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AGROCHEMICAL STRESSORS ON CROP REPRODUCTIVE HEALTH: PESTICIDE AND HEAVY METAL IMPACTS AND SUSTAINABLE MANAGEMENT PATHWAYS

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Abstract: The widespread use of pesticides in agriculture has raised concerns about their unintended effects on crop reproductive success and long-term sustainability. Reproductive organs, particularly pollen grains, are highly sensitive to pesticide-induced stress, yet limited studies have examined this issue in mustard (*Brassica juncea*), a major oilseed crop in India. Excessive pesticide uses and associated heavy metal contamination act as major agrochemical stressors in crop systems. These inputs trigger primary stress pathways, including reactive oxygen species (ROS) overproduction, nutrient disruption, enzyme dysfunction, and hormonal imbalance. Such disturbances impair reproductive processes, leading to reduced pollen viability, inhibited germination, structural abnormalities in pollen, flower damage, and lower seed set. The cumulative outcomes manifest as yield reduction, decline in crop quality, accumulation of toxic residues in the food chain, and risks to biodiversity. To mitigate these impacts, a combination of Integrated Pest Management (IPM), cultural practices, physical and mechanical controls, biological agents, biopesticides, and plant growth regulators (PGRs) offers a sustainable pathway to protect crop reproduction and maintain agricultural productivity under agrochemical stress. Given the heavy reliance on pesticides in mustard cultivation, such reproductive impairments pose risks not only to crop yield and quality but also indirectly to pollinator-derived byproducts such as honey. This review, together with our preliminary experimental findings on pollen abnormalities in *B. juncea*, highlights the urgent need for further investigations into combined pesticide effects, soil parameters, and molecular responses, as well as the adoption of integrated management strategies and stress-mitigation approaches for sustainable agriculture.

Keywords: Pesticide stress, Pollen viability, Reproductive traits, Oxidative stress, Integrated pest management

INTRODUCTION

Agrochemicals, particularly pesticides, play a critical role in modern agriculture by protecting crops from pests, pathogens, and weeds, thereby enhancing yield and productivity. However, the increasing dependence on chemical pesticides has raised major concerns about their unintended impacts on plant health, ecosystems, and food safety (Alengebawy *et al.*, 2021). Excessive application of pesticides imposes abiotic stress on plants, triggering a cascade of harmful effects at physiological, biochemical, and molecular levels (Sharma *et al.*, 2020). Under pesticide-induced stress, plants experience alterations in metabolism that compromise growth, development, and reproductive success (Shahid *et al.*, 2024). Key physiological processes such as photosynthesis, respiration, and nutrient uptake are disrupted, while tissues including roots, stems, leaves, and flowers—the reproductive organs essential for pollination and yield—are particularly vulnerable (Dubey *et al.*, 2020).

One major mechanism of pesticide toxicity is the overproduction of reactive oxygen species (ROS). Elevated ROS levels damage lipids, proteins, and DNA, leading to oxidative stress and reduced plant resilience (Sharma *et al.*, 2017). Pesticides also interfere with nutrient acquisition and translocation, creating deficiencies in essential elements such as nitrogen, potassium, and phosphorus. In addition, many pesticide formulations, especially older ones, contain heavy metal contaminants such as lead (Pb), cadmium (Cd), arsenic (As), and mercury (Hg), which can accumulate in plant tissues through root uptake (Sandeep *et al.*, 2019).

Heavy metal contamination poses dual risks—direct threats to human health via the food chain and indirect impacts on plant physiology. Within plants, metals disrupt enzyme activity, alter nutrient transport, and induce toxicity in reproductive organs such as flowers (Kumar *et al.*, 2022). These effects manifest as reduced fertility, impaired seed development, and lower yields (Sinha *et al.*, 2021) For example, cadmium disrupts photosynthesis and nutrient balance, often accumulating in high concentrations in crops grown under long-term pesticide use (Haider *et al.*, 2021), while lead destabilizes cell membranes and interferes with enzyme functions, thereby impairing growth and reproduction (Zulfiqar *et al.*, 2019). Among plant

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organs, flowers are especially sensitive to agrochemical stress. Pesticide exposure can disrupt pollen production, viability, germination, and fertilization (Hashimi *et al.*, 2020). Flowers subjected to pesticide overuse often exhibit reduced pollen viability, delayed stigma receptivity, and lower seed set, ultimately leading to poor fruit quality and decreased agricultural productivity (Gillespie *et al.*, 2014). Specific chemicals such as chlorpyrifos and other organophosphates have been shown to significantly reduce pollen viability and seed production (Koch *et al.*, 2018), while certain herbicides alter flower morphology and reduce flowering rates, further impairing reproductive success (Golt & Wood, 2021).

Taken together, pesticides and associated heavy metal contamination act as major agrochemical stressors that compromise plant reproductive health. Since reproduction is central to both crop yield and quality, understanding these impacts is critical for developing sustainable agricultural practices. This review synthesizes current knowledge on pesticide- and heavy metal-induced stress in crops, with a focus on their effects on reproductive traits, particularly pollen viability and morphology, while also highlighting management strategies and future research needs.

MATERIALS AND METHODS

This study comprised two complementary components to address the overarching objective of understanding pesticide-induced reproductive stress in crops.

(a) a systematic literature review examining the effects of pesticide- and heavy metal-induced stress on the reproductive traits of agricultural crops, and

(b) a preliminary experimental investigation evaluating the effects of pesticide exposure on pollen viability and morphology in mustard (*Brassica juncea* L.).

Systematic Literature Review

This review was conducted by systematically gathering and analyzing published studies related to pesticide- and heavy metal-induced stress in agricultural crops, with a particular emphasis on their effects on reproductive traits. Literature searches were carried out using databases including Web of Science, Scopus, PubMed, Science Direct, and Google Scholar. The primary keywords and their combinations were: pesticide stress, plant reproduction, pollen viability, pollen morphology, oxidative stress in crops, heavy metal accumulation in plants, and agrochemical impacts on yield.

Inclusion and Exclusion Criteria

Studies were included if they met at least one of the following criteria:

1. Investigated the physiological, biochemical, or molecular impacts of pesticides on crops.
2. Reported reproductive traits such as pollen viability, germination, morphology, seed set, or yield under pesticide or heavy metal stress.
3. Documented heavy metal accumulation in plant tissues, flowers, pollen, or crop products linked to pesticide application or soil contamination.
4. Discussed mitigation approaches such as integrated pest management (IPM), plant growth regulators (PGRs), biological control, or biopesticides.

Review articles, original research papers, and relevant book chapters published between 1990 and 2024 were considered. Studies not directly related to crop reproductive traits or agrochemical stress were excluded.

Data Extraction and Organization

Relevant information was extracted from each study, including: Crop species studied, Type of pesticide or heavy metal, Reproductive or physiological parameter assessed (e.g., pollen viability, ROS activity, enzyme function), and Reported outcomes and mechanisms.

Experimental Investigation

Field sampling was conducted in three agricultural sites located in Nadia District, West Bengal, India. Flowering mustard (Brassica juncea) plants were collected from both pesticide-treated and untreated (control) fields. Treated plots received Cypermethrin 25% EC and Chlorpyriphos 50% EC (approximately 5 mL/L each), while control plots were pesticide-free.

Pollen Sample Preparation and Staining:

Anthers from freshly opened flowers of treated and untreated plants were incubated in distilled water for 24 hours at room temperature. Pollen grains were separated using a 100 µm copper mesh and stained with 1% aqueous aniline blue and 1% acetocarmine solutions. After 5–6 hours, stained samples were mounted on slides and examined under a Leitz Laborlux Microscope fitted with an E3 Scientific Camera. Pollen viability and morphological abnormalities were assessed following standard cytological procedures.

Statistical Analysis:

Pollen viability, abnormality frequency, and equatorial diameter were compared between treated and control samples using one-way ANOVA at a 0.05 probability level ($p \leq 0.05$) to determine statistically significant differences.

Integration with Review Findings:

The experimental results complemented the systematic review by providing preliminary field-based validation of pesticide-induced effects on crop reproductive traits. Together, the review and experimental analyses offer an integrated framework for understanding and further investigating pesticide-related reproductive impairments in crops under varying agroecological conditions.

RESULTS

Pesticidal effects on reproductive traits of crops

Reproductive traits such as pollen viability, germination, tube elongation, ovule fertilization, seed set, and fruit development are particularly sensitive to pesticide exposure. Fungicides, insecticides, and herbicides have all been implicated in disrupting male gametophyte function, causing pollen deformities, reducing fertilization efficiency, and ultimately lowering seed and fruit yield (Table 1). At the physiological level, pesticides trigger oxidative stress, alter hormone signalling, and disrupt nutrient uptake, which collectively impair reproductive capacity. Structurally, they can damage pollen grains and tubes, while biochemically, they induce imbalances in antioxidant defences and membrane stability. These impacts not only reduce reproductive success but also pose long-term risks to crop productivity, biodiversity, and agricultural sustainability. Understanding these effects is therefore essential for balancing crop protection with the preservation of reproductive health in plants.

Table 1. Pesticide effects on pollen viability, germination, and abnormalities across different crops

Crop (Scientific name)	Pesticide(s)	Reproductive trait studied	Reported effects	Reference
Maize (*Zea mays*)	Pyraclostrobin + Epoxiconazole (fungicides)	Pollen viability & germination	Significant reduction in viability and germination; impaired pollen tube growth	Junqueira *et al.*, 2017
Blackberry (*Rubus armeniacus*)	Chlorothalonil, Pyraclostrobin, Benzimidazole	Pollen germination	Reduced germination frequency	Padilla *et al.*, 2017
Tree tomato (*Solanum betaceum*)	Chlorothalonil, Copper hydroxide, Pyraclostrobin, Epoxiconazole, Mancozeb, etc.	Pollen morphology	Deformation, abnormal pollen tube shapes, disintegration of grains	Padilla *et al.*, 2017
Dyer's woad (*Isatis tinctoria*)	2,4-D (herbicide), Ethephon (growth regulator)	Pollen viability	Reduced number of viable pollen grains due to hormonal disruption	Asghari *et al.*, 2000
Blackberry (*Rubus armeniacus*)	Mycob, Bitertanol, Kripton, Milsana	Pollen morphology	Abnormal pollen tube elongation, ruptured grains	Padilla *et al.*, 2017
Mustard (*Brassica juncea*)	Cypermethrin, Imidacloprid (insecticides)	Physiological stress markers	Increased proline, lipid peroxidation, altered antioxidant enzyme activities, reduced mineral uptake	Bashir & Jan, 2015; Ramzan *et al.*, 2022
Rapeseed (*Brassica napus*)	Napropamide (herbicide)	Antioxidant enzyme activities	Increased catalase, peroxidase, SOD, GST activity → oxidative stress defense	Sachdev *et al.*, 2021
Maize (*Zea mays*)	Atrazine (herbicide)	Lipid peroxidation (oxidative stress marker)	Elevated lipid peroxidation, indicating ROS damage	Bibi *et al.*, 2019
Sunflower (*Helianthus annuus*)	Cypermethrin (insecticide)	Proline accumulation (stress biomarker)	Increased proline → adaptive response to pesticide stress	Ramzan *et al.*, 2022
Tomato (*Solanum lycopersicum*)	Emamectin benzoate, Alpha-cypermethrin, Imidacloprid	Antioxidant enzymes (SOD, CAT, POD)	Enhanced enzyme activity due to ROS production under stress	Shakir *et al.*, 2018

Pollen viability and germination

Pollen viability and germination are fundamental to the reproductive success of flowering plants, as they determine the ability of pollen grains to fertilize ovules and ensure seed set. However, growing evidence indicates that pesticide applications, while protecting crops from pests and diseases, can have unintended detrimental effects on these reproductive processes across diverse plant species. In maize (*Zea mays*), exposure to the fungicides pyraclostrobin (a strobilurin) and epoxiconazole (a triazole) led to marked reductions in both pollen viability and germination. Viability was tested using 1% acetocarmine staining, whereas germination was evaluated on artificial media enriched with sucrose, boron, $Ca(NO_3)_2$, and KNO_3. The observed decline points to disruption of pollen metabolic activity and tube initiation, which are essential for successful fertilization. Such impairments may translate into reduced fertility and lower grain yield, highlighting the trade-off between disease control and reproductive performance (Junqueira *et al.*, 2017). Similarly, in blackberry (*Rubus armeniacus*) and tree tomato (*Solanum betaceum*), fungicides including chlorothalonil, pyraclostrobin, and benzimidazole significantly suppressed pollen germination *in vitro*. Experiments using sucrose- and boric acid-enriched media showed clear inhibition of pollen tube elongation, a process vital for sperm delivery to the ovule. This interference suggests that fungicidal residues may compromise fertilization efficiency and fruit set, thereby reducing reproductive success in these crops (Padilla *et al.*, 2017). In dyer's woad (*Isatis tinctoria*), treatment with the herbicide 2,4-D and the growth regulator ethephon resulted in fewer viable pollen grains, as determined by acetocarmine staining. These chemicals likely disturb the delicate hormonal balance required for proper pollen development and maturation. By impairing pollen formation at an early stage, they can substantially reduce the plant's reproductive capacity (Asghari, 2000). As such, the evidence indicates that pesticides, while serving as important crop protection tools, can negatively impact male gametophyte function. The disruption of pollen viability and germination not only lowers immediate fertilization success but may also have long-term consequences for crop yield, quality, and sustainability.

Pollen abnormalities and structural damage

In addition to reducing viability and germination rates, pesticides can also cause profound structural abnormalities in pollen grains and pollen tubes, further impairing reproductive success. In blackberry (*Rubus armeniacus*), exposure to fungicides such as Mycob, Bitertanol, Kripton, and Milsana led to abnormal pollen tube elongation, deformation, and frequent rupture. Scanning electron microscopy (SEM) revealed extensive damage to pollen structure, including compromised grain integrity and surface collapse. Such defects hinder pollen tube penetration and ovule fertilization, thereby reducing the likelihood of successful seed formation (Padilla *et al.*, 2017). Similarly, in tree tomato (*Solanum betaceum*), a wide range of pesticides—including chlorothalonil, copper hydroxide, pyraclostrobin, epoxiconazole, and mancozeb—induced pronounced abnormalities in pollen morphology. Observed effects included grain deformation, cytoplasmic disintegration, and irregular or collapsed shapes. These structural alterations not only impair pollen functionality but also interfere with pollen-stigma interactions and pollen tube growth, ultimately leading to reduced fertilization efficiency and lower fruit set (Padilla *et al.*, 2017). These findings emphasize that pesticide exposure does not merely reduce pollen viability but can also cause direct physical damage at both the cellular and subcellular levels. Such abnormalities compromise the structural and functional integrity of male gametophytes, with cascading impacts on fertilization success, fruit development, and crop productivity.

Physiological and biochemical stress responses

Beyond impairing pollen structure and function, pesticides also trigger a range of physiological and biochemical stress responses at the cellular level. These responses, often linked to oxidative stress and altered metabolic activity, further influence reproductive capacity and crop performance. Pesticides also alter physiological and biochemical markers of stress, which directly or indirectly influence reproductive capacity. In mustard (*Brassica juncea*), exposure to cypermethrin and imidacloprid triggered oxidative stress, evidenced by increased proline accumulation, lipid peroxidation, and elevated antioxidant enzyme activities (Superoxide Dismutase-SOD, Catalase-CAT, Peroxidase-POD). These changes reflect the plant's defense against ROS overproduction. Additionally, pesticides altered mineral uptake and oil biosynthesis, essential for crop yield (Bashir & Jan, 2015; Thakur *et al.*, 2020; Ramzan *et al.*, 2022). Napropamide exposure increased catalase, peroxidase, superoxide dismutase, and glutathione S-transferase activity, indicating activation of antioxidant defense pathways under oxidative stress in *Brassica napus* (Sachdev *et al.*, 2021; Ighodaro *et al.*, 2018). Atrazine exposure enhanced lipid peroxidation, a key marker of oxidative damage to membranes, reflecting ROS imbalance and impaired cell function in *Zea mays* (Bibi *et al.*, 2019). Cypermethrin exposure led to proline accumulation, reflecting stress adaptation mechanisms to maintain osmotic balance and stabilize proteins and membranes (Ramzan *et al.*, 2022) for *Helianthus annuus*. Emamectin benzoate, alpha-cypermethrin, and imidacloprid exposure elevated antioxidant enzyme activities (SOD, CAT, POD), indicating oxidative stress responses to pesticide toxicity found in tomato *Solanum lycopersicum*.

Heavy metal accumulation in crop

Beyond direct pesticide toxicity, pesticide residues can also act as sources or carriers of heavy metals, which accumulate in crop plants and their byproducts, such as honey. This dual contamination not only impairs plant reproductive function but also raises serious food safety concerns (Table 2). In *Brassica juncea* (mustard), cadmium has been detected in both flowers and honey, suggesting potential reproductive toxicity in plants and posing direct risks to human health through dietary exposure (Rashed *et al.*, 2009). Similarly, in *Brassica napus* (rapeseed), significant levels of Fe, Mn, Cr, Pb, Co, Cu, and Ni were reported in plant tissues, raising concerns about heavy metal interference with physiological processes, crop yield, and food quality (Tomczyk *et al.*, 2020). A wide range of metals—including Pb, Cd, As, Cu, Ni, Mn, Fe, and Cr—has also been identified in *Manihot esculenta* (cassava) and *Vernonia amygdalina* (bitter leaf). Among these, arsenic is particularly toxic due to its high mobility and potential to cause both metabolic and reproductive damage (Orisakwe *et al.*, 2019). In *Syzygium aromaticum* (clove), accumulation of Pb, Zn, Cu, and Fe was observed; at elevated concentrations, these metals disrupt enzymatic activity and metabolic balance, thereby affecting growth and productivity (Askari *et al.*, 2022). Furthermore, in *Tilia* sp., cadmium, copper, manganese, zinc was detected not only in plant tissues but also in honey samples sourced from this plant. This indicates both environmental contamination and the potential for transfer into pollinator-derived products, underscoring reproductive toxicity risks for plants as well as long-term health hazards for consumers (Barbes *et al.*, 2023). As such, these findings demonstrate that heavy metal accumulation in crops, often linked with pesticide use or environmental pollution, poses a dual threat—compromising plant reproductive performance while simultaneously raising food safety and public health concerns.

Table 2. Heavy metal accumulation in different crops due to pesticide application or contamination and reported reproductive impacts

Heavy Metal(s)	Primary Sources	Reported in Crops	Reproductive / Food Safety Impacts	Reference
Cadmium (Cd)	Pesticide residues, soil contamination	*Brassica juncea* (mustard) flowers and honey	Reproductive toxicity, reduced fertility, food safety risks	Rashed *et al.*, 2009
Fe, Mn, Cr, Pb, Co, Cu, Ni	Pesticide residues, agrochemicals, soil accumulation	*Brassica napus* (rapeseed)	Heavy metal accumulation lowers yield and raises food safety concerns	Tomczyk *et al.*, 2020
Pb, Cd, As, Cu, Ni, Mn, Fe, Cr	Soil and water contamination, pesticide by-products	*Manihot esculenta* (cassava), *Vernonia amygdalina* (bitter leaf)	Arsenic highly toxic; accumulation affects fertility, food safety, and crop quality	Orisakwe *et al.*, 2019
Pb, Zn, Cu, Fe	Environmental pollution, pesticide-metal interactions	*Syzygium aromaticum* (clove)	High levels disrupt metabolic activity, reducing plant reproductive fitness	Askari *et al.*, 2022
Cd, Pb, Hg, Al	Environmental and pesticide residues in soil and nectar	*Tilia tomentosa* (silver linden) – plant and honey samples	Environmental contamination linked to reproductive toxicity and human health risks	Barbes *et al.*, 2023

DISCUSSION

Pesticides were introduced to improve human life by enhancing crop yields and controlling pest- and vector-borne diseases. However, their adverse impacts on plants, ecosystems, and human health (Sule *et al.*, 2022) have gradually outweighed these initial benefits. Due to their persistence and slow degradation, pesticides accumulate in soils and water bodies, enter food chains, and ultimately affect higher organisms, including humans (Yadav & Devi, 2017). Numerous health issues, both acute and chronic, have been associated with pesticide exposure through contaminated air, food, and water. This review demonstrates that pesticides induce significant stress in crops, particularly affecting reproductive traits. Evidence from diverse species, including *Brassica juncea*, *Zea mays*, *Rubus armeniacus*, and *Solanum lycopersicum*, highlights reduced pollen viability, impaired germination, and morphological abnormalities in pollen grains. Structural deformities, disintegration of pollen walls, and compromised pollen tube growth reflect the extent of cellular and tissue-level damage. Our preliminary observations in a major oilseed crop in India - B. juncea (mustard) align with these findings, showing high frequencies of pollen abnormalities and reduced viability such as ruptured exine walls, cytoplasmic disintegration, reduced pollen size, and deformed shapes (Fig. 1) were observed at higher frequencies (up to ~35%) in pesticide (Cypermethrin 25% EC, Chlorpyriphos 50% EC) treated plants compared to ~5% in controls (untreated plants).
Nonetheless, detailed studies on soil quality, long-term pesticide accumulation, and crop-specific susceptibilities remain essential for a comprehensive understanding. Since complete elimination of pesticides is not feasible given their role in ensuring food security, sustainable strategies for managing pesticide-induced stress in crops are urgently required. Several approaches are available which collectively provide a holistic framework to reduce pesticide dependency while safeguarding crop reproductive health and ensuring agricultural sustainability (Fig. 2). Integrated Pest Management (IPM), which combines biological, cultural, physical, and chemical tools, has been widely adopted in more than 60 national programs (Ehler, 2006). However, in practice, IPM often degenerates into pesticide scheduling rather than true integration (Peshin & Zhang, 2014), underscoring the need to strengthen its biological and cultural components. Cultural practices such as crop rotation, sanitation, adoption of resistant varieties, adjusted planting times, and mulching are cost-effective and environment friendly strategies that help disrupt pest cycles and reduce reliance on pesticides (Gill & Garg, 2014). In parallel, physical and mechanical techniques—including steaming, solarization, manual removal, and barrier methods—have proven effective in reducing pest populations without chemical inputs and are increasingly incorporated into organic farming systems (Baldwin *et al.*, 2013). Biological

control also plays a key role, with natural enemies such as parasitoids, predators, fungi, and bacteria contributing significantly to pest suppression; notable examples include *Trichoderma* spp. and entomopathogenic fungi such as *Beauveria bassiana* (Sharon *et al.*, 2011). Precision in pesticide application further enhances sustainability: optimizing the timing of pesticide use—for example, avoiding crop flowering periods to protect pollinators—along with careful dose calibration and the use of advanced delivery systems such as drip irrigation and perimeter spraying, can improve efficacy while minimizing non-target exposure (Gill & Garg, 2014). Beyond these, biopesticides and biorational compounds offer safer alternatives with reduced ecological footprints, including microbial agents such as *Bacillus thuringiensis* and *Beauveria bassiana* as well as allelopathic plant residues for weed management (Zhang *et al.*, 2011). Finally, plant growth regulators (PGRs) such as brassinosteroids, salicylic acid, jasmonic acid, and cytokinins have been shown to enhance plant resilience under pesticide-induced stress by activating antioxidant defense systems, stabilizing membranes, and promoting detoxification pathways (Jan *et al.*, 2020).

While the current body of evidence clearly establishes the detrimental effects of pesticides on crop reproductive traits, several uncertainties and limitations remain. Much of the existing research has focused on a narrow set of crops and pesticides, often under controlled conditions that may not fully capture field realities. Moreover, variability in experimental methods and endpoints makes cross-study comparisons difficult. These limitations point to important research gaps that must be addressed to strengthen our understanding of pesticide-induced stress and to guide the development of sustainable agricultural practices.

Research Gaps and Future Directions: A Focus on Mustard

Despite extensive research on the impacts of pesticides on crop physiology and reproduction, significant knowledge gaps remain, particularly with respect to mustard (*Brassica juncea*), a crop of major agronomic and economic importance. First, only a limited number of studies have examined the reproductive organs of mustard, with little emphasis on the structural and biochemical traits of its pollen, flowers, and seeds. This lack of systematic investigation is concerning, as reproductive traits are directly linked to yield and seed quality, making mustard vulnerable to hidden productivity losses under pesticide stress. Moreover, the effects of widely used insecticides such as dimethoate, cypermethrin, and chlorpyrifos on pollen viability and germination remain understudied. The absence of standardized methodologies for assessing pollen germination and viability further complicates comparisons across studies and hinders the development of reliable datasets.

Most available research focuses on the effects of individual pesticides, whereas in reality crops are frequently exposed to mixtures of agrochemicals, creating unknown interactive or synergistic impacts on reproductive success. Mechanistic insights into structural damage, such as pollen abnormalities documented in other crops using advanced techniques like scanning electron microscopy (SEM), are scarce in mustard research. Similarly, stress physiology studies in mustard are minimal compared to crops such as maize and sunflower, where responses like proline accumulation and antioxidant enzyme activity have been characterized in detail. Another neglected area concerns heavy metal contamination: although cadmium, lead, and other metals have been reported in various crop systems and their byproducts, systematic investigations on their accumulation in mustard and mustard-derived products (e.g., oil and honey) remain largely absent.

Addressing these gaps is crucial, as mustard plays a vital role in food security, edible oil production, and pollinator interactions in South Asia and beyond. Without a comprehensive database of its reproductive responses under pesticide and contaminant stress, both yield stability and product safety remain at risk. Therefore, future research should prioritize multidisciplinary approaches combining reproductive biology, stress physiology, and environmental toxicology to safeguard mustard's agricultural sustainability.

CONCLUSION

Pesticides remain indispensable for safeguarding crops against pests and ensuring yield stability, yet their excessive use imposes profound costs on plant health, particularly reproductive processes. A growing body of literature demonstrates that pesticide exposure reduces pollen viability, inhibits germination, and induces structural deformities in reproductive tissues across diverse crops. The underlying mechanisms include excessive generation of reactive oxygen species (ROS), disruption of nutrient uptake, hormonal imbalance, and inhibition of enzymatic activities. Compounding these effects, pesticide residues often carry heavy metals such as cadmium, lead, and mercury, which further impair nutrient transport, enzyme function, and reproductive development.

Despite advances in pesticide research, critical knowledge gaps persist. Crop-specific investigations into pollen physiology, particularly in *Brassica juncea* and other oilseed crops, remain limited. The combined effects of multiple agrochemicals—representing the reality of field conditions—are poorly understood, while the lack of standardized assays for pollen viability and germination constrains meaningful cross-study comparisons. Our preliminary observations in mustard pollen highlight these concerns, with high levels of abnormalities and reduced viability suggesting long-term risks for fertility, genetic stability, and ultimately food security. Prolonged pesticide exposure also risks toxic accumulation in soils and food chains, compounding threats to both ecosystem integrity and human health.

Since complete elimination of pesticides is not feasible, the way forward lies in sustainable management. Strengthening integrated pest management (IPM), promoting cultural, physical, and biological control methods, developing safer biopesticides, and applying plant growth regulators (PGRs) to enhance stress tolerance collectively offer promising avenues to mitigate pesticide-induced reproductive stress. By integrating these strategies, agriculture can reduce dependency on hazardous inputs, safeguard crop reproductive health, protect biodiversity, and ensure secure and sustainable food supplies for future generations.

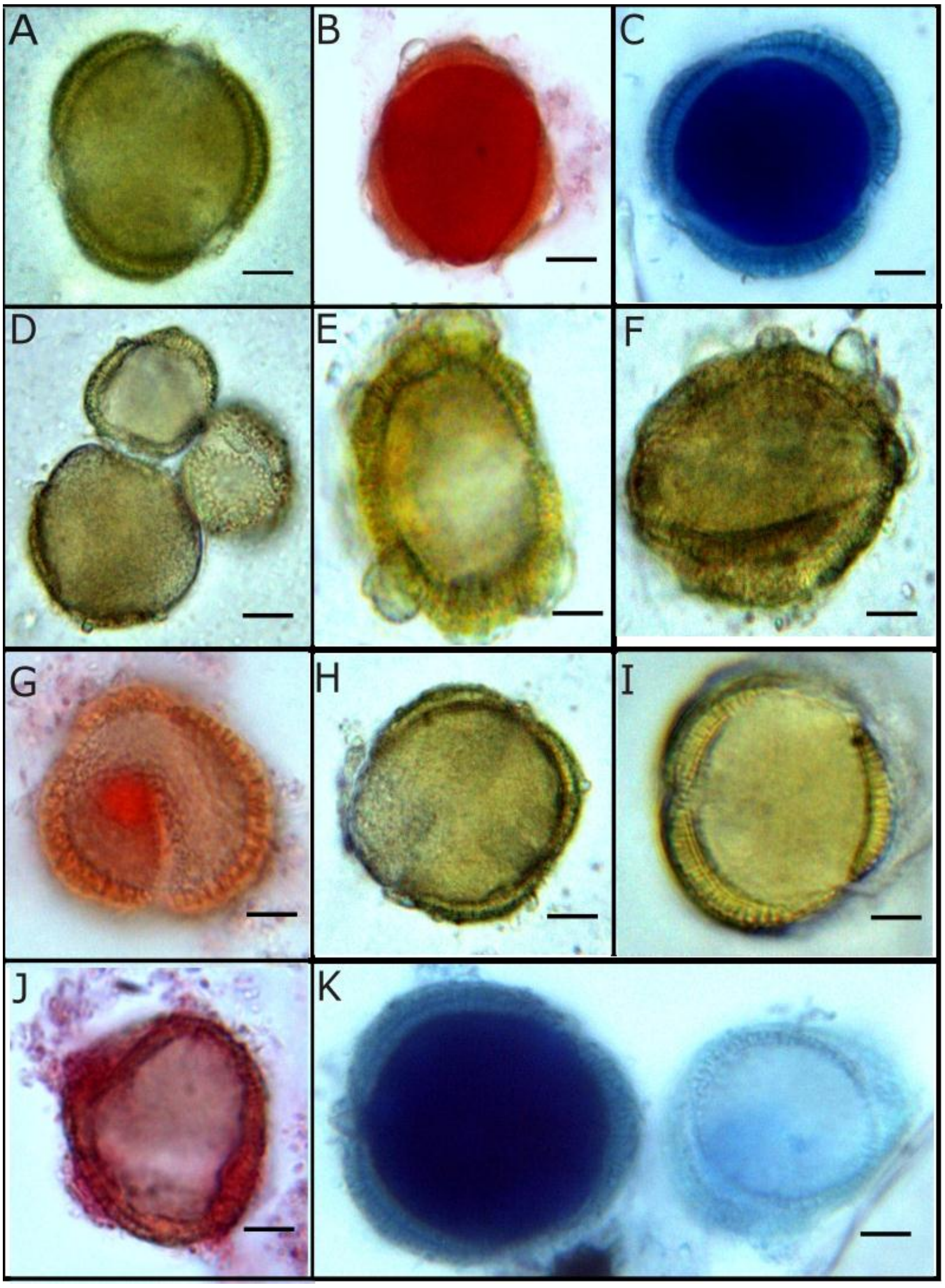

Fig. 1A–K. Normal and abnormal pollen grains of *Brassica juncea* (mustard) from control and pesticide-treated plants. **A–C:** normal; **D–F:** deformed; **G:** cytoplasmic breakage; **H–I:** ruptured exine wall; **J:** loss of intact cytoplasm; **K:** reduced, non-viable pollen adjacent to normal viable pollen. Scale bar = 10 µm.

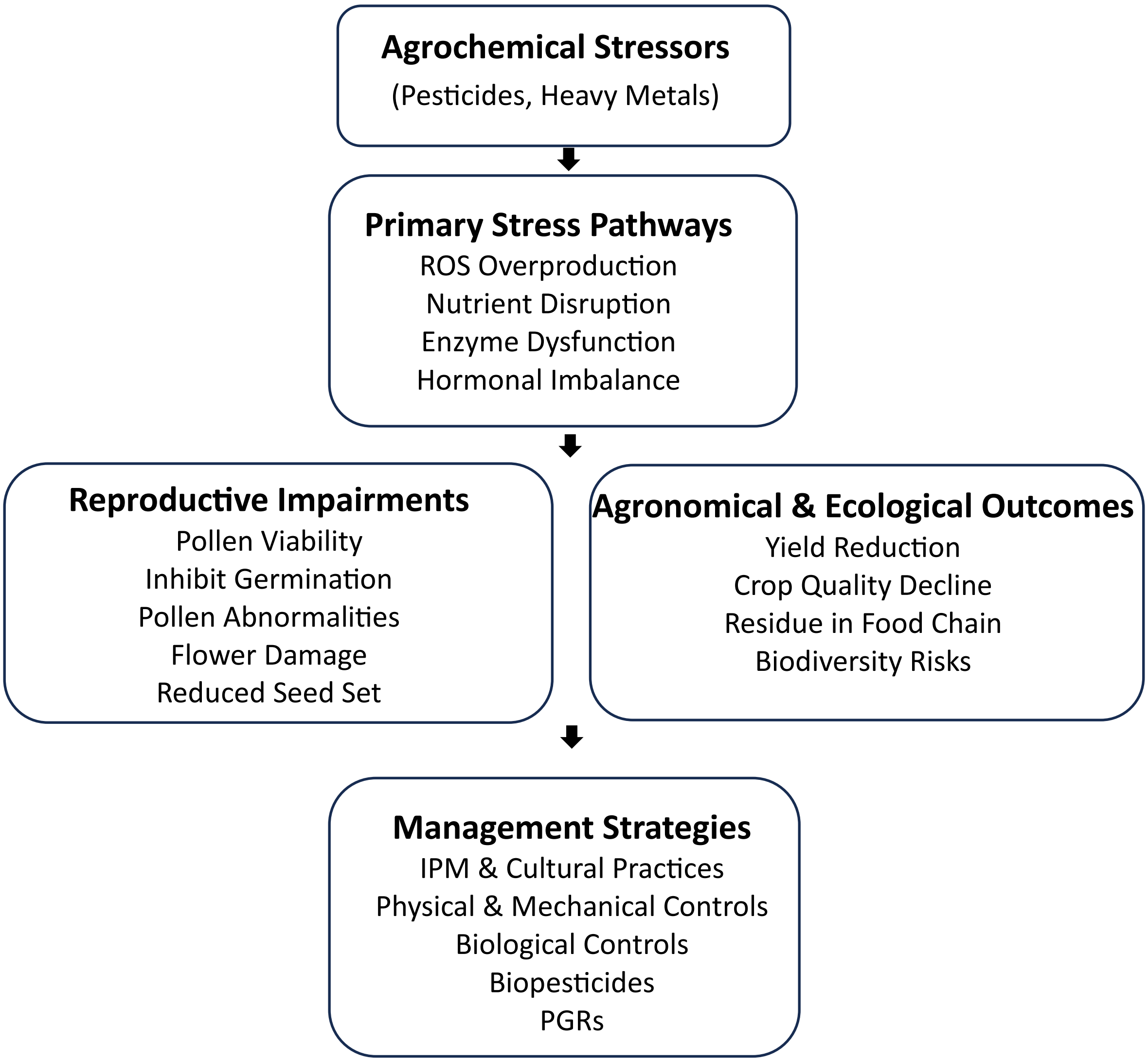

Fig 2. Conceptual framework of agrochemical stressors, their impact on crop reproductive health and mitigation strategies

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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