search was completed in June 2025 to ensure comprehensive coverage. Search filters were applied to include publications in English and document types such as research articles, review papers, reports, and policy documents.

The following Boolean search string was applied with minor adjustments depending on database syntax: ('climate change' OR 'global warming' OR 'climatic variability') AND ('pesticide' OR 'agrochemical' OR 'plant protection product') AND ('pesticide efficacy' OR 'pesticide degradation' OR 'environmental fate' OR 'runoff' OR 'leaching' OR 'volatilization' OR 'greenhouse gas emissions' OR 'carbon sequestration' OR 'pesticide resistance' OR 'climate–pesticide interaction').

A total of 400 records were identified through database searching. After removing 80 duplicate records, 320 unique articles remained for screening. These articles were screened based on title and abstract, resulting in 150 articles being excluded due to lack of relevance. The remaining 170 articles were assessed for full-text eligibility, of which 57 articles were excluded for reasons including insufficient relevance to climate–pesticide interactions, lack of environmental focus, or insufficient methodological detail. Finally, 113 articles met the inclusion criteria and were included in the review.

Data from selected studies were extracted into a structured database, including study location, pesticide type, analyzed climate factors, reported effects on pesticide behavior and efficacy, and key conclusions. Findings were synthesized qualitatively, and recurring trends were identified where applicable.

To ensure transparency, reproducibility, and methodological rigor, this review followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. PRISMA provides a standardized framework for systematic reviews, including clearly defined search strategies, eligibility criteria, study selection, and data extraction procedures. A PRISMA flowchart was developed to illustrate the study selection process, showing the number of records identified, duplicates removed, articles screened, full-text articles assessed, and studies included in the final review (Fig. 1). Additionally, a supplementary Excel file has been provided detailing the included and excluded studies, along with the reasons for exclusion (Supplementary Table S1). This approach ensures that the review process is transparent, reproducible, and clearly understandable.

This methodology provides a systematic, transparent, and reproducible approach, similar to the methodologies used in previous studies[24,25], to synthesize current knowledge on the interactions

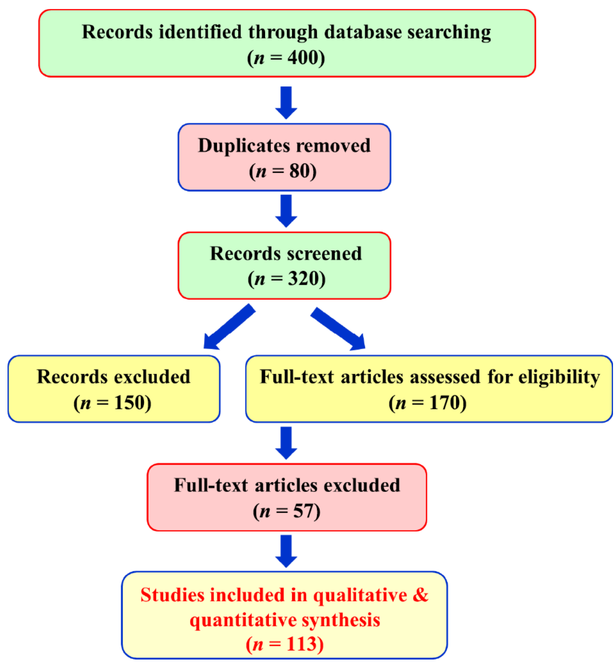

Fig. 1 PRISMA flow diagram of the literature screening and study selection process used in this systematic review. The diagram shows the number of records identified through database searching, duplicates removed, records screened based on titles and abstracts, full-text articles assessed for eligibility, and the final studies included in the review.

between climate change and pesticide use, enabling robust conclusions and identification of key knowledge gaps.

Main findings: challenges and solutions

Challenges of the mutual impacts between climate change and pesticides

Climate change alters soil conditions, crop distribution, pest pressure, and disease prevalence, which directly influence pesticide use patterns and application intensity[16]. These climatic shifts often lead to increased pesticide use and changes in their environmental persistence and behavior. As illustrated in Fig. 2, this creates a feedback loop between climate change, increased pest pressure, and rising pesticide dependence, intensifying environmental stress. At the same time, pesticide production, transportation, and application contribute significantly to greenhouse gas (GHG) emissions, fossil fuel consumption, and environmental degradation. Table 1 summarizes quantitative estimates of GHG emissions across the pesticide life cycle, while Table 2 presents soil and water contamination data associated with intensive pesticide use.

Challenges of the impacts of pesticides on climate change

Greenhouse gas emissions from pesticide production and use

Pesticides contribute to climate change through greenhouse gas (GHG) emissions across their entire life cycle, including production, transportation, application, degradation, and disposal[2,26,27]. Nearly 99% of synthetic chemicals, including pesticides, are derived from fossil fuels, making their production highly energy-intensive[28]. Although fertilizers often receive greater attention, pesticide manufacturing requires approximately ten times more energy per unit than fertilizer production[29]. In addition, fumigant pesticides release GHGs after application, further contributing to atmospheric emissions[30,31].

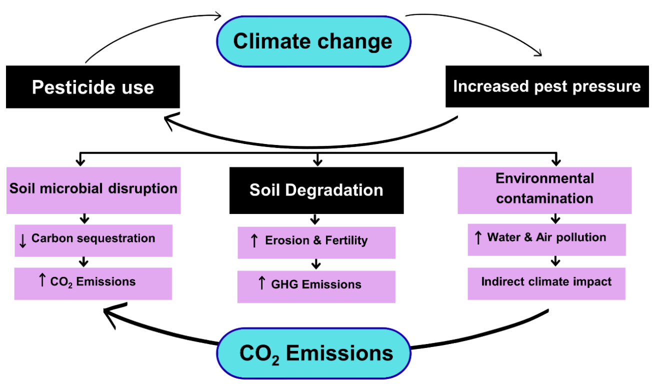

Fig. 2 Flowchart showing the feedback loop between pesticide use and climate change, highlighting how climate change affects pesticide application and how pesticides contribute to environmental impacts that may further intensify climate change.

Table 1. Estimated ranges of greenhouse gas (GHG) emissions associated with pesticide life-cycle stages, compiled from published life-cycle assessments and regulatory reports.

Life-cycle stage	CO_2-equivalent (kg CO_2e/kg pesticide)	Description/source
Production	4–10	Energy-intensive, 99% from fossil fuels[28,29]
Transportation	0.2–0.5	Fuel emissions during distribution[27]
Application and degradation	0.5–2	Fumigant emissions and degradation in field[30,31]
Total	4.7–12.5	Sum of all stages

As shown in Table 1, pesticide-related activities can account for up to 10%–20% of total agricultural GHG emissions in some production systems, highlighting the substantial climate burden associated with pesticide use. These emissions intensify global warming, increase atmospheric CO_2 concentrations, and undermine climate mitigation efforts. Reported GHG emission values for pesticides vary widely depending on compound, formulation, and production technology. Therefore, the ranges presented represent synthesized estimates derived from multiple life-cycle assessment studies and regulatory sources rather than single-point measurements (Table 1).

Soil degradation and reduced carbon sequestration

Intensive pesticide use negatively affects soil health by disrupting microbial communities responsible for organic matter decomposition and nutrient cycling. These soil microorganisms play a crucial role in carbon sequestration by stabilizing organic carbon within soil matrices and maintaining soil ecosystem functions. Pesticide-induced imbalances in soil microbial communities can reduce the soil's capacity to store carbon, leading to increased CO_2 release into the atmosphere[32]. In addition, repeated pesticide applications may degrade soil structure, enhance erosion, and reduce soil fertility, thereby weakening the soil's capacity to function as a long-term carbon sink (Fig. 2). This figure illustrates how soil degradation and diminished carbon storage can create a feedback mechanism that amplifies climate change processes.

Environmental contamination

Pesticide residues contaminate air, water, and soil ecosystems, contributing indirectly to climate change–related processes. Runoff and leaching transport pesticides into aquatic environments, where they disrupt biological functions and reduce ecosystem resilience to climate stressors. In addition, the volatilization of pesticides into the atmosphere contributes to air pollution and may interact with atmospheric chemistry, thereby influencing climate-related processes[2]. Persistent pesticide contamination also leads to biodiversity loss, weakening natural climate regulation services such as carbon cycling, vegetation stability, and ecosystem recovery.

The feedback mechanism linking environmental contamination, ecosystem degradation, and increased greenhouse gas (GHG) emissions is illustrated in Fig. 2. Mean concentrations of commonly used pesticides in soil and water demonstrate the widespread environmental contamination associated with agricultural pesticide use (Table 2). Compounds such as glyphosate, atrazine, chlorpyrifos, and fipronil were consistently detected in both matrices, indicating their persistence and potential ecological risks[2,16,26,27]. Reported pesticide residue levels vary widely depending on region, crop type, and sampling conditions; therefore, the values presented in the table represent representative means synthesized from multiple monitoring studies.

Table 2. Representative mean concentrations of selected pesticide residues in soil and water, compiled from monitoring studies.

Pesticide	Soil concentration (mg/kg)	Water concentration (µg/L)	Ref.
Glyphosate	0.15	0.8	[2,93,94]
Chlorpyrifos	0.05	0.4	[16,95,96]
Atrazine	0.12	1.2	[27,97]
Fipronil	0.08	0.5	[26,98]
Malathion	— (low-ppb ranges)	0.3	[99,100]

Challenges of climate change on pesticides

Climate change significantly influences the timing, rate, and methods of pesticide application, as well as pesticide efficiency and environmental fate, potentially leading to contamination and adverse effects on human and ecosystem health[2]. These impacts result in increased pesticide use, higher production demands, and greater environmental pollution. Pesticides disperse through air currents, runoff, leaching, and absorption by plants, animals, and humans. Furthermore, socioeconomic and environmental factors such as soil conditions, crop growth, and pest dynamics, which are also affected by climate change, modulate pesticide application patterns[16]. Tables 3–4 and Fig. 3 summarize key quantitative data supporting these challenges.

Effect of pesticide efficiency

Pesticide efficiency, defined as the ability of a pesticide to control target pests effectively, depends on multiple factors, including pest species, pesticide formulation, application methods, and environmental conditions[6,33]. Climate change significantly influences these factors by altering pest dynamics, distribution, and behavior, which directly impacts pesticide performance. Rising temperatures and shifting precipitation patterns expand the geographic range of pests, enhance overwintering survival, and modify interactions between pests, crops, and natural enemies[34]. These climatic shifts often reduce the effectiveness of biological control agents, leading to increased reliance on chemical pesticides[35]. Prolonged and repeated pesticide use further accelerates resistance development in pests, pathogens, and weeds, thereby diminishing efficacy over time[2,6,34,36,37]. Climate change also intensifies pest outbreaks, crop diseases, and herbicide-tolerant weeds[38−40], which may require higher pesticide dosages to maintain effective control[6,41]. Temperature extremes have dual effects on pesticide performance. Elevated temperatures can enhance pesticide toxicity for some compounds[42], while simultaneously accelerating degradation rates, which reduces field efficacy[43]. For example, organophosphates, carbamates, synthetic pyrethroids, and sulfonylurea herbicides undergo faster hydrolysis at higher temperatures[44]. Moreover, hot and dry conditions increase spray evaporation, further decreasing pesticide effectiveness[34]. High temperatures can alter weed physiology and pesticide performance, potentially reducing herbicide effectiveness under climate stress conditions. For example, glyphosate shows reduced effectiveness under climate stress[23]; atrazine and malathion degrade faster at higher temperatures[13,45]; chlorpyrifos has shorter persistence in warm conditions[12]; and fipronil exhibits temperature-dependent toxicity[46]. Additionally, several studies indicate that higher temperatures accelerate pesticide degradation and reduce field persistence, which can lower control efficacy[12,13,45].

Table 3. Climate change-driven pesticide resistance development.

Pest type	Pesticide	Observed trend	Ref.
Insects	Chlorpyrifos	Reduced efficacy and higher resistance under warming	[12]
Insects	Fipronil	Increased toxicity variability with temperature	[46]
Pathogens	Mancozeb	Reduced fungicide sensitivity under climate stress	[101]
Weeds	Glyphosate	Increased resistance risk under elevated CO_2	[23]

Increased pesticide resistance and usage

Climate change is expected to drive increased pesticide use due to rising temperatures, shifting rainfall patterns, and declining crop resilience. Drought conditions weaken plant defenses, making crops more susceptible to pests, while higher temperatures encourage insect population growth and expansion into new regions[16,17,47]. Weeds, often more adaptable to climate change than crops, will compete more aggressively for light, nutrients, and water, further reducing yields and necessitating additional pesticide applications[16]. As a result, global pesticide application rates are projected to increase[43]. Warmer temperatures and drought not only amplify pest pressures but also disrupt natural predator populations, requiring more frequent chemical interventions. Simultaneously, elevated temperatures accelerate pesticide degradation, reducing the duration of efficacy and compelling farmers to increase application frequency or dosage[2]. Changes in climate will also influence agricultural practices and pest management strategies, emphasizing the need for adaptive approaches. Climate-driven increases in pesticide usage may accelerate resistance in key pest types, including insects, weeds, and pathogens, highlighting the urgent need for integrated pest management and rotation strategies (Table 3).

Effect on pesticide dynamics and environmental fate

Climate change significantly affects the fate, behavior, and toxicity of pesticides[6,48−50]. However, research on climate change's impact on pesticide fate and transport remains limited[17]. Rainfall seasonality, intensity, and temperature fluctuations complicate pesticide behavior predictions. Increased precipitation will likely elevate pesticide runoff into waterways, while excessive rain could exacerbate pesticide leaching into groundwater[51]. Rising temperatures enhance pesticide volatilization, causing atmospheric pollution and health risks for agricultural workers and surrounding communities[28]. Many pesticides transition from soil and surface

Table 4. Effects of climate change stress on pesticide impacts in different ecosystems.

Pesticide/group	Ecosystem	Impact indicator affected by climate stress	Evidence-based source
Chlorpyrifos and other pesticides	Aquatic	Temperature–pesticide interactions alter toxicity (toxicity may increase or change with warming)	Systematic evidence that pesticide toxicity changes with temperature increase, influencing aquatic organisms' responses to contaminants[102−104].
Multiple pesticides (glyphosate, atrazine)	Soil	Altered soil microbial community functions and enzymatic activity	Pesticide exposure affects soil carbon cycling and enzyme activity, indicating impacts on microbial processes tied to organic carbon dynamics[105−107].
Mixed pesticides (atrazine, metolachlor)	Aquatic	Combined high temperature and pesticide exposure increase oxidative stress and tissue damage	Elevated temperature combined with pesticides causes greater biological stress in fish, showing interaction effects on organism health[108,109].
General pesticide classes	Aquatic & soil	Increased organism vulnerability under warming conditions (e.g., higher uptake, altered tolerance)	Reviews show that rising temperatures and acidification can increase pesticide effects on aquatic biota and make organisms more vulnerable[43,104,110].
Herbicides and insecticides	Aquatic & soil	Microbial community disruption and changes in diversity under pesticide exposure	Multiple pesticides (including herbicides and insecticides like malathion) have been shown to reduce microbial community diversity and alter ecosystem function[111−113].

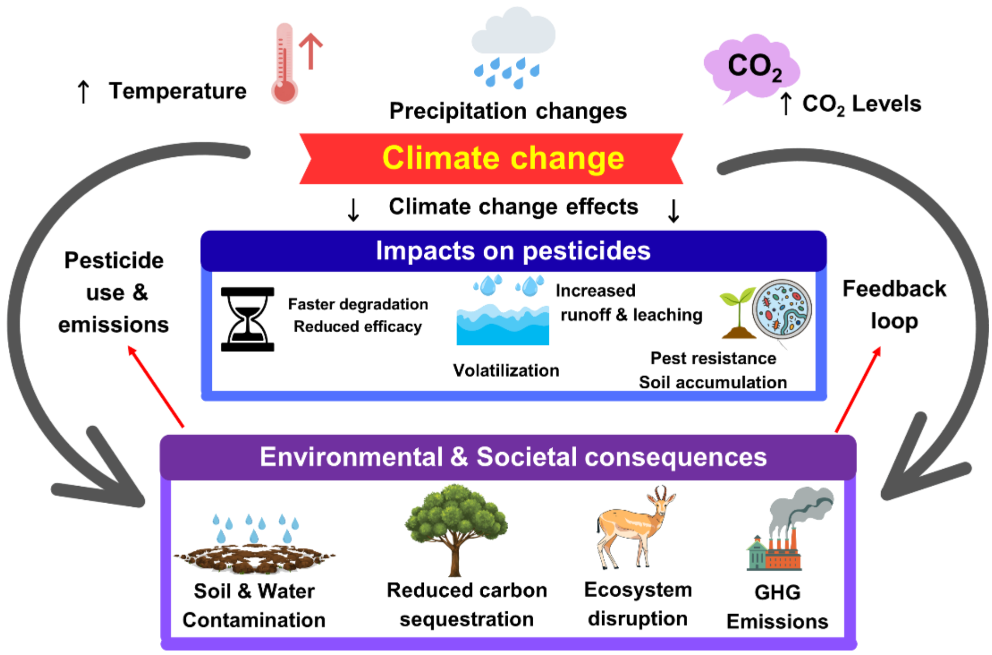

Fig. 3 Flowchart showing the feedback loop of climate change effects on pesticide dynamics, including changes in pesticide behavior, environmental fate, and potential impacts on ecosystems.

water into the air, with cumulative volatilization losses reaching up to 50% of the applied dose[52]. Wind speed, soil moisture, and temperature further influence volatilization rates[53]. Although increased volatilization reduces pesticide residue in soils, it increases air pollution and non-target exposure risks.

Soil properties also affect pesticide transport and persistence[54]. Warmer temperatures enhance chemical uptake and translocation in plant tissues[55,56]. There is a correlation between pesticide sorption and soil-bound residues, with stronger sorption reducing bioavailability[57−60]. Rainfall events replace soil water, prompting pesticide desorption and increasing contamination risks[61]. Pesticide losses can exceed European Union Drinking Water Directive limits (98/83/EC), with runoff events promoting soil erosion and contaminant transport[62,63]. Increased rainfall accelerates pesticide movement into drainage systems and surface waters, particularly during heavy storms[64]. Conversely, reduced rainfall and prolonged droughts minimize pesticide runoff but enhance soil cracking, allowing deeper pesticide infiltration and increasing groundwater contamination risks[17]. Dry conditions also inhibit pesticide biodegradation, extending residue persistence and environmental impact potential[6,33]. Elevated temperatures accelerate pesticide degradation across soil, vegetation, water, and air matrices[65,66]. Half-life reductions of approximately 60% per 10 °C increase in temperature have been observed[67,68]. Additionally, higher concentrations of hydroxyl radicals enhance atmospheric pesticide breakdown, altering the spatial and temporal distribution of airborne pesticide residues[17,69]. As shown in Table 2, climate change-driven shifts in temperature and precipitation not only affect pesticide efficacy and resistance but also increase environmental contamination, with glyphosate, atrazine, chlorpyrifos, fipronil, and malathion detected in both soil and water matrices.

Effect on pesticide impact

Climate change increases pesticide movement away from intended targets, amplifying environmental contamination risks. This includes potential exposure to agricultural workers through inhalation or dermal contact, as well as contamination of terrestrial and aquatic ecosystems[42,43,70]. Rising temperatures and altered environmental conditions can enhance pesticide bioavailability and toxicity in wildlife, increasing ecological risks[51,71−74]. The effects of climate change on pesticide risks in aquatic ecosystems remain inconclusive. Some studies suggest that climate change may elevate pesticide toxicity, increasing negative impacts on aquatic organisms[48,49,75], while other research indicates that enhanced biodegradation under warmer or altered conditions could mitigate these effects[37,76].

In general, climate change not only affects pesticide efficiency and resistance but also intensifies their ecological impacts. Elevated temperatures, altered precipitation, and extreme weather events can increase pesticide toxicity, persistence, and bioaccumulation while disrupting soil microbial activity and organic carbon dynamics. These changes pose serious risks to aquatic and terrestrial ecosystems, illustrating how climate stress modifies key impact indicators for commonly used pesticides (Table 4). Additionally, a visual summary of the feedback loop linking climate change, increased pesticide dependence, resistance development, altered dynamics, and environmental contamination highlights the compound effects of climate stress on agricultural systems (Fig. 3).

Strategies for addressing climate change

Climate change can be addressed through three key strategies (Fig. 4): minimization, mitigation, and adaptation. The minimization strategy focuses on reducing climate change by controlling its causes. The mitigation strategy aims to lessen the impacts of climate change, while the adaptation strategy involves adjusting to climate-related changes. Implementing a single strategy is insufficient; instead, these strategies must be applied in parallel at both national and international levels[25].

Minimization

The adoption of international agreements, such as the Paris Agreement reached at COP-21 on December 12, 2015, is crucial to accelerating actions toward a sustainable low-carbon future[25,77−79].

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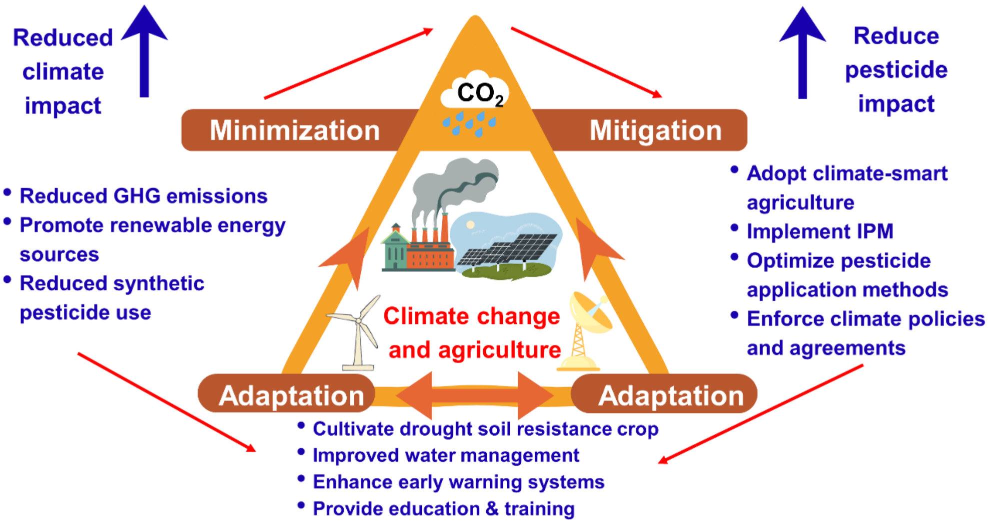

Fig. 4 Flowchart showing strategies for addressing climate change and pesticide impacts, including minimization, mitigation, and adaptation approaches.

A global transition to renewable energy must be prioritized[25,80,81]. Greenhouse gas emissions must be urgently controlled to mitigate climate change. Prioritizing renewable, environmentally friendly energy sources over fossil fuels is essential[82]. All nations, both developed and developing, should implement CO_2-free energy production and adopt eco-friendly transportation alternatives such as compressed natural gas (CNG), electric vehicles, solar-powered vehicles, and ethanol-based fuels[24].

Reducing GHG levels is crucial for protecting agriculture and ecosystems. Climate change solutions should include using organic fertilizers, reducing synthetic pesticide application, and implementing integrated pest management (IPM). Efforts to slow deforestation, reclaim and afforest degraded lands, and enhance soil organic matter through beneficial microbes will help sequester CO_2 and lower GHG emissions[83]. Since agriculture significantly contributes to anthropogenic global warming, reducing agricultural emissions, including methane, nitrous oxide, and CO_2, is vital for climate change mitigation[3,84].

Mitigation

Future climate strategies must integrate computational simulations based on field data to assess climate impacts across different agro-ecological zones[83]. Regional studies are necessary to understand localized climate change effects[85]. International protocols, agreements, and initiatives should be effectively upheld[6,86]. Further research is needed to develop environmentally friendly pest control methods[87]. Governments and local communities must actively contribute to mitigating climate change impacts on pesticide efficacy.

Mitigating climate change effects requires various actions, such as adopting climate-smart agriculture in alignment with FAO's vision. This includes changing crop cultivars, modifying sowing times, utilizing biofertilizers and biopesticides, and developing alternative agricultural systems. New crop species should be introduced, and synthetic agrochemical use, including fertilizers and pesticides, should be minimized or eliminated through IPM practices[22,88–90]. Additionally, optimizing pesticide application techniques can reduce environmental impacts[91].

Adaptation

Adaptation strategies involve modifying human behaviors to cope with inevitable climate change. Measures include water conservation, cultivating drought- and salt-resistant crops, hydroponics, constructing rainwater storage systems, and reinforcing protective leaves in coastal regions[9]. Action is also required in production trends, consumption habits, education, and research[82]. Farmers should be educated on the potential impacts of climate change on agricultural systems, pests, and pesticide use. Policies should offer technical support and incentives to encourage sustainable farming practices that protect communities and ecosystems. Weather monitoring and forecasting systems should be enhanced to provide early warnings[90].

Technological advancements, such as seawater desalination for agriculture and new irrigation techniques, can aid adaptation, though they may introduce additional environmental costs[92]. Sustainable farming systems must be prioritized, transitioning from conventional to organic and agroecological farming methods[6,87]. In modern agriculture, innovative pest management approaches are emerging to reduce reliance on synthetic pesticides. These include developing genetically modified crops that produce specific insecticides or exhibit resistance to broad-spectrum herbicides, reducing pesticide use, and minimizing environmental harm.

Conclusions

This review demonstrates that pesticide use plays a significant role in driving climate change. The emissions of greenhouse gases from pesticide manufacturing, transportation, and application contribute directly to global warming. In addition, intensive pesticide use degrades soil health, disrupts microbial communities, and reduces soil carbon sequestration, weakening the soil's role as a carbon sink. Environmental contamination of air, water, and soil further impairs ecosystem stability and climate regulation services. At the same time, climate change strongly affects pesticide efficacy, behavior, and usage patterns. Rising temperatures, altered precipitation regimes, and elevated CO_2 levels accelerate pesticide degradation, enhance volatilization, runoff, and leaching, and promote resistance development in insects, weeds, and pathogens. These changes reduce pesticide effectiveness, increase application frequency, and intensify environmental contamination.

Together, these processes create a self-reinforcing feedback loop in which pesticides contribute to climate change, while climate change increases pesticide dependence. This mutual interaction represents a critical challenge for sustainable agriculture, food security, and environmental protection. Addressing these challenges requires the parallel implementation of minimization (controlling emission sources), mitigation (reducing climate and pesticide impacts), and adaptation (adjusting agricultural practices) at both national and international levels. Climate-smart agriculture, sustainable pesticide use, and integrated pest management (IPM) are essential to reduce environmental risks, limit resistance development, and maintain pest control efficacy under changing climatic conditions.

Future research should prioritize field-based quantification of climate-pesticide interactions, long-term modeling of feedback mechanisms, and the development of environmentally friendly and low-emission pest control alternatives. In addition, greater emphasis is needed on pesticide resistance evolution under climate stress, impacts on soil carbon sequestration, and combined effects on non-target organisms and ecosystem services. Integrating socio-economic analyses and policy-oriented research will further support climate-resilient pest management, protect human health, and guide evidence-based decision-making in agricultural systems.

Ethical statements

Not applicable.

Author contributions

The author confirms sole responsibility for all aspects of this study and approved the final version of the manuscript.

Data availability

All data generated during this study are included in this published article. The author is responsible for correcting the statements provided in the manuscript.

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The author has no relevant financial or non-financial interests to disclose.

Conflict of interest

The author has no competing interests to declare that are relevant to the content of this article.

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