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Environmental approaches for reducing pests in chilli (*Capsicum annuum* L.): A review

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Abstract
Chilli (*Capsicum annuum* L.) is a commercially valuable spice crop grown in different agroclimatic zones. The productivity is significantly affected by the infestation of a number of insects such as thrips, aphids, whiteflies, and fruit borers. The historical reliance on chemical pesticides resulted in issues such as pest resistance, contamination of the environment, and risk to human health. Hence, in the current scenario, ecologically friendly management against pests is a very promising strategy. This review integrates the existing knowledge and developments in ecologically friendly methods of chilli pest control, such as agronomic and cultural practices, biological control, physical and mechanical, botanical insecticides, and integrated pest management. Integration and weaknesses and strengths are highlighted in these methods to assist in enhancing the sustainability of chilli production. The article further illuminates the questions of adoption and opportunities for the future through research, extension, and policy change. The review calls for a transition towards economically viable, environmentally benign, and socially acceptable sustainable pest management systems in the context of growing ecological pressure.

Keywords: *Capsicum annuum*, chilli pest management, biological control, integrated pest management (IPM), botanical pesticides, agroecological pest control, sustainable agriculture

1. Introduction

Chilli (*Capsicum annuum* L.) is one of the finest spice crops of the globe, which finds major cultivation in tropical as well as subtropical regions. It is of notable economic significance due to its multi-dimensional application as a vegetable, spice, and condiment. It is mainly cultivated in India and is included in the Indian agricultural as well as food system (Srinivasan, 2009) [7]. But chilli production is often hampered by a broad array of pest insects such as aphids, thrips, whiteflies, and fruit borers. Not only do these insects reduce the yield but also negatively affect the quality of the fruit and cause massive economic losses (Sharma and Singh, 2017; Karthik and Usha Rani, 2020) [6, 4]. Chemical pesticides have traditionally been the pillar of chilli pest control. Though helpful temporarily, synthetic pesticides have been misused, inducing resistance in the insects, contaminating the environment, exerting non-target effects, and leaving food product residues (Ahmad *et al.*, 2001; Al-Moajel and Rizwan, 2021) [1, 2]. This is a strong indication of how the world can do with environmentally friendly and sustainable methods of pest control. As they offer green and sustainable options, eco-friendly pest management methods such as the incorporation of natural enemies, botanic insecticides, trap crops, and agroecosystem interventions are gaining popularity (Ghosh and Bandyopadhyay, 2009) [3]. Environmental controls in IPM tactics are also significantly promoted by policymakers and scientists. These practices adhere to the ethos of ecological intensification and prioritize the use of biological over synthetic inputs, biodiversity, and soil health (Kumar and Kumar, 2020) [5]. Different environment-based methods of pest management in chilli crop are described and assessed here in this review. It tries to evaluate the present level of utilization of ecological and eco-friendly practices, give an approximate idea about their possibilities, and suggest directions for further research. This article provides a general scenario of future pest management methods being less chemically intensive and more sustainable-oriented by both biologically and ecologically referring to the current advancements and traditional ecological knowledge (Yadav and Sharma, 2021) [8].

2. Major Pests of Chilli and Their Impact

Capsicum annuum L., chilli, is highly susceptible to a number of insect pests that damage the crop at all stages of growth. Aphids (*Aphis gossypii*), thrips (*Scirtothrips dorsalis*), whiteflies (*Bemisia tabaci*), and fruit borers (*Helicoptera armigera*) are insect pests. These insects drastically reduce fruit quantity and quality as well as interrupt physiological processes like photosynthesis and nutrient uptake (Reddy and Kumar, 2004; Jagginavar and Biradar, 2017) [18, 11]. Whiteflies and thrips are the most destructive sap-feeding insects. Thrips cause leaf curling, yellowing, necrosis, and distorted fruits due to the damage of sensitive leaves and flowers. Besides, *S. dorsalis* is also found to be a vector for various viral diseases that cause widespread crop loss, for example, Chilli Leaf Curl Virus (ChiLCV) and Groundnut Bud Necrosis Virus (GBNV) (Riley *et al.*, 2011) [20]. Whitefly honeydew favors sooty mold development, inhibiting photosynthesis. They are also efficient vectors for viral disease which causes economic loss (Jones, 2003) [12]. *H. armigera* fruit borer is the most destructive insect chilli pest. Infestation by the larvae infects the fruits to consume the internal tissues and make the developing pods unmarketable. Individual fruits are invaded by a single larva that results in enormous loss of quality and quantity of the crop (Natarajan *et al.*, 2006) [15]. Heavy infestation by *H. armigera* can, in certain cases, contribute up to 60% to yield loss. Yield loss caused by pest damage in chilli has been estimated at between 30% and 80%, which is diverse based on pest species and environment (Patil *et al.*, 2014) [17]. Synthetic pesticides are most prevalently applied, though unselective application has led to thrips and whiteflies developing resistance biotypes (Dev *et al.*, 2015) [9]. Residue, resurgence, and resistance issues are an indicator of the necessity for environment-friendly pest management practices. Environmentally friendly pest management practices, therefore, must be developed based on knowledge of vector-borne disease epidemiology, seasonal prevalence, host preference, and pest biology. Site-specific IPM practices and low chemical input-based early warning systems are implemented based on this science as a foundation.

3. Agronomic and Cultural Practices

Cultural and agronomic practices are the cornerstones of ecologically friendly insect pest control in chillies. Cultural and agronomic practices are aimed at adjusting the cropping environment to reduce the environmental conditions favorable for pest occurrence. There are various benefits as preventatives to chemical use, including cost reduction, ecological balance, and compatibility with integrated pest management systems (Kumar *et al.*, 2016) [13]. Crop rotation is also one of the most powerful cultural controls. Life cycle of insect pest and disease of soil-dwelling pests is interrupted by replacing chilli with non-host plants like legumes or cereals, which in turn prevents their accumulation (Srinivasan, 2012) [21]. Similarly, it is also practiced to intercrop marigold (*Tagetes spp*.), the trap crop of *H. armigera*, with chilli. Adult moths lay eggs more in marigold compared to chilli, which is given protective cover. Pest population control also requires complementary practices like deep plowing, early harvesting, and field sanitation involving the removal of diseased plant trash. By regulating sowing season, one can steer clear of seasons with peak pest occurrence. As an example, sowing crops early on can deter whiteflies and thrips that are likely to be high during later crop growth (Ghosh *et al.*, 2015) [10]. By eliminating air stagnation and dampness, proper plant spacing does away with the necessity for infestation by pests and diseases. One of the most feasible agronomic methods is the application and utilization of pest-resistant or tolerant crop varieties, though limited in the case of chillies. In trial fields, some of the breeding lines exhibited resistance to severe pests and viral diseases (Nishant *et al.*, 2018) [16]. Aside from that, balanced nutrients and watering cause enhanced plant vigor that reduces the vulnerability of the crops to pest infestation. Aside from controlling weeds, organic mulch also renders the environment unfavorable to the survival of some soil pests. Soil solarization, or encapsulating sun's radiation in transparent plastic sheets, can control populations of nematodes and insect larvae. Organic amendments to soil like compost and farmyard manure also enhances microbial action with the end result being an increase in population size of beneficial organisms naturally controlling pest population size (Reddy and Yadav, 2020) [19]. All these agronomic and cultural practices together represent a worthwhile and sustainable approach to chilli pest control. They present an integrated and sustainable solution that may decrease dependency on chemical pesticides, eliminate pest resistance, and improve overall agroecosystem health when supplemented with mechanical and biological control methods.

4. Biological control

Biological control is part of ecologically acceptable management of pests in chilli production. Biological control employs predators, parasitoids, and microbial diseases as the agents of control of pests (van Lenteren *et al.*, 2008) [22]. Biological control reduces or eliminates the use of chemical pesticides to a considerable extent without compromising ecological balance and incorporation of IPM concepts (Bale *et al.*, 2008). Natural enemies contribute significantly to the regulation of key pests such as *Helicoverpa armigera*, aphids, thrips, and whiteflies in chilli agroecosystems. Aphids and thrips are among the soft-bodied insects being attacked by predators in great numbers such as ladybird beetles (*Coccinella septempunctata*) and green lacewings (*Chrysoperla carnea*) (Patel *et al.*, 2020). They can be used both in conservation and augmentative biological control owing to their high reproductive capability as well as greater field adaptation. Parasitoids are also found to contribute significantly to chilli IPM. Rear and release in the field at a commercial scale, egg parasitoids like *Trichogramma chilonis* and *T. pretiosum* infest *H. armigera* eggs before their larvae penetrate and destroy the pods (Kumar *et al.*, 2019). With other eco-friendly methods of control to enhance their impact, these parasitoids are inexpensive. Entomopathogenic fungi like *Beauveria bassiana*, *Metarhizium anisopliae*, and *Lecanicillium lecanii* are some of the microbial biocontrol agents that have been proved effective to control sucking pests, thrips and whiteflies. Fungi feed on internal tissues and kill pests after infecting them inside their cuticle (Sharma and Godika, 2015).

Bacillus thuringiensis (*Bt*) is a wide-spectrum bacterial agent for controlling the larvae of lepidopterans, especially *Helicoverpa spp*. (Sahayaraj and Kalidas, 2011). Overall, biological control agents are host-specific and will not harm pollinators or beneficial insects. Even though knowledge of pest biology is required to meet the demand for application, correct identification of natural enemies, and best environmental conditions for performance and survival (Jhala *et al.*, 2014), conservation of local predators and parasitoids can be maintained by reducing use of pesticides and offering flowering crops. Biological control tactics are not without constraint, however. In contrast to chemical pesticides, they can have a lag phase and at times may be environmentally sensitive, hence less desirable in these situations. They are still low-cost, long-term options when used as part of an integrated program. Their application is more convenient than ever with enhanced field procedures and enhanced availability of mass-reared bioagents (Gurr *et al.*, 2012).

5. Botanical Pesticides and Biopesticides

Botanical insecticides and biopesticides are now part of sustainable chilli pest control. Microbial and plant-derived products are chemical pesticide-free, eco-friendly options that are in line with conservationism and organic farming principles (Isman, 2006) [30]. One of the best-researched and utilized botanical insecticides is neem (*Azadirachta indica*). Azadirachtin, its active ingredient, is a substance with antifeedant, growth-regulating, and repellent activities. Neem products such as neem seed kernel extract (NSKE) and neem oil (0.5-5%) were effective against *Helicoverpa armigera*, aphids, and thrips in chilli vegetable. With low risks to pollinators and beneficial insects, the products are simple to incorporate in IPM programs. Some of the plants whose insecticidal and repellent activities have been demonstrated are garlic (*Allium sativum*), *Lantana camara*, *Vitex negundo*, and chilli per se extract. Garlic extract contains a compound called allicin, which is toxic to a variety of soft-bodied insects. Citronella, lemongrass, and eucalyptus essential oils, according to Rajendran and Sriranjini (2008) [34], exhibit neurotoxic or repellent activity against pests. *H. armigera* is controlled efficiently with the help of microbial biopesticides like *Bacillus thuringiensis* (*Bt*). The delta-endotoxins of *Bt* kill the insect gut tissues and ultimately result in their death. *Beauveria bassiana*, *Metarhizium anisopliae*, and *Verticillium lecanii* are fungi biopesticides of high potency against thrips and whiteflies, especially in wet climatic conditions (Singh *et al.*, 2017) [6]. This high safety and specificity are also guaranteed by viral biopesticides such as Helicoverpa nucleopolyhedrovirus (*HaNPV*), although they must be applied precisely at the right moment and in the right habitat. Biopesticides augment natural predators and pollinators and are less harmful to non-target organisms. They also break down rapidly and leave minimal residue. Their shortcoming is that their duration of action is longer, repeated usage is needed, and their field performance varies depending on environmental conditions (Glare *et al.*, 2012) [29]. Availability of products, storage, and familiarity are also issues that growers may find challenging. The use of botanicals and biopesticides in chilli cultivation is anticipated to expand despite these limitations. Adoption is driven by regulation incentives, growing consumer demand for residue-free crop yield and enhanced formulation technology. Such inputs are a sustainable and feasible way of substitution for chemical pesticides if combined with other cultural and biological practices.

6. Physical and Mechanical Methods

Apply One of the most ancient control methods, which is still a wide application for modern sustainable agriculture, especially for produce such as chillies where minimal chemical residues should be achieved, physical and mechanical methods make use of the force or manual intervention to actively kill, repel, or exclude the pest. They are the benefit of being moderately inexpensive, non-poisonous to non-target species, and compatible with application on organic and integrated pest management (IPM) systems, although in the majority of cases, they necessitate the use of labor. Manual handling of injured plant parts and insect instars is a widely accepted mechanical practice, particularly in organic cultivation or limited-scale production. *Helicoverpa armigera* larvae, *Spodoptera litura* larvae, and egg masses on chilli leaves can be picked by hand during regular crop scouting, resulting in considerable pest infestation decrease prior to economically viable levels of injury. It is though labor-intensive but efficient when infestations are minor and labor is within reach. Blue or yellow sticky traps are an efficient way of trapping and observing flying insect pests. Blue sticky traps trap primarily thrips, while yellow sticky traps trap aphids and whiteflies (Srinivasan, 2012) [21]. Trapping the adults prior to oviposition has the consequence of denying the pests a chance to settle in the field to reproduce. The traps are deployable at high density to impart greater suppression and are inexpensive and non-toxic. Night-flying insects like fruit borers are continuously monitored and their population minimized using light traps. The light traps minimize egg deposition on crops by pulling adult insects at night. Solar-powered light traps are most widely used in rural areas, achieving affordability along with environmental compatibility. Greater specificity of the target pest species may be achieved by manipulating light position and intensity. Mulching discourages insects by confusing them optically, especially when done using reflective plastic film or silver. At the initial crop phase, it is especially effective for thrips and aphids. Row covers and insect netting are physical barriers that allow light and air penetration but do not admit pests. One of the effective methods is soil solarization, by which transparent sheets of polyethylene mulch water soil for four to six weeks in mid-summer. It allows for improved establishment of crops and minimized initial pest infestation through heating the soil to lethal temperatures for weed seeds, insect pupae, and soil-borne pathogens. These techniques are essential elements of ecologically based pest control, but they typically entail great labour input and never guarantee complete control. They have the benefit of keeping chemical use to a minimum, avoiding the development of resistance, and maintaining diversity. They work best in situations with low resources, peri-urban agriculture, and organics.

7. Integrated Pest Management (IPM) Approaches

To manage pest populations economically and ecologically in an integrated manner, integrated pest management, or IPM, is a science-based, holistic approach to pest management. IPM on chilli (*Capsicum annuum*) is aimed at keeping pest pressure under economic threshold levels (ETL) without disrupting beneficial organisms, minimizing pesticide residues, and preserving agroecosystem health (Koul and Cuperus, 2007) [31]. Pest surveillance is a critical component of IPM. Continuous monitoring follows the population growth and identifies the occurrence of pests using sticky traps, pheromone traps, and ground scouting. All this information helps decide when and how to proceed considering the control practices are implemented only when they are economically viable (NIPHM, 2015) [32]. Such practices as intercropping with marigold or coriander, adjusting the date of sowing, rotation of crops, and crop residue removal can slow down initial pest infestation and disrupt the pest life cycle. Planting resistant or tolerant chilli genotypes also reduces exposure to primary pests such as thrips and fruit borers. Biological control comes under IPM. Conservation and inoculative release of natural enemies like *Trichogramma spp*., *Chrysoperla carnea*, and entomopathogenic fungi (*Beauveria bassiana*, *Metarhizium anisopliae*) are used to maintain the pest population below control economic thresholds. Biological agents are environment-friendly, target-specific, and compatible with other non-chemical methods (van Lenteren *et al*., 2008) [22]. Physical and mechanical pest control methods such as netting, light trap, sticky trap, and hand-picking larvae are among the other methods disseminating pest grouping without distorting the state of equilibrium. Botanical insecticides, especially neem-based and plant oils such as garlic or chilli (Isman, 2006) [30], are among the other lowest non-target-toxicity pest control provided. Chemical pesticides are employed only as a last resort under IPM. Pest population levels above ETL are supplied with selective insecticide treatments with further caution practiced during active ingredient rotation to prevent resistance accumulation. Low-residue insecticides and biopesticides that assist in protecting beneficial arthropods while lessening environmental hazards are favored (Stenberg, 2017) [33]. Accessibility of bio-inputs, extension services, and education for farmers are crucial for IPM success. Farmers can gain confidence in adopting IPM practices through demonstration plots, training schemes, and participatory research. IPM offers a robust and adaptable system of sustainable production of chilli as a reaction to enhanced issues of resistance of pests, climate change, and pesticide residues.

8. Challenges and Future Prospects

The large-scale application of eco-friendly pest control technologies in chilli production is being hampered by several issues, even though the economic as well as environmental benefits are obvious. These have to be sorted out at several fronts, i.e., technical, socioeconomic, institutional, and policy fronts, in order to bring about a transition towards sustainable pest control. Poor awareness and knowledge among farmers, particularly small-scale farmers, of effectiveness and use of environmentally friendly methods of pest control is one of the most pertinent challenges. As a result of extensive marketing, ease of application, and perceived speed of effect, chemical pesticide dependency tends to continue. Farmers can be untrained for the integration and scheduling of biologic control tactics, cultural controls, and mechanical controls. Poor access and availability of good quality bio-inputs are another significant constraint. Commercial pheromone baits, biopesticides, or entomopathogenic fungi are not found or very costly in rural and remote areas. Furthermore, variability in output, shelf life, and quality of inputs also lowers farmer confidence. Low-quality biocontrol products are saturating the market due to weak regulatory frameworks and lack of enforcement. Most ecologically based approaches have weak, locally useful backing among the research and technical communities. The performance of a particular biological agent or cultural strategy may differ substantially depending on local agroclimatic zones, cropping systems, and pest pressure. Field-scale tests and long-term studies are needed to adapt these strategies for predictable success in different environments. Policy and institutional support to pesticide-free pest management remain weak. Packages of chemical control with high-yielding varieties tend to dominate government extension programs. Extension staff and training and demonstration infrastructures with IPM specialization are poor. Subsidies and incentives also favor chemical inputs, at the cost of bio-based inputs. To overcome these kinds of challenges in the future, several opportunities can be used. Future advancements in microbial ecology, nanotechnology, and biotechnology can facilitate greater stability and activity of biopesticide formulations. IPM practices can be combined and pest prediction enhanced with the help of AI and precision agriculture technologies. Scaling up is achievable through capacity building and collaborative action by farmers, scientists, and extension agents. Promoting farmer field schools, public-private alliances, and community-based monitoring will enable information flows and build trust in environmentally sustainable techniques. Incentives for residue-free production, organic farming, and certification of safe products will also promote the transition towards safer management of chilli pests. In summary, while distance is still to be covered, a promising way to sustainable and green pest control for chilli cultivation is presented by the combination of sophisticated science, supportive legislation, and people's action.

9. Conclusion

A number of pest insects, some of which are responsible for significant yield and quality losses, are increasingly attacking sustainable production of chilli (*Capsicum annuum* L.). One possible and environmentally friendly alternative to the extensive application of chemical pesticides is the adoption of environmental pest management practices. Farmers can alleviate pest pressures with little loss in environmental and economic sustainability by incorporating mechanical, biological, cultural, and physical control techniques. Crop resistance and disruption of the pest life cycle is obtained by cultural techniques like crop rotation, intercropping, and field sanitation. Biological control involves biopesticides and natural enemies for direct suppression of the pest population without damaging useful organisms or causing harmful residues. The mechanical devices like traps and handpicking also complement environmental control practices. An overarching model which includes these various methods into a structured plan that can be used to local agro-ecosystems is provided by integrated pest management (IPM) systems. Although environmentally oriented pest management is obviously to be preferred in several respects, adoption is slow because there is a lack of institutional support, poor access to quality inputs, and low education levels. Improved extension services, farm training, policy incentive, and further research on regionally based approaches will all be required in order to transcend these shortcomings. In the next couple of years, the adoption of new technology, strong public-private collaborations, and aggressive farmer participation can hasten the shift to greener and cleaner chilli production. Sustainable pest control is essential in maintaining long-term productivity and diversity, minimizing environmental contamination, and harmonizing chilli production with world sustainability goals. Lastly, in the future of chilli farming in uncertain climate and ecologically vulnerable world, there has to be a paradigm shift towards holistic and eco-friendly management of pests.

10. Conflict of Interest
The authors declare that there is no conflict of interest regarding the publication of this review paper.

11. Consent to Publish
All authors have read and approved the final manuscript and consent to its publication.

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