

MAJOR INSECT PESTS OF AGRICULTURAL CROPS: BIOLOGY, ECOLOGY AND SUSTAINABLE MANAGEMENT

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FOREWORD

Agriculture remains the backbone of food security and rural livelihoods across the world. However, the increasing challenges posed by insect pests continue to threaten crop productivity, economic stability, and environmental sustainability. The need for scientifically sound, economically viable, and ecologically responsible pest management strategies has never been greater.

The book *Major Insect Pests of Agricultural Crops: Biology, Ecology and Sustainable Management* is a timely and valuable contribution to the field of agricultural sciences. It brings together comprehensive information on the biology, ecology, damage symptoms, economic significance, and management of major insect pests affecting important agricultural crops. The chapters are carefully structured to provide readers with a clear understanding of pest identification, life cycles, pest ecology, economic threshold levels, and integrated management approaches.

One of the notable strengths of this book is its emphasis on sustainable pest management. The authors have successfully highlighted the importance of integrating cultural, mechanical, biological, botanical, microbial, and need-based chemical control methods within the framework of Integrated Pest Management (IPM). Such an approach is essential for reducing pesticide dependence, conserving beneficial organisms, and maintaining ecological balance in modern agricultural ecosystems.

The book will serve as a valuable resource for undergraduate and postgraduate students, researchers, extension personnel, educators, and professionals involved in crop protection and sustainable agriculture. Its practical orientation, supported by scientific evidence and contemporary management strategies, makes it highly relevant to both academic and field applications.

We congratulate the authors and contributors for their dedicated efforts in compiling this comprehensive work. We are confident that this publication will significantly contribute to pest management education, research, and sustainable agricultural development.

PREFACE

Crop production plays a pivotal role in ensuring food security, nutritional well-being, and economic growth. However, insect pests continue to be one of the major constraints affecting agricultural productivity worldwide. Changing climatic conditions, intensive cultivation practices, monocropping systems, indiscriminate pesticide use, and the emergence of invasive pest species have further complicated pest management in modern agriculture.

This book, *Major Insect Pests of Agricultural Crops: Biology, Ecology and Sustainable Management*, has been prepared with the objective of providing a comprehensive and up-to-date account of economically important insect pests affecting major agricultural crops. The chapters included in this volume cover diverse aspects of pest biology, taxonomy, ecology, host range, distribution, economic importance, damage symptoms, economic threshold levels, and integrated management strategies.

Special emphasis has been placed on sustainable and environmentally friendly pest management approaches. The book discusses cultural practices, host plant resistance, biological control agents, microbial pesticides, botanical formulations, behavioural manipulation techniques, and judicious use of selective insecticides within an Integrated Pest Management (IPM) framework. Recent developments in pest monitoring, resistance management, molecular studies, and emerging technologies have also been incorporated wherever relevant. This publication has been designed to serve as a useful reference for students, researchers, teachers, extension workers, crop protection specialists, and agricultural practitioners. We hope that it will enhance understanding of pest dynamics and support the adoption of sustainable pest management practices that protect both crop productivity and environmental health.

We hope that this book will serve as a practical guide and a reliable source of information for those engaged in teaching, research, extension, and agricultural production. Any suggestions for improvement in future editions will be gratefully acknowledged.

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Chapter 1: Brown Planthopper (*Nilaparvata lugens*): Biology, Ecology and Management

Abstract

Nilaparvata lugens or brown planthopper is one of the most devastating rice pests. Asia, which leads to high yield losses due to direct feeding damage and infection of viral diseases. *N. lugens* had become a major pest once it was regarded as a minor pest, which was after the increase heightened. planting of rice, use of high yielding varieties, and overuse of insecticides. The pest has great fertility potential, is migratory, dimorphic on the wings, and spectacular flexibility and allowing a booming population and frequent epidemics. This chapter provides a statistical description of the brown plant hopper including its taxonomic features in detail. host range, life cycle regarding biology and life cycles, ecological distribution, and economic threshold levels, damage symptoms, and area economic losses. The focus is put on the management strategies, legal, physical, mechanical, cultural, biological, botanical, chemical and microbial formulations and dosages with a particular attention to approaches. The chapter brings to attention the role of insecticide resistance, pest resurgence and ecosystem disturbance in contributing to aggravating plant hopper in addition to emphasizing the significance of integrated pest management and conservation of natural enemies. Recent developments in the mobile genetics and the host plants and resistance are also much debated as potentially useful sustainable management tools. On the whole, the chapter generalizes past and modern studies to give a comprehensive perspective of *N. lugens* and presents clues to the way to go in the future towards the environmentally friendly and sustainable control strategy in rice ecosystems.

Keywords: Ecological design; sustainable rice farming.

Introduction:

The leading staple crop to over half the world population is rice (*Oryza sativa* L). Specialized in Asia where agricultural systems are predominantly agroecosystems based on rice. Among the rice pests, a brown planthopper (BPH) *Nilaparvata lugens* (Stal) (Hemiptera: Delphacidae) has come into the limelight to be one of the most threatening pests in intensive cultivation Systems. The pest inflicts harm by a constant feeding on the phloem sap and provoking. Physiological problems like hopperburn that resulted in great instability of yield and failure of the crop. Under the outbreak conditions the economic significance of *N. lugens* has

been raised drastically with the augmentation of rice production systems, particularly after the massive introduction of high yielding varieties increased use of Nitrogen fertilizers. Over nitrogen fertilization increases. Host plant adaptability, which led to high fecundity, survival and population increase of BPH. At the same time, blanket usage of insecticides has broken natural enemy complexes, forming favorable ecological conditions to allow the reproduction of the planthopper and secondary pests. Such processes have been well known as classical example of insecticide induced pest. Rediscovery of rice ecosystems. One of the key limits to the control of brown planthoppers is the quick.

Development of insecticide resistance. Neonicotinoids and phenylpyrazoles resistance has been reported in South and East Asia, which cripples the action of most likely used insecticides. Massive resistance surveys indicated that populations of BPH display. Much spatial heterogeneity in susceptibility, a measure of high pressure of selection by Long-term chemical containment measures. Resistance management is a challenge that has been induced.

International interest on the study of the mode of action and resistance to insecticides. The management systems of resistance focus on alternation of insecticides which exhibit varied modes of Action and incorporation of non-chemical methods to postpone the progression of the resistance against planthopper. Populations (Sparks Thomas C., Nauen Ralf. 2015), due to its high rate of reproduction, migration, and adaptation ability to changes at a high rate, BPH. Late studies have supported the practice of integrated pest management (IPM). Plans to minimize the use of insecticides by preserving natural predators/ ecosystem. The brown planthopper has been used as a model organism of studying pesticide resistant. Evolution and ecological unbalance within modern farming, emphasizing the outcomes of Unsustainable pest management (Heckel David G. 2012). Thus, an all-embracing knowledge of the biology, ecology, damage capacity and control opportunities of *N. lugens* is critical in the formulation of sustainable measures to protect rice. This chapter is a synthesis of the research findings that are available on brown planthopper focusing on the emergence, biological features of this insect in history. Adjustability, financial effect, and management, basing solely on researched materials and studies.

History :

The first insect to be identified as a rice associated insect is the brown planthopper (*Nilaparvata lugens*) of small significance to conventional rice-growing methods. Ecological research in the early nineteenth century suggested that the predator complexes as well as the low-input naturally regulated the planthopper populations. Agronomic procedures, which produce infestations only occasionally (Pathak, 1968). The shift in pest status *N. lugens* during the post-

Green Revolution era was highly altered. The large-scale introduction of high yielding rice varieties, the use of nitrogen fertilizers and calendar based use of insecticides changed rice agro ecosystems and provided favourable environment of fast results. Planthopper multiplication.

Such alterations affected the natural enemies and favored their populations. The emergence of a new stage in the development of *N. lugens* as a secondary pest to a major pest is known as planthopper survival. Epidemic in rice production systems in Asia (Dyck and Thomas, 1979). Massive epidemics the initial records of these were made in the 1970s in the Asian countries. Severe infestations by Planthoppers had been reported in Philippines and some of South and southeast Asia where their infestation resulted in the hopper burn and crop failures. These epidemics were tightly connected with Extensive chemical management processes and defoliation of resistance in host plants. By the late 1970s and In the beginning of 1980s, regional literature had shown that resurgence by insecticides was a major one. Powerhouse of epidemics of brown planthopper. Frequency of usage of mass-spectrum insecticides. Lost their predators and parasitoids, and populations of *N. lugens* quickly came back, frequently. Overcoming pre-spray concentrations. This case was considered as a typical case of pesticide-induced rebirth of pests in the rice ecosystems (Heinrichs and Mochida, 1984). Ecological studies proved that the brown planthopper attacks were cyclical. Merely cultivated paddy fields. These were population booms which were blamed on a complex of factors. Varietal susceptibility, the utilization of excessive fertilizers of nitrogen and ecological simplification of rice fields with time, it also was found that the populations of *N. lugens* exhibit. High biological diversity, so it adapts to resistant alter types of rice and manages them. This historical realization underlined the necessity of the integrated pest management. Therefore, the historical development of *Nilaparvata lugens* as one of the most dangerous rice pests demonstrates interactions over a long term (Kalode & Krishna, 1979). Crops intensification, pest adaptation and ecological balance destruction in rice Production systems.

Life Cycle of Brown Planthopper (*Nilaparvata lugens* Stal) and biology.

The brown planthopper is a hemimetabolous insect that undergoes the egg, nymphal and adult Stages of life. Host plant condition, nitrogen nutrition, temperature, and ecological interaction of Rice systems are strongly involved with developing and increasing its population (Bae & Pathak, 1970; Mochida and Okada, 1979).

Egg Stage

The ovipositor is used to insert the eggs in batches into the parenchymatous tissues of the rice leaf Sheath or midrib by the females. Eggs are long, oval, a little curved and creamy white

when freshly Laid and they change to yellowish later before hatching. 1.0 to 1.3 mm length per egg. The number of eggs in egg clusters is 2-12 eggs, which depend on female fecundity and nutritional condition of plants (Mochida, 1964). Under tropical conditions, incubation period ranges between 6 to 9 days. An increase in the level of nitrogen in rice plants leads to high egg viability and fecundity hence leading to high population growth (Lu, Heong, Yu and Hu, 2004). Eggs are hidden in the tissues of plants and this step is hard to attack using contact insecticides.

Nymphal Stage

The nymphal stage has five instar stages and it can be completed within 12 to 18 days (with regard to temperature and quality of the host) (Bae & Pathak, 1970). Nymphs are like adults except that they do not have wings or reproduction organs. Nymphs instar are pale white to light yellow, they are initially very active and live near the site of oviposition. They also start feeding as soon as they insert stylets through phloem tissues. Second and third instar are darkened to light brown by degrees and get larger in size. The feeding intensity increments significantly within these stages and nymphs converge in the lower part of rice tillers and suck huge amounts of phloem sap (Mochida & Okada, 1979). Fourth instar have greater locomotion and wing pad formation. At this point, the stress on the plant is manifested at the physiological level because of the active loss of sap. Whereas in fifth instar nymphs, they are dark brown, large and feed more amount of sap. This instar has a major contribution to hopper burn symptoms in high population (Bae & Pathak, 1970). During the nymphal stage, the growth is quicker on nitrogenous rice varieties, establishing that fertilization is a factor of outbreak (Rashid, Jahan and Islam, 2017a).

Adult Stage

Adults are dimorphic, where macropterous are long-winged and brachypterous are short-winged. The macropterous adults are in charge of long distance migration and colonization of new fields and brachypterous adults are in charge of the stable field populations and their fecundity is increased (Denno, Olmstead & McCloud, 1989). Adults are brown with slim body and 4-5 mm when measured. Under good conditions, females are bigger than males and they can lay 200 to 400 eggs in a lifetime (Mochida, 1964). The span of adult life ranges between 10 and 20 days. Feeding of adults also inflicts direct and indirect damages by sucking of sap and transmission of viral diseases like the grassy stunt and ragged stunt (Cabauatan, Cabunagan and Choi, 2009). An important feature of ecology is adult migration, and seasonal long-distance migrations have been observed in East and Southeast Asia, which has led to population

synchrony in the region and Outbreak transmission (Riley, Cheng, Zhang, Reynolds & Smith, 1991).

Host Range

Nilaparvata lugens Stal is a monophagous to oligophagous insect, which is highly host-specific, i.e. it strongly prefers cultivated rice (*Oryza sativa* L.). The ample host suitability research attests that *N. lugens* only successfully finishes its life cycle when feeding on rice plants, but success when feeding on other grasses is low and short lived (Bae & Pathak, 1970). In rice ecosystems, there is a markedly high difference in the susceptibility of varieties. Initially, traditional tall varieties in the habitats favored moderate population whereas with the introduction of semi dwarf, nitrogen sensitive high yield types, host suitability dramatically increased, allowing higher fecundity, quicker development and better nymphal survival (Pathak, 1968). Some species of wild and domesticated rice have been considered as alternative or a resistant hosts. Antibiosis and tolerance are some of the mechanisms of resistance that have been reported in some rice genotypes, which affect the feeding behavior, oviposition as well as survival of *N. lugens* (Kalode & Krishna, 1979). Nevertheless, the long-term sustenance feeding and population increase is largely confined to the cultivated rice ecosystems. The host nutritional status is very important in host suitability. Plant nitrogen value improves greatly the feeding capacity, egg output and population increase of the pest, supporting the close correlation between the pest and the intensively fertilized rice plots (Lu, Heong, Yu & Hu, 2004). Therefore, in spite of the temporary appearance of brown planthopper on grasses, only economically harmful populations are linked with rice and it can be stated that This pest is a specific rice pest.

Ecological Distribution

Its brown planthopper is broadly spread across South, Southeast and East Asia which are the major Rice growing areas. It has a geographical scope of India, Sri Lanka, Bangladesh, China, Japan, Korea, Philippines, Vietnam, Thailand, Malaysia and Indonesia (Dyck, Misra, Alam and Heinrichs, 1979). Ecological research shows that *N. lugens* can survive in humid tropical and Subtropical climates especially in irrigated lowland rice ecosystem where there is year round Availability of hosts due to continuous cropping (Grist and Lever 1969). Pest has been found to be Absent or scarce in upland rice system because of adverse microclimatic condition and low host Persistence. Most important ecological characteristic of bph is the large-scale migration. The Possibility of seasonal migration between tropical sources and temperate rice area has been Recorded such that recolonization of rice fields is possible every crop season (Riley, Cheng,

Zhang, Reynolds, and Smith, 1991). These migrations are very important in harmonizing the outbreaks at The national level. Agronomics is a significant determinant of population density and distribution. High rate of nitrogen fertilization, close planting, and irregular planting of plants all favor the Multiplication and distribution of the planthoppers in the regions (Zhong- Xian, Villareal, XiaoPing & Heong, 2006). Ecological distribution is also determined by natural enemy diversity. In fields consisting of more predators and parasitoids, planthopper populations are lower, which Underlines the significance of ecosystem complexity in the regulation of the population (Settle, Ariawan, Astuti, Cahyana, Hakim, Hindayana & Lestari, 1996). Generally, ecological patterns of *Nilaparvata lugens* demonstrate that climate, crop management, the migration process, and the Structure of the ecosystem in rice-based agroecosystems interact closely.

Economic threshold level (ETL) of Brown Planthopper (*Nilaparvata lugens* Stål):

The brown planthopper has its economic threshold level (ETL), which is determined as the level At which the pest is present in the field and the management action must be implemented in order To ensure that the pest does not reach the economic injury level (EIL) whereby yield lost would be More than the cost of control (Higley and Pedigo, 1993). Since *Nilaparvata lugens* is a pest, which Leads to direct feeding losses not to mention indirect losses due to virus-induced losses, ETL Determination must be critically considered considering the state of the crop, the plant itself, and the surrounding environment. Field based tests also showed that ETL values are modified through Nitrogen fertilization whereby plant attractiveness and pest survival increases. The risk of low Nitrogen levels makes the rice plants less tolerant of planthopper feeding and therefore the Threshold rate of economic damage is lowened (Lu, Heong, Yu & Hu, 2004). Therefore, ETL is Not fixed but has to be modified in relation to agronomic practices. ETL has also been enhanced in sequential sampling techniques that use natural enemies in order to enhance the accuracy of the Sampling process. Rajna and Chander (2013) demonstrated that the presence of predators strongly inhibits the population of planthoppers, thus one can endure high pest populations without financial losses. According to these studies, the practical ETL recommendations in irrigated rice Are usually within the range of 5-10 planthoppers per hill at initial growth stages and it is important To note that regular monitoring and ecosystem-based decision making is more effective compared To prophylactic use of insecticides.

Damage and symptoms:

Direct Feeding Damage

The nymphs and adults of brown planthopper feed on the phloem sap of rice plants with their Stabbing-sucking mouths where the tiller bases are the most frequented. The extraction of sap on a continuous basis leads to lowered movement of nutrients, retarded growth and yellowing of lower Leaves. In extreme cases, plants present the classical hopper burn, with whole hills or areas of rice Drying out early because of damage to the vascular and toxic secretions of saliva (Dyck & Thomas, 1979). It also has early symptoms such as poor tillering and decreased plant height where it Becomes likely to get lodged during heavy rain or high wind.

Physiological and Metabolic Effects of brown plant hopper

Feeding of brown planthopper causes a lot of physiological stress to the rice plant. It has been Indicated that the chlorophyll level, photosynthetic rate and carbohydrate storage have been Reduced after being infested. Although it is true that nitrogen rich plants sustain high population of Pests, they experience more serious physiological damage because of increased feeding activity (Lu, Heong, Yu & Hu, 2004).Prolonged feeding also modifies the plant metabolism leading to the reduction of grain filling, poor panicle exertion, and sterility of the spikelets, in case of infestation At the reproductive stages (Rashid, Jahan & Islam, 2016).

Indirect loss through Virus spreading

N. lugens also serves as a reservoir of economically significant rice viruses including rice grassy Stunt virus and rice ragged stunt virus in addition to direct feeding injury. Symptoms of the infecting plants include excessive tillering, narrow and pale leaf, ragged leaf margins, stunting and Deformed panicles (Cabauatan, Cabunagan & Choi, 2009).Plants infected with the virus seldom Resulted into harvests, epidemics are often associated with large population of the planthoppers, And it is known that additional yield loss occurs due to feeding on other plants, not to mention the Losses that occur due to feeding only (Palmer and Rao, 1981).Symptoms at the Field Level and Crop Loss Pattern Harm is usually manifested in patches because of aggregated distribution of the planthoppers. Under good conditions, the infestation hotspots increase at a massive rate, resulting in the total Failure of the field in severe scenarios. Weakened base of the plants could also contribute to lodging Making the harvest process more difficult (Bottrell & Schoenly, 2012).Therefore, harm inflicted By brown planthopper is an intricate combination of feeding harm, physiological interference and Pathogen transmission that highlights the necessity to identify and control it early and combine Control and management methods.

Economic loss:

The outbreak of brown planthoppers has caused extensive loss in yield in Asia, with geographical Variations depending on the mode of farming, the vulnerability of the varieties, and the dynamics Of the pest populations. In Indonesia, the recurring outbreak of epidemics in 1977-1979 and 1984-1986 wiped off millions of hectares of rice, and losses were estimated to be between 25-60 per Cent on the affected fields (Dyck and Thomas, 1979). Equally, in the Philippines, the heavy Infestations in the wet season resulted in hopper burn and epidemics of viruses causing a loss of Up to half of yields in prone rice types (Varca & Feuer, 1976).The initial mass outbreaks of brown Planthoppers were reported in Kerala in the periods between 1973 to 1974, and also in Andhra Pradesh, Bihar, Haryana, Punjab, Uttar Pradesh, Odisha and Tamil Nadu. Preliminary field Observations indicated losses of 20-45 percent of the yields based on the rice type and time of Planting (Kulshreshtha, Anjaneyulu & Padmanabhan, 1974; Abraham and Nair, 1975). The collapse of varietal resistance and overuse of insecticides that resulted in hopper burn and massive Crop failure were common in areas where the severe outbreaks took place. These articles highlights on the importance of monitoring the BPH populations and implementing integrated pest management methods that are specific to the particular region.The use of modern high yielding Rice and continuous cropping in China has also led to recurrent outbreak of BPH. Field surveys revealed that yield losses in affected areas were 10-30% with high populations of planthoppers in Jiangsu, Zhejiang, and Hunan provinces that resulted in virus spread (Zhang, Liu, Zhu, *et al.*, 2014). The BPH population explosion during 1970s and early 1980s in Thailand led to the massive Hopper burn and virus infection leading to a huge economic loss in both rainfed and irrigated rice Based systems (Tirawat, 1975).In general, place-wise studies reveal that the economical losses are Highly diverse based on varietal susceptibility, agronomic activities, environmental conditions, and Efficacy of pest control. The knowledge of the regional BPH population trends and the Incorporation of ETL-interventions are essential in reducing the losses of yields.

The Brown Planthopper (*Nilaparvata lugens* Stal) is a pest that is managed through the use of fungicide:

Legal method

Control interventions involve the application of insecticide use regulations and the introduction of Resistant varieties to curb the BPH outbreaks. Regional and national policies limit excessive use of broad-spectrum insecticides promoting the use of integrated pest

management (IPM) (Heong, 2009). Such legal frameworks in Southeast Asia have gone a long way to curb the re-occurrence of BPH that is caused by insecticides (Bottrell & Schoenly, 2012).

Mechanical and physical control

The physical control techniques include elimination of the hosts of weeds, and burning of the Infected stubble to minimize BPH carry-overs across seasons (Heong, 1975). Light traps and sticky traps are some of the mechanical means that have been used to track and trap migrating adults especially during their peak migration seasons (Riley, Xia-Nian, Xiao-XI, 1991).

Cultural Control

Synchronous planting, optimal spacing, balanced fertilization, and use of resistant rice varieties are some of the cultural practices. The optimal management of nitrogen can lower the susceptibility of plants, and crop rotation and intercropping with non-host plants such as marigold and onion can be used to control the BPH (Iamba & Homband, 2020; Lu, Heong, Yu, *et al.*, 2004).

Biological Control and chemical Control

The BPH is also naturally suppressed by predators like *Cyrtorhinus lividipennis* and spiders and By egg parasitoids such as *Anagrus spp* (Gurr, Liu, Read, *et al.*, 2011; Ooi & Shepard, 1994). Biological control of conservation using nectar plants helps to increase the survival and Effectiveness of predators (Zhu, Lu, Heong, *et al.*, 2014).

Botanical insecticides

Like neem (*Azadirachta indica*) extracts decrease neemal survival rates when used at 5-percent Concentration (Heong, 1975) and in the Chemical Control, Chemical insecticides such like Imidacloprid and fipronil are active when used at the recommended dosage: imidacloprid 0.3-0.5 G a.i./ha and fipronil 0.2-0.3 g a.i./ha (Garrood, Zimmer, Gorman, *et al.*, 2 Resistance development is reduced by taking care of label instructions.

Microbial Insecticides

Entomopathogenic fungi like *Beauveria bassiana* and *Metarhizium anisopliae* have demonstrated the ability to infect both adult and nymphal stages of BPH in the field. Treatment of 1×10^{13} Conidia/ha in water based formulations results in a large population decrease of the pests without Any effect on their natural predators (Gurr, Liu, Read, *et al.*, 2011). To keep the production of

rice Sustainable and minimize its impact on the environment, the combination of these methods, i.e. Legal and cultural, biological and selective, is suggested.

Conclusion:

Nilaparvata lugens, or brown planthopper, remains a thorny issue in the sustainable production of Rice in Asia. The decades of works and field observations have proved that the contemporary state of the pest as a significant economic constraint is not only a result of its biological adaptability, But also caused by the anthropogenic alterations in rice agro-ecosystems. The long- term change of *N. lugens* to a primary outbreak species is a clear example of the unintended effects of excessive And untimely use of insecticides. Resurgence caused by insecticides has been cited as one of the main factors in population explosions as periodic exposure of chemicals to organisms destroys Natural enemy complexes and favors highly resistant planthopper populations (Heinrichs and Mochida, 1984).The use of chemical control on its own has failed time and again to offer Sustainable control of brown planthopper populations. Rather, it has led to ecological imbalance, Resurrection of pests and long-term unpredictability of rice production systems. Heinrichs and Mochida (1984) strongly proved that not only insecticide misuse enhances the survival of the Planthopper but also hastens the reproductive potential so that the *N. lugens* populations could Quickly recover after being sprayed. These discoveries highlight the importance of exercising Restraint in the application of chemical control because when applied blindly, the control ends up Being an epidemic menace.Conversely, ecologically-oriented methods of pest management Indicate a more viable approach of the brown planthopper in the long term. The experimental Evidence collected in the field has demonstrated that conservation of generalist natural enemies is Important in controlling planthopper population in tropical rice ecosystem. Early-season control Enables predator and parasitoid communities to develop in the presence of alternative prey and Decreased chemical disturbance thus averting planthopper population accumulation (Settle,Ariawan, Astuti, Cahyana, Hakim, Hindayana & Lestari, 1996). This buffering ability of the Ecological setting is necessary in keeping the pests at a level that can be economically injured Without the use of chemicals often.Moreover, ecosystem-based management strategies facilitate Resilience in rice agro-ecosystems through enhancing trophic interactions and recovery of Biological regulation processes. The application of Settle *et al.*, (1996) showed that rice fields with Low levels of insecticides provided better biodiversity and the fields had much fewer outbreaks of Pests. These discoveries support the idea that the control of brown planthoppers should be changed To being reactive (chemical control) to

proactive (ecosystem stewardship). To sum up, the Management of *Nilaparvata lugens* should be approached sustainably, which means that it is Necessary to redefine the pest control practices. The past experiences of failures with insecticides (Heinrichs & Mochida, 1984) and the existence of very good empirical evidence that conservation Biological control is ecologically sound (Settle et al., 1996) all point to the need of integrated Ecologically sound solutions. This can only be done through reduction of chemical dependence And natural enemies conservation, and holistic agro-ecosystem management practices, which will Ensure long-term rice productivity and environmental safety.

Future Work:

Future studies regarding brown planthopper *Nilaparvata lugens* should pay more attention to the Realization of the molecular, genetic and ecological processes that allow such a pest to survive in The conditions of the intensive rice farming systems. Although the traditional methods used in management have been focusing on the short-term control of the population, the long-term solutions demand more information about the adaptive capacity of the pest and its relationship with the host plants and other symbionts. Such investigations depend on critical foundations made by genomic research developments. Global metabolic and physiological adaptations that lead to Survival, nutrient use, and resistance evolution have been identified through whole- genome Analysis of *N. Lugens* and its endosymbionts, and present novel molecular targets in pest control (Xue, Zhou, Zhang, Yu, Cheng, Yu, Jiang, Huang, Wang, Cheng, Zhu, Lou, Yu & Zhang, 2014). The Work to be done in the future should focus on the functional characterization of genes related to Insecticide resistance, the detoxification pathways, and host adaptation. The realization of the Relationship between genetic plasticity and rapid evolution in field populations will be important In designing resistance-management strategies that either delay or prevent control failures. Genomic tools can also be used to aid in the identification of resistance alleles at an early stage, as Well as in supporting evidence-based insecticide rotation programs by integrating with population monitoring. Genomic observations presented by Xue *et al.*, (2014) also indicate that symbiont-mediated nutrient provisioning could be a new point of intervention that has new opportunities to Control biologically informed strategies. The other hot spot that will require research in future is In the creation and implementation of long-lasting host-plant resistance. Even though resistant rice Varieties have been playing a leading role in the management of brown planthoppers, the resistant Breakdown has been a challenge. The prospects of durability are optimistic as molecular Characterization of

resistance genes and high-resolution mapping provide active opportunities in an effort to enhance gene pyramiding and selection of a marker-assisted selection. The discovery and mapping of the resistance genes including Bph18 prove the possibility of breeding of molecular breeding to improve resistance of rice against the changed populations of the planthopper (Jena, Jeong, Lee, Choi, Brar & Kim, 2006). The breeding programs should be designed in future to combine more than one resistance gene with a different mechanism of action to decrease the selection pressure on one gene. Furthermore, host resistance could be applied together with ecological methods, i.e., conservation of natural enemies, to increase the resistance stability of the fields of farmers. The article by Jena *et al.*, (2006) indicates the significance of accurate genetic instruments in the production of next generation rice varieties that have the ability to resist the evolution of biotypes. To conclude, future studies on brown planthopper should be of a multidisciplinary approach that incorporates genomics, molecular breeding, population ecology, and sustainable management of pests. To provide sustainable control of *Nilaparvata lugens*, relying upon genomic information (Xue *et al.*, 2014) and a combination of superior resistance breeding methods (Jena *et al.*, 2006) will be critical to the long-term sustainability of the rice production systems.

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Chapter 2: Yellow Stem Borer (*Scirpophaga incertulas*) of Rice: Bionomics and Integrated Pest Management

Abstract

In Asia, yellow stem borer (YSB) *Scirpophaga incertulas* (Walker) (Lepidoptera: Crambidae) is the most economically significant and common insect pest of rice (*Oryza sativa* L.) especially in the irrigated and rainfed lowland ecosystems. It is monophagous, cryptically internally fed, and highly synchronized to rice growth stages, which allows chronic damage to both the vegetative and reproductive stages with symptoms that include the dead heart and white ear and severely diminish the tillering and grain harvest. The review gives a synthesis of YSB taxonomy and geographic distribution, life cycle biology (egg, larval, pupal, and adult stages), damage mechanisms, physiological effects on host plants and variables affecting population dynamics (nitrogen fertilization, planting timing, and climatic variables). The traditional and new management techniques are talked about in the presence of economic threshold levels (ETL) and monitoring devices like pheromone traps. It focuses on integrated pest management (IPM) methods, including cultural control methods (optimal planting dates, balanced fertilization, water management), host-plant resistance (morphological and biochemical), biological control (egg parasitoids such as *Trichogramma japonicum*, *Telenomus spp.*, *Tetrastichus schoenobii*), biorational insecticides (e.g., spinosad), selective chemicals (e.g., chlorantraniliprole), and behavioral control (e.g., using the mating dis The review points out the transition of depending on general insecticides with a general approach to sustainable and environmental-friendly strategies to reduce the resistance, recurrence, and environmental hazards. The future directions involve the exploitation of genomic understanding, accuracy tracking, and climate-tolerant IPM as a means of managing this chronic rice pest effectively and in the long-term.

Keywords: *Scirpophaga incertulas*, white ear, dead heart, biology, integrated pest management, host plant resistance, biological control, pheromone technology

Introduction

The most significant cereal crop of Asia is rice (*Oryza Sativa* L.) that sustains the food security and million people livelihood (Khush, 2005). Many insect pest categories were found to cause major problem in rice production of which chronic and extensive damages are caused by stem borer (Savary *et al.*, 2000). *Scirpophaga incertulas* (Walker) (Lepidoptera:

Crambidae) is known as the most destructive and economically significant species of stem borer in irrigated and rainfed lowland rice systems of South and Southeast Asia (Dale, 1994; Khan *et al.*, 1991).

Its monophagic status, internal feeding behavior and tightness to the stages of crop growth render it a constant menace during the rice production period (Dale, 1994). Damage is caused by the larval stage of the yellow stem borer which feeds internally into the growing tissues by boring holes into the rice stem (Khan *et al.*, 1991). This is a hidden feeding mechanism that safeguards the larvae against natural predators and contact insecticides making it difficult to manage (Heinrichs and Mochida, 1984). Symptoms of damage are dependent on the stage of the crop: during the vegetative stage, there is the so-called damage of the heart (infestations leading to drying up and death of the central shoot), which is observed in the reproductive stage as the so-called damage of the ear (white ear), or damage of the head (white head), when panicles develop without grain being filled (Dale, 1994; Khan *et al.*, 1991). The two symptoms lead to extensive decrease in the effective tiller count and grain yield and in many cases have no early external evidence of infestation (Savary *et al.*, 2000). The significance of YSB as a pest has grown with the growth of high yielding rice varieties, high fertilizer application and all year round rice production (Heong *et al.*, 2015). The continuous availability of hosts is due to excessive nitrogen application, promotion of larval survival, and asynchronous planting and overlapping crop seasons (Horgan *et al.*, 2016). Besides, climate changes, especially higher temperature and humidity, have also been linked with higher survival rates, accelerated development and more generations per year, further worsening the incidence of YSB (Horgan *et al.*, 2016). Yellow stem borer has long been controlled using chemical insecticides, although excessive and indiscriminate use has resulted in ecological imbalance, resistance occurrence and comeback of pest populations (Heinrichs and Mochida, 1984; Heong *et al.*, 2015). As a result, it has switched to integrated pest management (IPM) approaches involving the combination of cultural practices, host-plant resistance, biological control, and need-based use of selective insecticides (Khan *et al.*, 1991; Horgan *et al.*, 2017). Recent progress in the pheromone technology, parasitoid enrichment, and molecular research of YSB biology have given a new avenue of more precise and sustainable control (Prakash *et al.*, 2007). This chapter is a detailed description of the yellow stem borer including its taxonomy, biology, the symptoms of its damage and the current management measures. To come up with effective, environmental sound and economically viable strategies to control *Scirpophaga incertulas*, it is important to understand the biology and ecological relationship of

this rice pest (Dale, 1994).

Taxonomy and Geographic Distribution

Scientific name – *Scirpophaga incertulas*

Taxonomic position:

Kingdom: Animalia

Phylum: Arthropoda

Class: Insecta

Order: Lepidoptera

Family: Crambidae

Genus: *Scirpophaga*

Species: *incertulas*

The adult males of *S. incertulas* are light brown bigger than female (Dale *et al*, 1994). They have forewings with a bit of color in them, hind wings are white. The forewings of the females are yellowish. The hind wings of the *S. incertulas* are pale white. (Shravani Sanyal, *et al*. 2025) the paddy yellow stem borer is a type of insect that belongs to the family called Crambidae. This family is under the order called Lepidoptera. The paddy yellow stem borer was first described by Francis Walker in the year 1863.

The paddy yellow stem borer is really widespread, it is found in Afghanistan and many countries, in South and Southeast Asia. Includes countries like India and Bangladesh and Sri Lanka and Myanmar and Vietnam and Malaysia and Indonesia and the Philippines and China and Japan.

Economic Importance

The stem borer is a problem for rice crops because it can damage the rice at any stage of growth. This means the stem borer can directly reduce the amount of rice that is harvested and also damage the crop in ways. The stem borer is thought to be the damaging insect to rice crops in the areas where it is found (Savary *et al*, 2000)

When the stem borer infests rice crops things like rainfall and temperature can make a difference, in how quickly the stem borer population grows and how often a new generation of stem borers is produced. The yellow stem borer, which is also known as *Scirpophaga incertulas* is a problem, for rice crops. It attacks the rice plants at every stage of growth. There are types of stem borers that also damage rice crops. We saw some bugs on our crops. These bugs are

called Dark headed stem borer, which is also known as *Chilo polychrysus* and Pink stem borer, which is also known as *Sesamia inferens*. There were also Stripped stem borer, which is also known as *Chilo supressalis* and White borer which is also known as *Scirpophaga innotata*. We found these Dark headed stem borer and Pink stem borer and Stripped stem borer and White borer when our crops were, at the tillering stage (DP Singh *et al*, 2019).

The yellow stem borer causes serious damage, at the beginning of the plants life its damage results in a loss of 0.28 percent. When the plant is getting ready to produce rice the loss is 0.62 percent (Shamik Dey, 2020). This being problem in rice crop cultivation. We need to find ways to stop them from causing so much damage, which means it is important to use a combination of methods to control pests, grow rice varieties that can resist the yellow stem borer and keep a close eye on the crops to minimize loss and keep producing a lot of rice.

Biology

Four stages are seen in Yellow stem borer lifecycle: the egg, the larva, the pupa and the adult. It passes through these stages one after the other. The larva stage of the stem borer has five parts. The larval stage of the stem borer causes damage to rice plant because larva feed inside the stem.

Egg stage

Eggs are flat, bit long (Sanchez *et al*, 2023). They are laid on the outside of rice leaves or the leaf covers. The Yellow Stem Borer prefer to lay eggs on the underside of the part of the leaf portion (Jenny Faith Sanchez *et al*, 2023). Each bunch of eggs can have 50 to 200 eggs in it. Females of yellow stem borer cover these eggs in order to prevent drying out and safeguard from natural enemies. Freshly laid eggs are creamy white and before hatching turns into yellowish gradually. Depending on the humidity and temperature the incubation period varies from 5 to 9 days. Egg laying generally occurs during night hours, and egg survival is higher under warm, humid conditions typical of rice-growing environments.

Characteristic	Description
Appearance	The eggs are creamy white. They are flattened (Kumar <i>et al</i> , 2020). They are oval, in shape and kind of scale-like. These eggs are laid in masses. The masses of eggs are made up of lots of eggs from the thing the eggs.

Oviposition	In the tip of the leaf blade 50 to 200 eggs are laid on the dorsal side.
Protection	The egg mass has a covering. This covering is made up of fuzzy hairs that are a brownish color. These hairs are really silky and feel like velvet. The female's abdomen produces these hairs at the end often called the tuft. Because of these hairs the egg mass really stands out. You can see it easily.
Duration (Days)	5 to 9 days (typically 6-8 days).
Favorable Factors	Optimum Temperature: 24 to 29 degree Celsius. High Relative Humidity: 90%to 100% RH is optimal for high hatching rates; hatching is severely reduced below 70%RH.

Larval stage

The larval stage of the insect has five parts. During these parts the caterpillar eats from the inside of the rice stem. The caterpillar is inside the rice stem for a while. It keeps eating. The larval stage is very important as it cause damage.

Characteristic	Description
Appearance	Newly hatched: Yellowish-green with a dark brown/black head (Gautam <i>et al</i> , 2021). Full-grown: Pale yellow to dirty white, fleshy, with a distinctive dark brown head and a prominent prothoracic shield. Larvae are typically about 20mm long at maturity
Instars	This thing usually goes through 4 to 5 larval instars. When it is really hot the number of instars is lower. When food is hard to find the number of larval instars may go up.

Behavior	When the larvae hatch they spread out. Dig into the leaf sheath. Then they tunnel into the stem of the rice plant (Dale, 1994). The larvae eat the tissue inside the plant. This causes two problems for the rice plant: Dead Heart and White Earhead. The larvae are really good at hiding while they feed.
Duration (Days)	21 to 34 days (average 25-29days).
Favourable Factors	Temperature is a deal for larval development. It gets faster when it is warmer. The best temperature for this is between 23 and 29 degrees Celsius. If it gets too cold at 12 degrees Celsius the development just stops. If it gets too hot at 35 degrees Celsius the larvae die. Diapause: Mature last-instar larvae can enter a state of diapause (dormancy) inside rice stubbles during unfavourable conditions, such as cool winter months or lack of host plants.

First instar larva

The larva is a tiny thing the colour of the larva is grey and the head of the larva is black and dark brown prothoracic shield as well as white bands before mesothorax is present (Kumar *et al*, 2020) . Soon after emergence, it migrates to the plant base and bores into the leaf sheath or stem. This instar causes minimal visible damage externally and lasts about 4–5 days.

Second instar larva

The second instar larvae are bigger. They are creamy yellow, in color. The larvae start eating a lot more. They go deeper into the stem, damages the vascular tissue. The second instar larvae stage usually lasts for about 3 to 4 days.

Third instar larva

The feeding and body size of the larvae increases. The larvae eat a lot of the tissues of the plant. This makes the stem weak, inhibiting translocation of nutrients. The damage symptom is seen externally. The third instar of the larvae lasts for 5 to 6 days.

Fourth instar larva

This stage causes extreme damage internally. Feeding during this stage commonly results in dead heart symptoms during the vegetative phase. The fourth instar larvae stage goes on for 4 to 5 days.

Fifth instar larva

Most destructive stage of larva is the fifth instar. The larvae eat a lot of the stem tissue. Get ready to turn into pupae, inside the stem. Infestation during the reproductive stage results in white ear formation (Dale *et al*, 1994). The fifth instar of the larvae lasts for 6 to 7 days. The larval period totally ranges from 27 to 29 days during kharif (Gautam *et al*, 2020), depending on environmental conditions.

Pupal stage

The rice stem is where pupation happens. It happens inside a silken cocoon. The pupa is a yellow color or sometimes it is dark brown. The pupa stays with its head pointing upwards. This makes it easy for the adult to come out. Before the pupation happens the larva makes a hole, in the wall of the rice stem. The larva then covers this hole with silk. The pupal period of the moth lasts for 5 to 12 days. After that the adult moth comes out through the exit hole. This usually happens in the evening or, at night when it is dark.

Characteristic	Description
Appearance	Pale to dark brown, elongate, and enclosed within a white silken cocoon (Katti et al, 2021). The average size is about 12mm to 3mm.
Pupation Site	The pupation of the moth happens inside the rice stem. This usually takes place near the base of the tiller or just above the water level. Before the larva turns into a pupa it cuts a hole, in the wall of the rice stem, it can come out easily when it is time for the adult moth to emerge from the rice stem.
Duration (Days)	5 to 12 days (average 7-10 days), with duration being inversely related to temperature. The developmental threshold temperature is approximately 15 to 16 degree Celsius.

Favorable Factors	The pupal period shortens at higher temperature than optimum
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Adult stage

These moths are medium size. They have yellow- or straw-coloured wings and body. The females are brown or straw coloured. They have a black spot on their wings right at the centre near the lower edge on the forewing. Hind wings are straw coloured. The females are bigger than the males (Katti *et al*, 2021). They have a tuft at the back which they use to cover their eggs. The male moths are different. They have lots of dark spots near the tip of their brown coloured front wings. These spots are not very easy to see on the wings of the male moths. Adults are nocturnal. The life of an adult is very short it only lives for 2 to 4 days (Kumar *et al*, 2023). Overlapping of many generations occurs in a single rice cropping season.

Sexual Dimorphism in Adult Moths

Adult *S. incertulas* moths display prominent differences in size, color, and specific morphological features, which are vital for identification and reproductive success.

Feature	Female Moth (<i>S. incertulas</i>)	Male Moth (<i>S. incertulas</i>)
Size	Larger (wingspan approx. 24 to 36 mm).	Smaller (wingspan approx. 20mm to 30mm).
Forewings	Bright yellowish-brown or straw colored (Kumar <i>et al</i> , 2023). Possesses a conspicuous single black spot near the center toward the lower angle of each forewing.	Pale yellow to brownish-ochreous or grey. Usually lacks the prominent single black spot. May have a few smaller, less distinct dark spots near the tip of the forewing.

Abdomen	Shorter, wider and stouter. The tip has a lot of golden or yellowish hairs on it. These hairs are really dense. They make a special tuft known as anal tuft or anal scale.	More slender and longer. The anal end has less hair.
Function of Anal Tuft (Female)	The hairs of this tuft are used to cover the laid egg masses on the rice plant. This helps to protect the egg masses. The hairs providing camouflage and make a barrier against natural enemies and dessication	Used for general protection of the genitalia, but not involved in egg covering.
Longevity	Generally lives slightly longer than the male (average 3 to 4 days).	Generally lives a shorter period (average 2 to 3 days).

Life cycle duration

Under favourable tropical conditions, the complete life cycle of *Scirpophaga incertulas* is completed in 42–44 days (CPN Gautam *et al*, 2020), allowing several generations per year.

Damage Symptoms with ETL YSB larvae give typical

Dead heart: During vegetative stage the central leaves shrivel and wither to create a dead tiller which can be easily pulled out; small holes of entry as well as frass can be seen.

White ear: At maturity, panicles become white and chaffy with no grain content, usually with the frass at the base.

The highest and peak incidence of dead heart induced by yellow stem borer was observed after 30 and 40 DAT (Shamik Dey, 2020). In the meantime, the highest and

optimum incidence of white ears caused by yellow stem borer infestation was at 90 and 100 DAT (B N BALAJI and L VIJAYKUMAR, 2025) Yield losses are greater caused by white ears than dead hearts since plants can partially compensate the vegetative damage. 5-10% dead hearts, 1 egg mass per m^2 or 1 adult moth per m^2 K. (CHAKRABORTY, *et al.*) Favourable condition to damage is in heading stage of the crop.

Food and Physiology of Yellow Stem Borer (*Scirpophaga incertulas*)

The yellow stem borer is an internally feeding monophagous pest. Its physiological and feeding behaviour makes it one of the major pests of rice. The larval stage is the only stage that causes feeding damage but adults do not inflict direct damage on the crop.

Feeding habit and location of feeding

This special repertoire of genes may enable YSB to sense the cues and recognize the rice host selectively by eliminating the non-host species, thereby evolving into a strictly monophagous pest (Divya Kattupalli *et al.*, 2021). After being hatched, the newly born larvae move to the lower part of the rice plant and tunnel into the leaf sheath or the stem within a short duration of its hatching. Internally, larvae feed on the growing tissues, such as the apical meristem and vascular bundles. This secret feeding pattern guards the larvae against external interference, predators and contact insecticides which makes it hard to control.

Mechanism of feeding and tissue destruction

The larvae also have powerful mandibulate mouth parts that are designed to chew and these help to destroy the apical growing point and the essential vascular tissues. This internal tunneling impairs the work of xylem and phloem, preventing the movement of water and nutrients, causing the typical mechanical and physiological weakening of the stem called dead heart and white ear (Katti *et al.*, 2021).

Degradation and damage per instar

The intensity of feeding is incremental with the successive larval instar. The initial instar leads to minimal damage which can usually go undetected as compared to middle instar (3rd -4th) which results in severe internal damage. The fifth instar is associated with the highest destructive power, as it feeds on high amounts of stem tissue and leaves permanent damage (Katti *et al.*, 2021; Litsinger *et al.*, 2006).

Physiological effect on rice plants

Constant feeding of the larvae interferes with the physiological processes of rice

plants and decreases the translocation of carbohydrates, the movement of water in the stem, and the chlorophyll content and photosynthetic efficiency (Litsinger, *et al.*, 2006; Rajadurai, *et al.*, 2017). During the vegetative stage, damage to the apical growing point causes the formation of a dead heart and damage to the reproductive stage causes the formation of white ears heads because of the full inhibition of nutrient flow into the developing grains (Satpathi *et al.*, 2012; Katti *et al.*, 2021).

India (according to NIPHM and usual guidelines): Economic Threshold Level (ETL):

- Nursery: 1 egg mass/m²
- Tillering stage: 2 egg masses/m² or 10% dead hearts or 1-2 moths/m². Panicle formation/flowering 2 egg masses/m² or 5 percent dead hearts/white ears. (Ghosal *et al.*)

Management Style - (Conservative to Innovative)

Agronomic and Cultural Management

- Agronomical and cultural practices are main pillars of Integrated Pest Management (IPM) (Ghosal *et al.*) which provide a sustainable and economical method of reducing the infestation of yellow stem borer (YSB) by interfering with the environment and the life cycle of the pest.

Optimized Planting Dates

The time of transplanting is an essential tactic to avoid high seasons of pest attacks of the crop. Studies have shown that timely or early transplanting has a high effect in reducing the number of dead hearts and also white ear heads (Sudeepa Kumari Jha 2021). Namely, rice seedlings transplanted between the second and fourth week of July had the lowest rate of stem borer damage in contrast to late-transplanted crops in the second week of August. Late transplanting has a tendency of aligning the susceptible stages of the rice plant with the peak population of *S. incertulas* and hence the damage would be more serious (Mohammad Abbas Ahmad, *et al.*, 2025)

Balance of Fertilization and Nitrogen

The intensity of the stem borer infestations is directly correlated with the level of nitrogen (N) application. Overuse of nitrogenous fertilizers encourages healthy vegetation

growth, and this is very appealing to the YSB moths to oviposition, and can support the development of the larvae with a good quality of nutrition. Research indicates that 80 kg N/ha to 100 kg N/ha application yields considerably low percentages of dead heart and white ear head than when dosages are increased to 120 kg N/ha (N.B. Pawar, *et al.*, 2023). The management strategies should then aim at balanced fertilization reducing plant vulnerability and ensuring that the yield is maximized

Water and Microclimate Management

Larval movement and survival can be discouraged with the use of proper water management such as intermittent drainage. Moreover, the spacing of plants and the development of an alleyway in the field enhances the aeration and penetration of sunlight. This alteration of the microclimate in the field decreases the amount of humidity which is otherwise conducive to the larvae to survive and so, the pest population is naturally checked.

Host-Plant Resistance and Choice of Varieties

Host plant resistance (HPR) is a foundation of Integrated Pest Management (IPM) against the yellow stem borer (*Scirpophaga incertulas*), which is a sustainable substitute of chemical interventions (Mandras, 1991). The review by Chavan and Patel (2018) states that the resistance is regulated by a complex of morphological and biochemical characteristics that disrupt the selection, feeding, and development of the pest. In morphology, the characters that are positively related to resistance are high trichome density, smaller stem diameter and height of the plant, which serves as a physical barrier or deterrent to oviposition and larval entry. On the other hand, genotypes prone to attack are usually wider in stems and expansive in the area of the leaf. The biochemical study indicates that resistant varieties retain considerably high amounts of total phenols, tannin and silica (Prakash *et al.*). The presence of high silica material is especially critical since it causes physical wearage on the mandibles of larvae resulting in a high death rate among the larvae. Moreover, biochemical resistance is associated with a reduced level of total sugars and proteins, thus diminishing the nutritional value of the host, thus eliciting the antibiosis mechanism, which inhibits the larvae survival and growth. Silica enhanced the growth of plants and the level of attack resistance by *S. incertulas* (Patchane and Khan, 1990). Response of the harder epidermal cells on the stems and leaf sheaths to silica slowed larval penetration. The moderately resistant RG 53, RG 74, RG 148, and TPS 5 genotypes were resistant in oviposition and white ear (N Devasena, *et al.*, 2018). According to Chatterjee *et al.* (2021), the selection of resistant genotypes is among the main defense mechanisms that limit the use of chemical pesticides. Their findings indicate that

early duration variety viz. Narendra 97 and IR 50 as well as mid-early duration variety i.e. IR 64 and IET 17904 are especially useful as multiple-pest resistant donors that can sustain damage levels that are much lower than the original Economic Threshold Levels (ETL) even with a high pest pressure (Chandramani *et al.*, 2010).

Biological and Bio-rational control

Application of inundative releases of *Trichogramma* wasps is also a potential non-chemical approach to the management of the yellow stem borer (*Scirpophaga incertulas*), the most important pest in rain-fed lowland and flood-prone rice ecosystems. A study by Tang *et al.* (2017) compared the performance of two species, *Trichogramma japonicum* and *T. chilonis*, and the results showed that both species could both successfully parasitize YSB egg masses in the laboratory, but their performance in the field was significantly lower. Field trials found only 9%- 7.7% egg mass parasitism in *T. japonicum* and 15%-14.1% in *T. chilonis*, and no significant difference between release densities was found of 50,000, 100,000 and 200,000 wasps/ha³. The biorational management of the yellow stem borer is aimed at the use of selective insecticides and biological derivatives that would cause minimal disruption of the ecology and be highly effective. Chatterjee and Mondal (2014) found the bacterial derived insecticide Spinosad 45% SC to be the most effective biorational treatment with a high reduction of 80.27 percent in dead hearts, and 67.10 percent in white ears over untreated controls. The experiment showed that two treatments of Spinosad that began 31 days following transplantation increased the yield by a significant margin of 69.96. Botanical extracts like Azadiractin is also efficient, many where less potent than Spinosad. In addition, entomopathogenic fungi like *Metarhizium anisopliae* and *Beauveria bassiana* were moderately effective with *M. anisopliae* being the more effective microbial agent. These results imply that the use of Spinosad and botanical formulations in the management of the YSB in rice can effectively control the population of this pest without the need to increase the environmental hazards of the common synthetic neurotoxins.

Chemical Controls

The use of chemicals as a control measure against yellow stem borer (*Scirpophaga incertulas*) is also a critical aspect of managing the pests when they are in excess of the economic threshold levels. The review by Roy *et al.* (2022) states that the larvae is effectively suppressed with the use of multiple insecticide groups, such as organophosphates, carbamates, and the newer chemistry molecules. The conventional agents like Carbofuran 3G (used at 25 kg/ha) and Cartap hydrochloride 4G (used at 25 kg/ha) are commonly used due to its

systemic effect on the internal feeding larvae. Moreover, recent molecules such as Fipronil 5% SC (1000150 ml/ha) and Chlorantraniliprole 18.5% SC (150 ml/ha) have been found to have great efficacy with comparatively reduced doses (Rahamam *et al.*, 2019). Phosphamidon 40% SL and Quinalphos 25% EC are other recommended chemicals that are used to reduce cases of dead hearts in the vegetative stage and white ears in the reproductive stage. The next-generation insecticides provide very effective and more ecologically compatible solutions to the management of the yellow stem borer (YSB), *Scirpophaga incertulas*, than the traditional chemical treatments. Rahaman and Stout (2019) discuss the anthranilic diamide chlorantraniliprole 0.4% G (which is used at the rate of 10.96 kg/hm²) as the best molecule, as it has the highest reduction of the symptoms of deadheart and whitehead and the greatest increase in the grain yield. The insecticide is especially mentioned to have a good safety profile to natural enemies, with it being the least detrimental to generalist predators and egg parasitoids such as *Trichogramma sp.* and *Telenomus sp.*

Pheromone and Manipulation of Behaviour

Mating disruption as a behavioral control method has been very effective and is a non-chemical way of controlling the yellow stem borer (*Scirpophaga incertulas*) in rice ecosystems. Using slow-release pheromone preparations, scientists have shown that male moth communication can be impaired to the point where traps catches are decreased by up to 98 percent relative to insecticide-treated sites. It is important to note that research has shown that even the unnatural pheromone mixtures or those that target other related species like *Chilo suppressalis* can be useful in inhibiting *S. incertulas* damage, which implies some degree of elasticity in the control of pheromones. These pheromone treatments can be used in the early stages of crop development (as early as 9 days after transplanting) to offer season-long protection, which is very beneficial since white head and yield increases 5-12% when compared to the practice of traditional insecticides (Cork *et al.*, 1996). Specialized Pheromone and Lure Application Technology (SPLAT) as a formidable substitute of conventional insecticides. Recent studies show that wax-based SPLAT-YSB lures are better than powder-based or talc-based ones because they present a season-long duration of existence and may be deployed with minimal oversight of the field. Namely, application of 10 g per hectare at 1000 locations has been found as the best dosage to saturate the field environment, which effectively interferes with male mating behavior and dramatically decreases the number of cases of dead heart and white ear damage. In contrast to short-term talc preparations, the slow-release character of the wax-based pheromones provides a steady

protection throughout the harvest period, providing a sustainable and labor-saving approach to integrated pest management in rice ecosystems (Badari Prasad *et al.*, 2023).

Integrated Management Recommendations (Field Focus)

For the efficient control of yellow stem borer (*Scirpophaga incertulas*), an integrated pest management strategy should be adapted. This involves compatible incorporation of cultural, mechanical, biological and chemical approaches in managing the pest. Prevention measures include seed treatment, seedling root dips with carbendazim 12% + mancozeb 63% WP. Carbofuran granules are to be applied in nursery at 160g / cent at 20 days after sowing (DAS), 15 days afterwards at transplanting (DAT), followed by a main field application at 25kg/ha. Adaptations of the culture such as skip-row transplantation; skipping two rows between every ten increase the penetration of light and ventilation and the environment is less favourable to the growth of the pests. Physical and mechanical measures are necessary namely, collection and destruction of egg masses, installation of pheromone traps at a density of 10 to 20 traps per hectare to track and mass-trap the male adults (Ghosal, *et al.* 2017). The biological control is also aided by constructing bird perches and special structures that promote the growth of spider population. The economic threshold levels (ETL) must form the basis of chemical interventions with early applications of chlorantraniliprole 0.4% GR at 1530 DAT or cartap hydrochloride at 2g/l at the panicle initiation stage (c. 45 DAT). It has been shown that these holistic models can reduce the occurrence of dead heart to as little as 2.50% and the number of hibernating larvae per stubble to 1.10, and that these models will reduce the incidence of the white ears by 64.74 on average than the traditional practices. This results in increased mean grain yields (as high as 7750 kg/ha) and increased benefit cost ratios (Ramulamma, A., *et al.* 2022).

Conclusion and Future Directions

Scirpophaga incertulas Walker is one of the most resistant and potent pest of rice. The pest has proved to be an issue because of the type of damage it causes caused by consuming the rice plant tissues internally. The stem borer contains host plants. It has lifecycle in sync with rice. This has made it an issue since it targets rice plants at their different stages of life and this has made sure that regardless of the many measures that have been established over the years to attempt to contain the pest, they have not been successful. In this regard, the present paper will seek to gather the different available information concerning the pest. It seeks to highlight the ineffectiveness of management using one approach. According to the facts reinforced in this paper, it is clear that the management of the pest would need a mix of

approaches. The cultural practices that hamper the formation of the pest, the application of rice varieties that is resistant/conduction of research on pest-resistant varieties of rice through the research and development of tolerant varieties using genetic manipulation strategies. An important part of this aspect is the conservation of the own predators of the pest especially the egg-laying wasps. Behavioral control mechanisms by relying on pheromone-based mechanisms; by mechanisms that focus on mating behavior of the pest have been effective. These methods can make sure that prevention is done before the pest breeds. The strategies are viable because they do away with the excessive use of general purpose insecticides. The selective application of insecticides depending on a particular amount has been found to be effective in the control of the pest without causing additional harm to non-target organisms. The future strategies in managing the pest should entail the deliberations of the requirements of rice production under a fluctuating climatic conditions by applying the integrated pest management strategies. The information levels of the scientific community in the various fields of genetic modifications are promising to improve due to the emergence of advances in the field of molecular biology/genomics.

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Chapter 3: Fall Armyworm in Maize: Biology, Invasion Ecology and Integrated Management

Abstract

Fall armyworm (*Spodoptera frugiperda*) is a highly destructive, migratory lepidopteran pest of maize with global economic importance. Native to the Americas, it has recently invaded Africa and Asia, causing serious yield losses. Its polyphagy, high reproductive potential, and resistance to several insecticides complicate management. This chapter summarizes its history, taxonomy, biology, damage, economic impact, and integrated management strategies with emphasis on biological and eco-friendly approaches. (Abrahams *et al.*, 2017; Day *et al.*, 2017; Prasanna *et al.*, 2018)

Key words: Fall armyworm, maize, *Spodoptera frugiperda*, invasive pest, IPM

Introduction

Maize (*Zea mays* L.) is a principal cereal crop cultivated worldwide, forming a cornerstone of food security, livestock feed, and economic stability—especially for smallholder farmers in Africa, Asia, and the Americas. Among the numerous pests that threaten maize production, the fall armyworm (*Spodoptera frugiperda*) has emerged as one of the most destructive and economically important insect pests in recent decades (Capinera, 2000). Native to the tropical and subtropical regions of the Americas, fall armyworm is a highly polyphagous Lepidopteran capable of feeding on more than 350 plant species, including major cereals such as maize, rice, and sorghum—a versatility that enables its establishment across diverse agro-ecological zones.

The pest's larvae feed voraciously on maize leaves, whorls, and reproductive structures, leading to extensive defoliation and reduced grain yields if not managed properly. In 2016, fall armyworm was first reported in West and Central Africa, marking a significant invasive spread beyond its native range, and it has since expanded to many countries in Africa, Asia, and beyond. Its rapid global spread has exacerbated maize yield losses and heightened concerns over food security, particularly in regions where maize is a staple crop and farmers lack access to effective management resources.

The pest's high reproductive capacity, migratory ability, and adaptability to diverse

climates make control challenging. Adult females can produce large numbers of eggs and populations can build rapidly under favorable conditions. Consequently, understanding the biology, ecology, and integrated management strategies for fall armyworm is essential for safeguarding maize production and ensuring sustainable agricultural systems in affected regions. (Capinera,2000).

Fall armyworm attacks maize at all growth stages, but severe damage is commonly observed during the vegetative phase, where larvae feed voraciously on whorl leaves, resulting in extensive defoliation and yield reduction (Hruska and Gould, 1997;). In Africa, reported yield losses range from moderate to complete crop failure under severe infestation, posing a serious threat to food security. The pest's ability to develop resistance to several insecticides and its adaptability to diverse agro-ecological zones further complicate management efforts (Sparks, 1986; Prasanna *et al.*, 2018). Therefore, understanding the biology, ecology, damage potential, and management options of fall armyworm is essential for developing sustainable and integrated pest management strategies in maize-based farming systems.

History of Fall Armyworm

The fall armyworm (*Spodoptera frugiperda* J.E. Smith) was first recognized as a serious agricultural pest in the early twentieth century in the United States. One of the earliest comprehensive studies on its biology, seasonal occurrence, and damage described its recurrent outbreaks on maize and other cereals in the southern United States. Subsequent studies confirmed that *S. frugiperda* is native to the tropical and subtropical regions of the Americas, where it has long been a key pest of maize, sorghum, cotton, and several other crops (Vickery, 1929; Sparks, 1979).

Throughout the mid- and late-twentieth century, fall armyworm was extensively studied in North, Central, and South America due to its severe economic impact and its strong migratory behavior. Research during this period highlighted its inability to diapause, necessitating annual long-distance migration from warmer regions to temperate maize-growing areas (Rose *et al.*, 1975; Sparks, 1986). Advances in population ecology and migration modeling further demonstrated that seasonal wind patterns facilitate large-scale movement of adult moths across continents (Nagoshi *et al.*, 2012; Westbrook *et al.*, 2016).

A major turning point in the history of fall armyworm occurred in 2016, when the pest was reported for the first time outside the Americas, causing widespread outbreaks in West

and Central Africa (Goergen *et al.*, ;2016) Within a short period, it spread rapidly across sub-Saharan Africa, severely affecting maize production and raising significant concerns regarding food security (Day *et al.*, 2017; Abrahams *et al.*, 2017). By 2017–2018, the pest had become firmly established across most maize-growing regions of Africa, prompting international attention and coordinated management efforts led by organizations such as FAO .The invasive success of fall armyworm is largely attributed to its high reproductive capacity, polyphagous nature, and adaptability to new agro-ecological environments, marking it as one of the most significant invasive insect pests of modern agriculture.

Host Range

The fall armyworm, *Spodoptera frugiperda*, is a highly polyphagous pest with a broad host range that contributes to its persistence and rapid spread across agro-ecosystems. Although maize is its preferred host, the insect has been reported to feed on more than 80 plant species belonging to different botanical families. Cereals such as maize, sorghum, rice, and millet serve as primary hosts, supporting complete larval development and high reproductive potential.

Apart from cereal crops, fall armyworm also infests several grasses and weed species, which act as alternate hosts and reservoirs during off-seasons. Weed-infested fields enhance larval survival and facilitate population carryover between cropping cycles (Norris & Kogan; 2000). Variation in host suitability has been observed among maize genotypes, with certain cultivars exhibiting partial resistance that reduces larval growth and feeding efficiency (Lara *et al.*, 1984)

The wide host adaptability of *S. frugiperda* enables it to persist under diverse ecological conditions and complicates management strategies. Therefore, understanding host preference and crop-weed interactions is essential for designing effective integrated pest management programs.

Taxonomic Classification of Fall Armyworm

The fall armyworm is a lepidopteran insect belonging to the family Noctuidae, which comprises many agriculturally important nocturnal moths. Its taxonomic position has been well established through classical morphology and later supported by genitalic and molecular studies.

Kingdom:Animalia

Phylum:Arthropoda

Class:Insecta

Order:Lepidoptera

Suborder:Glossata

Infraorder:Heteroneura

Superfamily:Noctuoidea

Family:Noctuidae

Subfamily: Noctuinae (often placed in Amphipyridae in earlier classifications)

Tribe:Prodeniini

Genus:*Spodoptera*

Species: *frugiperda* (**J.E. Smith**)

Stage-wise Biology of Fall Armyworm

The fall armyworm undergoes complete metamorphosis, passing through egg, larval (six instars), pupal, and adult stages. Each stage has distinct biological and ecological characteristics that contribute to its pest status

Egg Stage

Eggs are laid in masses containing approximately 100–200 eggs, usually on the underside of maize leaves. The egg masses are often covered with a layer of grayish scales from the female abdomen, which protects them from desiccation and natural enemies (Luginbill, 1928a; Capinera, 2000). Eggs are dome-shaped, creamy white when freshly laid, and turn darker before hatching. The incubation period generally ranges from 2 to 3 days under warm tropical conditions.

Larval Stage

The larval stage of the fall armyworm (*Spodoptera frugiperda*) is the most damaging phase in its life cycle and consists of six instars before pupation. Larvae feed intensively on maize foliage and whorls, leading to significant crop damage and yield loss if unmanaged. (Pathak *et al.*, 2024).

The larval stage consists of six instars and is the most damaging phase.

1st instar: 2.60 ± 0.49 days

2nd instar: 2.70 ± 0.46 days

3rd instar: 2.50 ± 0.50 days

4th instar: 3.10 ± 0.83 days

5th instar: 3.30 ± 0.64 days

6th instar: 4.50 ± 0.67 days

Pupal Stage

Fully grown larvae drop to the soil and pupate at a depth of approximately 2–8 cm. The pupa is reddish-brown and smooth. The pupal stage typically lasts 7–14 days, with development influenced by soil moisture and temperature. Pupae are subject to predation and parasitism in the soil environment (Pair and Gross, 1984)

Adult Stage

Adult moths are medium-sized, nocturnal, and strong fliers capable of long-distance migration. Forewings of males are mottled gray-brown, while females are generally lighter and more uniformly colored (Brown and Dewhurst, 1975). Adults mate soon after emergence, and females may lay up to 1,000–1,500 eggs during their lifespan. The lack of diapause and high migratory capacity enable continuous reproduction and rapid spread in favorable environments.

Host Range and Ecological Distribution

The fall armyworm (*Spodoptera frugiperda*) is a highly polyphagous and ecologically adaptable pest with an exceptionally wide host range and broad geographic distribution, factors that contribute to its status as a major global agricultural threat. In its native Americas, FAW feeds on a diverse array of plant species; larval host plant lists include more than 350 species across 76 plant families, with grasses (Poaceae) such as maize and sorghum being the most

preferred hosts cited in (Montezano *et al.*;2018). Beyond cereals, fall armyworm larvae are capable of completing their life cycle on crops including rice, sugarcane, soybean, cotton, wheat, barley, and various vegetables (e.g., tomato, cabbage) under suitable conditions, although performance and survival vary across hosts. Field surveys in India have similarly documented FAW infestations on maize as well as on cowpea, chilli, sugarcane, cabbage, cauliflower, and sorghum, indicating its ability to exploit diverse hosts in varied agroecosystems.

Apart from cereal crops, fall armyworm also infests several grasses and weed species, which act as alternate hosts and reservoirs during off-seasons. Weed-infested fields enhance larval survival and facilitate population carryover between cropping cycles (Norris and Kogan, 2000). Variation in host suitability has been observed among maize genotypes, with certain cultivars exhibiting partial resistance that reduces larval growth and feeding efficiency (Lara *et al.*, 1984)

Ecologically, FAW is native to tropical and subtropical regions of the Americas, where it completes multiple generations per year and is constrained by cold winters only in the far northern limits of its range. Its migration capability enables seasonal movement into temperate regions of North America but prevents overwintering outside warm areas. Since its first detection outside the native range — in West and Central Africa in 2016 — FAW has rapidly expanded across sub-Saharan Africa, Asia, and Australia, establishing in diverse climates and cropping systems (reviewed generally in the literature on invasive distribution; In South Asia, reports indicate that FAW was first observed in India in 2018 and has since spread widely across maize-growing regions, demonstrating strong ecological plasticity and adaptation to new environments

The adaptability of FAW to a wide host range and its ability to exploit both primary hosts such as maize and alternative hosts in cereal, legume, and horticultural crops underscore the challenge of management across landscapes. This broad distribution and host flexibility make FAW a persistent threat to food security in tropical and subtropical agroecosystems worldwide.

Economic Threshold Level of Fall Armyworm

The economic threshold level (ETL) is defined as the pest density at which control measures should be applied to prevent the pest population from causing economic damage. For *Spodoptera frugiperda*, ETL varies depending on the crop growth stage, planting density,

and local environmental conditions. In maize, early vegetative stages are particularly vulnerable, and even low larval infestations can significantly reduce yield if left uncontrolled. Studies suggest that ETL ranges from 4–5 larvae per plant during early vegetative stages, and higher thresholds can be tolerated in later stages (Prasanna *et al.*, 2018). The threshold is also influenced by natural enemy presence, as predators and parasitoids can suppress FAW populations naturally, potentially increasing the ETL (Murúa *et al.*; 2015). Monitoring techniques such as regular scouting, pheromone traps, and visual larval counts are essential to estimate pest density accurately and apply interventions at the correct time to minimize yield loss while avoiding unnecessary pesticide use.

Damage and Symptoms of Maize Fall Armyworm (*Spodoptera frugiperda*)

Fall armyworm (*Spodoptera frugiperda*) is a major pest of maize worldwide, causing severe yield losses at different crop stages (Sparks, 1979). Its larvae are highly polyphagous and feed on leaves, whorls, tassels, and ears, leading to progressive defoliation and direct ear damage (Barfield *et al.*, 1980; Busato *et al.*, 2005).

Seedling and Early Vegetative Stage

At the early growth stages, newly hatched larvae feed on tender leaf tissue, producing small pinholes or “windowpane” damage, where the upper epidermis is eaten but the lower remains intact. Feeding in whorls results in ragged leaf edges and skeletonized areas, which can reduce photosynthetic efficiency and weaken young plants

Late Vegetative Stage

As larvae develop through successive instars, damage becomes more severe and conspicuous. Later instars consume large portions of the leaf blade, leaving irregular holes and skeletonized leaves with frass accumulation in leaf whorls (Pashley *et al.*, 1987b; McMichael and Prowell; 1999). Heavy infestations at this stage can lead to “dead heart” symptoms, where the central growing point is destroyed, stunting plant growth (Nagoshi and Meagher; 2004).

Reproductive Stage – Tassels and Ears

During the reproductive stage, FAW larvae attack tassels, silks, and cobs, causing tassel shredding, poor pollination, and direct kernel damage (Westbrook and Sparks, 1986). Ear feeding reduces kernel set and quality, while secondary infections may occur through feeding wounds. Yield losses at this stage are particularly economically significant.

Field Indicators

- Windowpane or pinhole leaf damage on seedlings.
- Ragged, skeletonized foliage on older plants
- Frass accumulation in whorls
- Dead heart formation in heavily infested plants
- Tassel and ear damage, leading to reduced pollination and grain quality

Economic Loss (Place-wise)

Maize yield losses due to *Spodoptera frugiperda* vary widely depending on location, environmental conditions, and maize genotype. In Brazil, (Figueiredo *et al.* ;2005) reported that infestation during early vegetative stages can reduce grain yield by 20–50%, with significant reductions in both dry matter production and ear weight. (Cruz *et al.*;1999) observed that soils with higher aluminium saturation exacerbated larval damage, leading to further yield decline.

In regions with intensive maize cultivation under conventional practices, economic losses are also influenced by weed competition, which can intensify pest damage (Gomes *et al.*, 2007). Intercropping systems and proper nutrient management have been shown to partially mitigate these losses.

Overall, the impact of fall armyworm on maize production demonstrates the need for location-specific integrated pest management strategies to reduce both direct and indirect economic losses

Management

Legal Methods

Chemical insecticides approved by local agricultural authorities are commonly used for fall armyworm control. Pyrethroids such as deltamethrin and organophosphates are applied according to recommended doses to reduce larval populations and prevent economic damage (Badji *et al.*;2004). Farmers must strictly follow label instructions to avoid environmental hazards and development of resistance.

Physical and Mechanical Control

In small-scale maize fields, physical removal of egg masses and early instar larvae can significantly reduce infestations. Handpicking or crushing egg masses on leaves prevents larval

emergence (Figueiredo *et al.*;2005). Light traps and pheromone traps are also used for monitoring and reducing adult moth populations.

Cultural Management

Cultural practices are a sustainable way to reduce maize fall armyworm infestations. Intercropping maize with legumes such as cowpea or soybean can reduce larval survival, feeding damage, and enhance the presence of natural enemies (Carruthers *et al.*;1998). Adjusting planting dates to avoid peak oviposition periods helps seedlings escape early larval attack. Crop rotation and removal of infested crop residues minimize pest build-up. Proper weed management also contributes to reducing pest survival, as weeds may serve as alternate hosts or shelter for larvae

Biological Control

Natural enemies such as predators (ladybird beetles, ants) and parasitoids (*Trichogramma* spp.) play an important role in controlling fall armyworm. Parasitoids can be released at rates of 50,000–100,000 per hectare during peak egg-laying periods to effectively reduce larval populations. Conserving natural predators through reduced pesticide use also enhances biocontrol efficiency.

Botanical Chemicals

Botanical insecticides like neem (*Azadirachta indica*) are effective against all larval instars. Neem seed extracts or aqueous solutions (0.03–0.05%) are sprayed on foliage at 7–10 day intervals, causing growth inhibition, reduced feeding, and mortality. (Maredia *et al.*; 1992.)

Microbial Management

Microbial insecticides, particularly *Bacillus thuringiensis* (Bt), are effective against early larval stages of fall armyworm. Bt formulations act on the larval gut, causing mortality within a few days after ingestion (Morreira *et al.*; 2006). Recommended application rates are typically 1–2 kg/ha, targeting young larvae for maximum efficacy. Combining microbial insecticides with cultural practices, such as intercropping or adjusting planting dates, enhances pest suppression while reducing dependence on chemical insecticides.

Chemical Management of Maize Fall Armyworm (*Spodoptera frugiperda*)

Chemical control remains an important component of fall armyworm management, particularly under severe infestations where economic threshold levels are exceeded. Several classes of insecticides have been reported to provide effective control when applied at early larval stages. Pyrethroids such as deltamethrin (2.8 EC at 12.5–15 g a.i./ha) and lambda-cyhalothrin (5 EC at 15–20 g a.i./ha) are commonly used due to their rapid knockdown effect on larvae (Badji *et al.*; 2004). However, repeated use of pyrethroids may lead to resistance development and adverse effects on non-target arthropods.

Organophosphate insecticides, including chlorpyrifos (20 EC at 500–750 g a.i./ha), have also been reported as effective against early and mid-instar larvae by causing nervous system disruption. Newer insecticide molecules such as emamectin benzoate (5 SG at 10–12 g a.i./ha) and spinosad (45 SC at 75–100 g a.i./ha) have gained prominence due to their high efficacy at low dosages and relatively safer environmental profile.

Future Work

Future research on maize fall armyworm (*Spodoptera frugiperda*) should prioritize the development of sustainable and long-term management strategies. Breeding and deployment of maize varieties with stable resistance to fall armyworm remains a key research area, particularly through the identification of resistance genes and incorporation of host plant resistance traits. Molecular tools and genomic approaches may further enhance resistance breeding programs.

Greater emphasis is required on strengthening biological control through conservation and augmentation of native predators and parasitoids, as well as improving mass-rearing and field release techniques. Research on the integration of biological agents with botanical and microbial insecticides will improve the effectiveness of integrated pest management (IPM) programs.

Continuous monitoring of insecticide resistance and understanding resistance mechanisms are essential to guide rational pesticide use and delay resistance development (Hardke *et al.*; 2015). Additionally, climate change effects on pest migration, population dynamics, and outbreak patterns require further investigation to develop accurate forecasting and early warning systems. Farmer participatory research and decision-support tools should also be strengthened to enhance adoption of IPM strategies in maize based cropping systems.

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Chapter 4: Green Leafhopper (*Nephotettix* spp.) in Rice Ecosystems: Biology, Ecology, Climatic Interactions and Integrated Pest Management

Abstract

Oryza sativa L. (Rice) is the major food crop to over half of the world population and other countries which are Asian countries contribute the greatest number of the world production and consumption. Sap-feeding hemipteran is one of the many types of arthropod pests that have been increasing to a problematic status because of the feeding injury, as well as in transmitting of viral diseases in rice. The green plant hopper (*Nephotettix* spp.) is one of the most harmful insects pests that affect rice in tropical and subtropical areas economically. Besides undermining plants by constantly sucking out phloem sap, *Nephotettix* species are very helpful vectors of rice tungro disease, a viral complex that causes devastating losses in yield and periodical epidemics.

The past decades are characterized by a high rise in the frequency and severity of green plant hopper occurrences, which are driven by enhanced rice cultivating, overuse of nitrogen fertilizers, erosion of agroecosystem biodiversity, the indiscriminate use of insecticides, and the continuous climate change. This review is a of current studies dedicated to the biology, distribution, host relationships, damage processes, ecological relationships, and control of green plant hopper in rice ecosystems. Specific focus is made on the pest population ecology, the responses under climate mediation, development of resistance to insecticides, resistance against host plants, and biological control through conservation. There is a critical analysis of the integrated pest management (IPM) strategies which focus on ecological engineering, use of resistant cultivar, balanced nutrition, and selective chemical intervention. New uses of digital agriculture and predictive pest management are also considered as the elements of future climate-resilient rice IPM. It is hoped that by reserving existing knowledge on science, this review can be used to either facilitate the adoption of sustainable pest management practices or provide information to support research and policy interventions towards long-term stability of the rice production systems.

Introduction

Over 165 million hectares of rice are cultivated worldwide and rice cannot be replaced by alternative foods as it is considered a major contributor to daily caloric intake especially in

Asia where it accounts to a considerable portion of food security. Although the production of rice has undergone considerable improvement with regard to breeding and crop management, the production is still affected by constant biotic constraints where the production will incur tremendous losses due to insect pests. Insect pests are able to decrease rice yield by 20-30 per cent under conditions of limited management, and sap feeding hemipteran hosts have emerged as a major dominant factor in intensely managed systems of production (Savary *et al.*, 2019). Among these species, green plant hoppers of the genus *Nephotettix* have become especially useful because of their adaptability in the ecology of host species, marked population increase rates, and the ability to transmit viral pathogens.

Many economically significant species belong to the *Nephotettix* species complex, the first most famous being *Nephotettix virescens* and *Nephotettix nigropictus* that are numerous in South and southeast Asia. The insects feed on phloem sap as their main preference, which imposes chronic physiological stress as indicated by stunted tillering, ineffective mobility of assimilates to the grain, and grain filling. Contrary to the chewing herbivores, the damage can take time and become invisible at initial stages of the infestation by leafhoppers. The economic damage is not felt, and thus before it is realized, populations grow exponentially making it difficult to take timely measures to combat them.

An important consideration that puts greater significance on *Nephotettix spp.* is their capability to cause a viral syndrome known as rice tungro disease caused by the joint action of rice tungro bacilliform virus and rice tungro spherical virus. Tungro outbreaks are closely linked with high population of green plant hopper and may cause massive yield loss or total crop failure in case of a major epidemic (Horgan *et al.*, 2015). This means that the control of green plant hopper populations not only forms the core of direct feeding damage reduction but also in alleviating the spread of the virus in the rice ecosystems.

High nitrogen fertilization leads to higher nitrogen levels in plants and plants become succulent, thus host suitability and higher survival, fecundity and population growth of hoppers (Lu *et al.*, 2007). Never-ending rice culture, planting out of time, and simplified landscapes also contribute to the persistence of pests as well as reduced the performance of natural predators. Moreover, because of lengthy-term use of broad-spectrum insecticides, ecological control has been broken, and the development of insecticide resistance among hopper groups has intensified (Bass *et al.*, 2015; Zhang *et al.*, 2018).

Climate change is another factor that is increasing in power in the outbreak of green plant hoppers. The increasing temperature, changing the rainfall regimes, and the increasing variability of climatic conditions are changing the rate of increase of pests, the abundance

seasonally, and distribution. According to the world assessments, there is a likelihood that climate warming will increase pressure of insect pests on major cereal crops such as rice, and therefore it will lead to increased threat to food security risks in the vulnerable areas (Deutsch *et al.*, 2018; Bebber *et al.*, 2013).

With these forces of pressure in view, management of green plant hopper under sustainability demands an ecological based and integrative approach. Even more recent developments in the ecological engineering field, diversification of habitats, and digital technologies in decision-support optimize the chances of managing pests in the changing climate conditions (Gurr *et al.*, 2017; Prasanna *et al.*, 2023). This is a review of the existing peer-reviewed literature on the ecology and management of green plant hopper with an aim of assisting in the development of climate-resilient IPM policies applicable in the production of rice sustainably.

Green plant hopper Distribution, Host Range and Alternate Hosts.

The two main variables are the Geographical Distribution and Prevalence in Rice.

The green plant hoppers (*Nephotettix spp.*) are found in the key areas of rice production of South, southeast, and East Asia where the climate and cropping conditions offer unending chances of survival and reproduction. The conditions favoring the establishment of population are very good due to warm temperatures, high relative humidity and extensive irrigated rice plantations. The species complex most likely to be found in tropical and subtropical rice ecosystems is *N. virescens* and *N. nigropictus*; the populations data of these species are highly dependent on seasonal weather conditions and intensity of harvesting (Kiritani, 2019).

With the advanced use of high-yielding rice and other production practices which have intensified, the infestation of green plant hoppers has risen. The patterns of planting crop denoted by continuous rice crop and overlapping history of crop planting and absence of planting synchrony allow perpetual reproduction of pests and intersecting pests across agricultural landscapes. Lack of fallow periods in most regions where rice is grown means that the populations of hoppers remain active all year round, causing early-season attacks and high rates of virus spread in newly planted areas (Ali *et al.*, 2017). Continuous climatic warming has also increased the range of potential distribution of *Nephotettix* species, where colonization was formerly constrained by temperature (Bebber *et al.*, 2013).

Differences in the practices used in crop management, the availability of host plants and diversity of natural enemy communities are key determinants of their spatial variation in

the abundance of green plant hoppers. High nitrogen based intensive managed monocropping systems typically have increased pest pressure as compared to diversified systems with habitat management and ecological engineering. There is empirical evidence indicating that with greater vegetation diversity, predator and parasitoid populations improve, and populations of predators and parasitoids are predicted to increase, resulting in biological control and reduced hopper outbreak frequency (Gurr *et al.*, 2017).

The host range and host specificity

Green plant hoppers have a high level of specialization to cultivated rice (*Oryza sativa* L.) as the primary and most appropriate host, although this crop has been strongly specialised to green plant hoppers under natural field conditions. Both nymphal and adulthood stages are nearly totally replete on phloem sap of rice plants, and the highest-quality demographic performance occurs when the crops are actively growing through the vegetative stage and in early reproductive stages. One of the greatest factors of hopper fitness is host nutritional status because the feeding activity, survivorship, and reproductive capacity are directly dependent on plant quality. Plants with high nitrogen application are especially preferable, which promotes the quicker growth and a higher fecundity of hopper populations (Lu *et al.*, 2007).

In spite of the obvious preference of rice, the green plant hoppers are less flexible in their host choice and are not obligate monophags. Empirical evidence suggests that *Nephotettix* species are able to endure at low nebulosity on various graminaceous weeds and relatives of wild rice. These alternative hosts do not assist in the optimal growth of the population, but how, they allow the survival and restricted multiplication of the bacteriophage in times when the cultivated rice is not available, thus, role as ecological brokers between the ecological cycles of productions (Horgan & Crisol, 2013).

Genetic differences between different rice cultivars also affect host-associated variation. Resistance screening has shown that some varieties hinder feeding in the hopper, slack development rates as well as slack fecundity and bringing down the population growth. Nevertheless, there is a significant difference in the susceptibility of modern high-yielding cultivars and hybrid cultivars. Otherwise, due to increased plant health and better nutritional value that comes with yield improvement, particular hybrids become more susceptible to hopper infestation (Horgan and Crisol, 2013; Fujita *et al.*, 2013).

Alternate Hosts in Epidemiology of Diseases and Pest Persistence.

Alternate host plants are also very important in sustaining the green plant hopper populations during periods when rice was not growing. *Panicum* spp., *Leersia* spp., *Cynodon Dactylon* and a variety of grasses and weeds such as *Echinochloa* spp. are some of the grasses and weeds commonly infested along the field margins, irrigation canals and unmanaged bunds. Hopper populations can survive in these types of plants because they offer a place to shelter and very few nutritional resources, either in fallow periods or when rice plants are not physiologically fit in feeding them (Ali *et al.*, 2018).

The fact that green plant hoppers persist in alternate hosts has significant implications to disease epidemiology especially what concerns the rice tungro virus. Vectors which pick up tungro viruses during a feeding experience on an infected rice plant may be infectious during a stay on weed hosts and then transfer the virus to a newly established crop of rice. Such a mechanism facilitates a pathogen to be carried between seasons by way of early disease outbreak and consecutive outbreaks of tungro disease in its endemic areas (Horgan *et al.*, 2015). Consequently, the weed management is more than a crop husbandry practice as it is also a major preventive strategy in the integrated pest-disease management.

Under both field research and laboratory experiments, it was always observed that under-managed and heavily-weeded landscapes enable early settlement of rice fields by green plant hoppers. On the other hand, pest establishment can be adequately slowed and population growth minimized by strategic elimination of alternate hosts alongside the ability of habitat manipulation to increase the abundance of predators. Ecological engineering, which allows replacing the weed refuges with flowering plants that serve as food to natural enemies, has been proven effective in breaking the continuity of hopper populations and enhancing the work of biological control (Ali *et al.*, 2018; Gurr *et al.*, 2017).

Implication on the stepped approach of Integrated Pest Management.

The host specificity and alternate host use knowledge are critical in the realization of effective IPM services to green plant hopper management. Techniques of control that only concentrate on rice crop but leave the surrounding vegetation unattended usually do not prevent the early infestation or the cessation of the transmission of the disease. Conversely, in combination with weed suppression, timed planting, and habitat diversification, integrated-based strategies prove to be more effective regarding weeding off pests occurrences across the landscape.

Ecological significance of alternate host addresses the issue of the need to use area-wide pest management, as opposed to field level measures. Cooperative execution of coordinated farming routines and regular weeding of the crops of adjacent farms can break the continuity of attacks and contain their potential. These organized interventions are also becoming more and more vital in conditions of climate change, as it is anticipated that such factors will prolong the existence, spreading potential, and intrusion stress on pests throughout the rice-expanding territories (Deutsch *et al.*, 2018).

Biology and Damage Potential of green plant hopper.

The bacteria are coccobacilli in shape, but they can also appear as pairs. The morphology of the bacteria is of coccobacillus, although they may also be present in pairs. The small hemipteran insects of the family Cicadellidae are called green plant hoppers (*Nephotettix spp.*), as their body shape is in the form of a wedge, and is designed to allow them to move quickly within the canopies of crops. Adults measure between 3 and 4 mm long and are highly colored to a bright green which offers them a perfect hiding place in the rice leaves. Their slim shape and perfectly developed wings allow them to have a short distance dispersal in the field as well as ability to move over a longer distance in favorable climate conditions. Sexual dimorphism is evident, uniquely females are larger and heavier than males because of more reproductive investment (Kiritani, 2019).

Proper identification to species level may be necessitated by a close scrutiny of morphological features like wing venation, markings in the thoraces and male genitalia. Proper identification is critical when comparing the species of *Nephotettix* because each has varying vector competency, host interactions as well as reaction to control options. The inability to recognize species can and will lead to poor management decision making and underestimation of risk of tungro disease especially in endemic countries (Horgan *et al.*, 2015).

The subject of life cycle and developmental biology is closely related to the current development, knowledge-building and research on the issue of human development.

Development cycle Green plant hoppers development is directly correlated with rice growth stages and influenced greatly by the temperatures, quality of the host plant and the environments of localities. Women lay their oval-shaped transparent eggs in groups in the sheaths of leaves or along the midribs with help of ovipositors. Such hiding oviposition locations minimize desiccation and predation. In the tropical climate, egg development

normally takes 6-9 days, and faster embryonic development occurs when it is hot (Lu *et al.*, 2007).

After their emergence, the nymphs undergo five instar stages before they attain their adulthood. Under good conditions, the nymphal stage takes 12-15 days and, in that period, the individuals consume phloem sap actively and grow larger with each passing day. Nymphs, since they do not possess wings, and they are not very mobile, are more susceptible to predation compared to adults. Adult lifespan typically lasts between 10 and 20 days, based on the quality of the host as well as the environment, and a female can lay multiple hundreds of eggs in a lifetime (Ali *et al.*, 2017).

The life cycle normally takes 25-30 days to be complete, and several concurrent generations may have one rice-growing season. Such a rapid turnover + high fecundity and the constant availability of hosts of intensively managed systems (characters that contribute to rapid population growth) may lead to the rapid accumulation of population and the risk of developing an outbreak (Horgan & Crisol, 2013).

Feeding Behaviour and Interactions between Plants and Insects.

The hoppers are specialized green plant phloem feeders that contain piercing-sucking mouthparts that are developed with efficient sap harvesting functions. The nymphs as well as adults put in their stylets in the vascular tissues and tend to target phloem elements that are abundant and full of carbohydrates and amino acids. Activity in food feeding normally occurs around the lower end of rice plants where the largest amount of flow of assimilation occurs. Constant feeding disturbs migration of photosynthates causing chronic physiological stress on a host plant (Lu *et al.*, 2007).

Hoppers release enzymes and effector molecules into the saliva in which stylet penetration and inhibition of plant defense mechanisms occur during feeding. Long-term feeding causes a change in hormone broadcast and resources in the plant, which will ultimately lower growth potential and yield. Several researches have shown that plants containing high levels of nitrogen promote feeding performance and nutrient physiological assimilation by hoppers leading to higher survival rates and reproduction (Lu *et al.*, 2007; Ali *et al.*, 2017).

Hopperburn and Physiological damage.

Lesions resulting due to the green plant hoppers become progressive and in most cases, these diseases become tricky to spot at the initial levels of infestation. The first ones are slight

chlorosis, decreased vigor of the plants, and retarded tillering. With the increase in the intensity of feeding, photosynthetic activity reduces, B stores are depleted, and root growth is crippled. Severe cases result in hopperburn, a disease-like condition that has several signs, such as the brownness, wilting, and death of the plant (Ali *et al.*, 2017).

Hopperburn occurs due to the depletion of phloem and tissue damage caused by toxins which causes collapse of the vascular functioning. Obstruction of nutrient transportation causes a quick process of desicating and necrosis of plant tissues. The damage is usually in spots relating to the pest aggregation but in cases with good conditions it can spread very fast. When hopperburn takes place in a vulnerable period like tillering or panicle development, the losses incurred when such events are experienced may be extreme.

Role in Virus Transmission

Besides causing direct feeding damage, the green plant hoppers are also very effective vectors of the tungro disease in rice. Infection takes place when the virus is being fed on infected plants, and the retention and subsequent used as the mode of transmission in later feeding. The age of the virus vectors, feeding period, and the condition of the host-plant determine the interaction between the virus vectors and the plant. Infected plants range from being severely stunted to developing yellow-orange leaf discoloration, low tillering as well as unfilled grains, which tend to result in massive losses in yield (Horgan *et al.*, 2015).

Their mobility, high reproductive ability and their ability to survive on alternative hosts enhances the epidemiological significance of green plant hoppers. Higher densities of vectors enhance chances of spreading the virus within and between fields and hence population suppression forms a major part of the tungro management. The strategies in place to deal with IPM should therefore consider the dynamics of populations of insects and the process of transferring the virus to attain sustainable yield protection.

The damage caused by green plant hoppers in rice ecosystems may be divided into two more components that are interconnected in that case the damage is directly caused by the activity of feeding and indirectly caused by the pathogen transmission. The two forms are a significant cause of instability of the yields and in extreme circumstances, crop failure. The prolonged feeding of phloem by nymphs and adults results in direct injury that disrupts normal physiological functioning among rice plants. By taking away nutrients, continuous removal of assimilates breaks down nutrient distribution and leaves plants without carbohydrates and other vital metabolic compounds needed to grow and develop. The first signs are often ignored

since they are not pronounced and are characterized by occasional cases of chlorosis and weakened plant growth. With the escalating amount of infestation, such symptoms advance to the manifestation of suppressed growth, decreased tiller growth, and retarded panicle initiation (Ali *et al.*, 2017).

In extreme population needs, prolonged feeding will cause hopperburn which is a typical condition of damage syndrome which is characterized by instant leaf yellowing, browning, and desertion, ultimately resulting in the death of the plant. Hopperburn usually appears in discrete patches in areas, which show the generalized spatial distribution of populations of hoppers. These infected regions can grow very quickly especially when the circumstances are favorable, that is, when there is excessive nitrogen fertilization, favourable temperature and moisture conditions. Damages in the first few vegetative stages will restrain tiller production and canopy growth, and damages in the reproductive phase will directly lower the number of grains and the weight of the grain causing severe losses in yields.

The green plant hoppers are vectors that cause contagious diseases in rice and thus their role in causing the indirect damage is significant. Tungro viruses cause severe stunting and yellow-orange leaf discoloration, loss of tillering ability and poor grain filling in the plants infected. Fields with an infected area tend to have patchy symptom expression and uneven vegetation growth which resembles the pattern of the populations of vectors. In epidemic outbreaks, the losses due to the transmission of the virus often exceed those due to the feeding injury itself, which is why the epidemiological significance of the pest cannot be underrated (Horgan *et al.*, 2015).

Economic Losses and Yield Effects.

The level of yield loss due to the attack of green plant hopper is quite significant when it is associated with pest concentration, the level of crop development at the time of treatment, the relationship between the cultivar and the effectiveness of the treatment points. Infestations of low level usually cause capital losses of about 5-10 percent, moderate infestations usually cause losses in between 20-30 percent. Contrary to that, in extreme cases of outbreaks harmed by extensive hopperburn and tungro outbreaks, yield loss has been reported to occur over 60 percent, and sometimes almost all crops fail (Ali *et al.*, 2017; Savary *et al.*, 2019).

The overall economic impacts of green plant hopper at regional and national levels are large. The rice producing nations suffer losses of great magnitude every year because of low production, high costs of using the inputs to control pests and the requirement of applying the

insecticides over and over again. The same affects smallholder farmers who may not easily access the pest surveillance systems and timely advisory services. Economic costs are not restricted to yield loss, as expected surplus costs arise due to agroecosystem impaired health/degradation and compounded hazards of human health related to excessive exposure to pesticide application (Savary *et al.*, 2019).

Insect pests are predicted to pose an economic challenge that is set to grow in future with regard to climate change projections. Increasing temperatures should cause insects to improve their metabolic rate, feeding rates, and reproductive production, and hence aggravate crop damage. The year-round soil structure and climate that promotes the successful pest survival and reproduction predispose tropical rice systems in particular (Deutsch *et al.*, 2018).

Agronomic Practices and their Influence on the Pest Dynamics.

Crop management activities have a strong impact on populations of the green plant hoppers, and frequently dictate the presence or absence of populations within populations at the damaging threshold or result in the occurrence of an outbreak of populations. Nitrogen fertilization has been found to be a leading cause of hopper increment among other agronomic factors. High nitrogen levels bring about plant succulence and amino acid levels which are concentrated in phloem sap that increases hostness to sap-sucking insects. There exist many studies with positive high correlations between the rates of application of nitrogen and high rates of hopper survival, fecundity and population growth (Lu *et al.*, 2007; Ali *et al.*, 2017).

Extensive planting and over tillering leads to high humidity and low air movement and conditions, which promotes the existence and reproduction of the hoppers. The constant field of rice cultivation and the absence of planting in accordance to the landscapes eliminate any natural time difficulties to the formation of the pests, resulting in them being able to continue breeding and multiplying continuously. Conversely, planting on sync and crop rotation create intervals in the presence of hosts, interfering with their life cycles, and creating reduced infestation pressure at the landscape scale (Kiritani, 2019).

Poor application of insecticides has also contributed to the resurgence of pests. Regular insecticide usage has also contributed to the rapid evolution of hopper resistance, which results in the growth of increased pest prevalence and low efficacy of control in most rice-growing areas (Bass *et al.*, 2015; Zhang *et al.*, 2018).

Climate Change and Hopper Green Plant Dynamics.

Climate change is becoming more and more known to be among the significant drivers of ecology and effect of the green plant hoppers. Increase in temperature will lend insects rapid development, reduce the generation time and increment the number of generations which can be posted in a particular growing season. The changes encourage high population growth and increase the risk of an outbreak. Secondly, warmer conditions promote the increase of ranges, which allows pests to live in places where colder temperatures used to limit them (Bebber *et al.*, 2013).

The dynamics of pests are also influenced by alteration of the rain patterns. Long dry periods can also boost the hopper activity and dispersal, whereas unusual or extreme rainfall occasions can interfere with crop growth as well as destabilize the natural enemy communities. Stresses caused by climate of rice plants can lead to augmentation of vulnerability to infestation and the interplay between pest pressure and environmental stress. Combined theoretical and measurement estimates indicate that, unless there is an adaptation and climate-resilient handle, the pressure of the pests within the rice systems will increase in the future under climate conditions (Deutsch *et al.*, 2018; Prasanna *et al.*, 2023).

Integrated Pest Management of Green plant hopper in rice ecosystems.

Integrated pest management (IPM) offers a scientifically sound and ecologically sound system of destroying the population of green plant hoppers in rice fields. Instead of applying single control measures, IPM combines several strategies that are compatible with each other and reduce the levels of pest densities below levels that can cause economic damages, and risks to non-target organisms, human health, and ecosystem integrity are minimized. The need to have IPM in handling green plant hoppers has been on the rise owing to the concerted forces of agricultural intensification, climate unpredictability, and prevalent insecticide resistance. Consequently, IPM is a versatile and adaptable methodology that is able to respond to the ecological complexity as well as the challenges of the production in the future (Kiritani, 2019; Prasanna *et al.*, 2023).

Strategies to Control Culture

The cultural practices form the base of IPM as they alter the crop environment to attenuate the establishment, colonization and multiplication of pests. Synchronized planting in the surrounding rice fields is one of the best cultural practices that help in the intervention of

cultural activities. Planting of rice crops close to the size of a defined planting window allows the permanence of hostile ongoing and inhibits further season succession in populations of hoppers. Planting at the right time has always been linked to fewer cases of infestation in the early time period and less occurrence of tungro virus transmission (Kiritani, 2019).

Cultural control is mainly centred around nitrogen management that is a component of nutrient management. High nitrogen build-up levels augment the succulence of plants and the levels of amino acids in sap, making the plants more attractive to sap-sucking insects. Empirical evidence shows that high amounts of nitrogen greatly enhance the population of hopper feeding, survival, and fecundity. Balanced fertilization, in contrast, lowers the pest pressures and maintains crop productivity in the conditions of split nitrogen application, matching nitrogen demand to crop requirements, and the application of organic amendments (Lu *et al.*, 2007; Ali *et al.*, 2017).

Weed and residue management are also the other significant cultural measures. Existence of many graminaceous weeds are alternate hosts whereby hopper population can survive during fallow periods. Early removal of the weeds in the field borders, bunds and irrigation channels decreases the off-season weeds and restricts early colonization of crops. Rice stubble is destroyed after harvest and cannot be used as a oviposition site and seasonal carryover of pests are broken. Besides that, water management, including intermittent drying, can provide poor microclimatic conditions to those hoppers to survive and reproduce (Ali *et al.*, 2018).

Host Plant Resistance

Rice varieties are resistant to green plant hoppers by using many mechanisms such as antixenosis (loss of attraction), antibiosis (adverse effects on insect development and reproduction) and tolerance (capability to bear yield with infestation). Through intensive screening programs, many resistance genes have been identified and most have been integrated into better rice varieties using conventional breeding and molecular techniques (Yamasaki *et al.*, 2010; Fujita *et al.*, 2013).

Resistant cultivars hamper hopper feasting performance, extend development period, and diminish fecundity and so the population increase and the spread of virus is crippled. Nevertheless, the adaptation range of hopper populations limits the usefulness of resistance over the long-term. A high genetic variation in the *Nephotettix spp.* allows the development of virulence biotypes such that they surpass individual genes of resistance. To address this threat,

the deployment of resistance genes must be strategic via pyramid, rotation of resistant varieties as well as combination with other IPM to diminish the selection pressure (Saxena *et al.*, 2014; Fujita *et al.*, 2013).

Naturally, there is no such resistance as balancing nutrition and saving natural enemies, preventing recurrence and sluggish progression of biotypes. Further research on breeding of resistance using genomic tools and markers aided selection is needed to ensure sustainable management of hoppers in rice ecosystems.

Biological Control and Protection of Natural Enemies.

One of the systems of regulation in ecologically balanced rice systems is the biological control. Rice fields host a wide range of natural enemies which cause huge predation pressure on the population of green plant hoppers. Hopper eggs, larvae and adults are prey to predators like *Cyrtorhinus lividipennis*, spiders (e.g., *Lycosa* and *Tetragnatha spp.*), dragonflies, damselflies and ground beetles and in most cases these predators ensure that low-input management regimes do not lead to outbreaks (Settle *et al.*, 1996).

Biological control conservation aims at improving the abundance and performance of these natural enemies by altering the habitats and decreasing the disruptive activities. Other food sources, shelters and micro-habitat of predators and parasitoids are offered by ecological engineering methods, such as introduction of flowering plants on field bunds and marginal areas. Field experiments prove that natural enemies are more effectively concentrated in such habitat diversification because it more effectively suppresses hoppers than strategies that rely on insecticides (Ali *et al.*, 2018; Gurr *et al.*, 2017).

Biological control is only successful when an ecological balance is established in rice agroecosystems. Generalized insecticides interfere with predator prey relationships and often have the effect of causing the re-emergence of pests by preferentially killing beneficial predators. Therefore, preserving desirable arthropods is the focus of IPM and can lead to sustainability of pest control, decrease in the use of pesticides and increase in ecosystem services.

Resistance management: This section offers the complete set of instructions for the subsection, outlining the tasks to perform and the materials to use. Chemical Control and Resistance Management: In the sub-section, the entire sub-section of the instructions is presented and the tasks to be carried out and the materials to be used.

The use of chemical management is the supplementary aspect of IPM but not a

dominant component since it must be deployed only in situations whereby the pest population surpasses the set economic considerations. The preference is inclined to the use of selective insecticides like buprofezin and pymetrozine with the specific mode of action influencing the insect development and feeding habits and at the same time with a relatively low toxicity to natural predators (Zhang *et al.*, 2018).

The intensive appearance and distribution of resistance emphasize the shortcomings of the prescribed strategy of chemical interventions alone, and it is essential to demand the strategies to control resistance, such as the alternation of insecticides of disparate mechanisms of action and complementary with non-chemical implementations (Bass *et al.*, 2015).

Successful application of chemicals in IPM models also entails frequent monitoring of pests, proper identification of species, and making of informed decisions. The new opportunities of optimal insecticides timing and dosage emerge because of advances in digital agriculture, such as the real-time pest surveillance, climate-based forecasting, and decision-support tools. Such innovations are capable of rendering unwarranted usage, hindering resistance development, and boosting the sustainability, in general, of pest management under more variable climatic situations (Prasanna *et al.*, 2023).

Conclusion and Future Perspectives.

The green plant hopper (*Nephotettix spp.*) is one of the most troublesome and destructive insect limitations to the sustainability of rice farming in Asia and some other areas that practice rice farming. The significance does not only lie in causing phloem-feeding damage to plant physiological activity and yield development, but their prime position in the spread of rice tungro disease, which may trigger catastrophic and massive crop losses. These increasing roles of green plant hoppers in contemporary rice are a part of larger changes in agro-system activities such as the intensification of monocropping, increased nitrogen usage, shortened agro-ecosystem organization, and extended reliance on chemical insecticides.

The evidence that is synthesized in this review indicates that green plant hopper outbreak is essentially an ecological process of complex interactions between host plant quality, pest life-history characteristics, natural enemy, agronomic management and climatic conditions. The short generation period of the insect, its great reproductive capability, and its

ability to utilize other hosts enable the populations to bloom when the regulatory measures are compromised. Increased host suitability, resulting as a consequence of agronomic intensification, especially over-fertilization with nitrogen and the cultivation of rice on continuous instead of intermittent basis, and the breakdown in biological control, has led to increased resurgence and increased severity of pests and a faster rate of evolutionary resistance to insecticides.

Climate change is serving as a boost to these issues by changing the rate of pest development, seasonal presence, and distribution. An increase in temperature, changes in the rainfall cycle and the climatic variability will further favor the survival and dispersal of green plant hopper and at the same time increase crop susceptibility to infestation and diseases. These fashions indicate that those control methods, which are reactive and revolve around the use of insecticides, will continue to prove inefficient and will be costly to the environment in the production environment of the future.

The most feasible way to go is integrated pest management where the way to go to sustainable green plant hopper control is through this approach. Cultural needs, like planting time synchrony, nutrient management, and managing weeds and residues, and proper water control are the components that make up the successful IPM, making the conditions less conducive to the pests and breaking their life cycle.

The use of chemical control, though it is still a condition in some cases, has to be applied sparingly in a IPM system. The prevalence in increasing cases of insecticide resistance in hopper populations of green plants highlights the shortcomings of using chemical only strategies. Certain insecticides used selectively, applications done depending on threshold parameter as well as management methods on resistant have been necessary in order to maintain the effect of the chemicals as well as to protect other beneficial organisms. In its part, new digitalized means of monitoring pests, climatic forecasting, and decision support provide great opportunities to enhance precision and sustainability of the management interventions.

In the future, the management of green plant hoppers will need a paradigm shift towards system and holistic solutions that combine ecological international and technological innovations. The close integration of research and extension will be important to enlarge-scale implementation of IPM, the access of farmers to decision-support tools will be improved, and policies that encourage sustainable practices should be promoted. Further funding of interdisciplinary research which would include insect ecology, climate science, plant breeding and digital agriculture will be critical to come up with climate resistant pest management

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Chapter 5: Red Cotton Bugs (*Dysdercus koenigii* and *Dysdercus cingulatus*): Biology, Ecology and Integrated Pest Management

Abstract

The red cotton bug, belonging to genus *Dysdercus* (Hemiptera: Pyrrhocoridae), represents one of the most economically devastating insect pests of cotton and associated host crops in Indian agriculture and tropical regions globally. Species *Dysdercus koenigii* Fabricius and *Dysdercus cingulatus* Fabricius cause substantial damage through stylet-mediated sap-sucking and contamination of lint with fungal pathogens, resulting in quantifiable economic losses ranging from 10-30% of total cotton production. The pest exhibits polymorphic morphology with distinct color morphs and possesses a complex lifecycle requiring 40-47 days under laboratory conditions with multiple overlapping generations annually. This review synthesizes contemporary research on taxonomic characterization, bioecological dynamics, host plant associations, economic injury and threshold levels, symptomatology of damage, and integrated pest management (IPM) approaches encompassing legal, mechanical, cultural, biological, botanical, microbial, chemical, and genetic resistance strategies. Emphasis is placed on sustainable management paradigms incorporating ecological principles, conservation of natural enemy complexes (predatory reduviids, parasitoid flies, entomopathogenic fungi), and judicious application of synthetic pesticides following economic threshold protocols. Emerging research directions including resistance management in Bt cotton systems, molecular characterization of host-plant interactions, and development of host-plant resistance germplasm are discussed.

Keywords: *Dysdercus*, cotton stainer, Hemiptera, Pyrrhocoridae, lint staining, integrated pest management, economic threshold, biological control, reduviid predators, host resistance

Introduction

Cotton (*Gossypium spp.*), a perennial dicotyledonous plant cultivated for fiber production and edible oil, represents a cornerstone of global agriculture and textile industries. India's position as the world's largest cotton-growing nation, occupying approximately 120.55 lakh hectares of cultivated area with annual production exceeding 5.34 million metric tonnes (21% of global production), underscores the strategic importance of cotton pest management to national agricultural security. The hemipteran insect complex constitutes the primary biotic

constraint to sustainable cotton production, with sucking pests, leaf-feeding arthropods, and phytophagous lepidopteran larvae collectively responsible for 40-50% potential crop loss under unmanaged conditions.

Among hemipteran pests, the red cotton bug complex—comprising *Dysdercus koenigii* Fabricius and *Dysdercus cingulatus* Fabricius—occupies particular significance in cotton-growing zones of India, Pakistan, and tropical Africa. These insects, colloquially termed "cotton stainers" or "cotton stainers bugs," inflict damage through direct sap-extraction and indirect pathogenic contamination, rendering harvested lint unsuitable for premium textile applications. The pest's association with the entomopathogenic fungus *Nematospora gossypii* amplifies economic injury through secondary infection of developing seeds and lint staining phenomena.

Historical perspective and geographic distribution

The red cotton bug was first formally described by Fabricius in the late 18th century, with comprehensive bioecological documentation emerging during the twentieth century from Indian agricultural research institutions. Maxwell-Lefroy's seminal monograph (1908) on cotton pests of India documented *Dysdercus cingulatus* as a pest of regional significance in erstwhile British India. Subsequent research by Kamble (1971) on *D. koenigii* bionomics established the foundation for modern understanding of lifecycle dynamics and host-plant interactions.

Geographic distribution of *D. koenigii* and *D. cingulatus* encompasses cotton-growing regions across Asia (India, Pakistan, Bangladesh), Africa (Ghana, Sudan, Nigeria), and parts of the American tropics. In India, economically significant infestations are recorded in major cotton zones: the North zone (Punjab, Haryana, Rajasthan), Central zone (Gujarat, Madhya Pradesh, Maharashtra), and South zone (Tamil Nadu, Andhra Pradesh, Karnataka). The pest thrives in tropical and subtropical agroecosystems characterized by temperatures exceeding 27°C and intermediate moisture availability. Seasonal population dynamics demonstrate peaks during post-monsoon months (August-October) coinciding with cotton boll development and maturation phases. [Ranjan & Kumar (2018)]

Taxonomy and morphological characterization

Taxonomic Classification

Kingdom: Animalia

Phylum: Arthropoda

Class: Insecta

Order: Hemiptera

Family: Pyrrhocoridae

Genus: *Dysdercus* Fabricius

Species: *D. koenigii* Fabricius; *D. cingulatus* Fabricius

The family Pyrrhocoridae comprises phytophagous hemipteran insects primarily distributed in tropical and subtropical regions. The genus *Dysdercus* encompasses approximately 16 recognized species, of which *D. koenigii* and *D. cingulatus* are predominant agricultural pests. Both species exhibit reproductive isolation and distinct morphological characteristics despite overlapping geographic distributions and host ranges.

Morphological Characterization

General Body Features: Adult red cotton bugs measure 11-14 mm in length, with distinctive deep red or dusky brown coloration attributable to high concentrations of carotenoid pigments. The integument exhibits characteristic aposematism (warning coloration), signaling chemical defense mechanisms via volatile pheromones.

Morphological Dimorphism: Sexual dimorphism is pronounced, with females (13-14 mm) noticeably larger than males (11-12 mm). Female abdomen exhibits lateral compression and moderately sclerotized ovipositor apparatus. The rostrum (feeding apparatus) is characteristically long and needle-like, adapted for deep tissue penetration and phloem-sap extraction, measuring approximately 40-50% of head length.

Taxonomic Diagnostic Characters:

Antennae: Composed of four segments (following hemipteran convention), with intermediate segment typically darker than others

Pronotum: Bearing lateral margins with distinctive pronotal shape; in *D. koenigii*, the lateral margins are nearly parallel; in *D. cingulatus*, margins demonstrate slight anterior convergence
Hemelytra (Forewings): Deep red or rust-colored with characteristic darkened costal and subcostal regions; membranous posterior portion displays transparent coloration

Legs: Femora and tibiae exhibit variable coloration; many instars possess black glandular spots on femoral and tibial segments

Abdomen: Displays red dorsum with characteristic black markings on dorsal surface; ventral surface pale yellowish to cream-colored

Scent Glands: Located on metathorax and abdomen, producing characteristic pheromonal complex involved in aggregation behavior

Nymphal Morphology: Five nymphal instars are recognized, exhibiting progressive color change from pale orange in first-instar nymphs to brick-red in later instars. Early instars measure 2.5-3.0 mm; final-instar nymphs reach 10-12 mm in length. All instars possess vestigial wing pads (ptilonotum) that progressively develop across successive instars. [Ahmad & Mohammad (1983)]

Host plants and ecological associations

Primary and Secondary Hosts

Primary Host: *Gossypium spp.* (cotton), particularly the cultivated species *G. hirsutum* (Upland cotton) and *G. arboreum* (Desi cotton)

Secondary and Alternate Hosts:

- i. *Abelmoschus esculentus* (Lady's finger/Okra)—significant alternate host supporting off-season population maintenance
- ii. *Corchorus spp.* (White jute, Mesta jute)
- iii. *Zea mays* (Maize)—utilized during inter-crop phases
 Citrus spp. (Citrus fruits)
- iv. *Tectona grandis* (Teak)
- v. *Hibiscus spp.* (Ornamental hibiscus)

vi. Wild malvaceous plants in cotton ecosystems (Abutilon, Sida, Malva)

Host-plant selection exhibits feeding preference hierarchy, with cotton bolls and developing seeds representing optimal feeding substrates. Field observations indicate preferential colonization of cotton during boll development and maturation phases, with population shifts to alternate hosts during inter-crop periods and post-harvest intervals. Plant nutritional quality, particularly seed oil content and protein composition, influences fecundity and developmental rates.

Life cycle, development, and biology

Life cycle Duration and Development

Laboratory studies under controlled conditions (26-28°C temperature; 70-80% relative humidity; 12L:12D photoperiod) document the following lifecycle parameters:

Egg Stage: Females deposit eggs singly or in small clusters within soil debris, dried plant material, or cryptic microhabitats proximal to host plants. Eggs are spherical, yellowish in coloration, and measure approximately 1.2-1.4 mm in diameter. Incubation period ranges 6-7 days, demonstrating temperature-dependent variation (shorter at elevated temperatures; prolonged at cool conditions).

Nymphal Stages: Five nymphal instars recognized, with cumulative nymphal period spanning 34-40 days under laboratory conditions. Individual instar durations:

-1st instar: 2-3 days

-2nd instar: 3-4 days

-3rd instar: 6-7 days

-4th instar: 9-11 days

-5th instar: 14-15 days

Adult Stage: Newly-emerged adults are pale orange, gradually darkening to characteristic red coloration within 2-3 days post-emergence. Sexual maturity is attained within 5-7 days. Male

longevity averages 20-23 days; female longevity 16-18 days under laboratory conditions. Fecundity (egg production per female) ranges 54-64 eggs, with maximum recorded values reaching 90+ eggs per female under optimal nutritional conditions.

Complete Life cycle: Total development from egg to adult emergence spans 40-47 days under standard laboratory conditions, with field populations demonstrating considerable variation attributable to temperature fluctuations, host-plant nutritional status, and natural-enemy pressure. Estimated 6-8 overlapping generations annually in cotton-growing regions of central and peninsular India; reduced to 3-4 generations in northern zones.

Reproductive Biology and Population Dynamics

Dysdercus species exhibit bisexual reproduction with predominantly arrhenotokous sex determination. Sex ratios approach 1:1 (males:females) in field populations. Mating behavior commences 5-7 days post-emergence, with females demonstrating polyandrous mating patterns. Oviposition initiation typically occurs 3-5 days post-mating, with peak oviposition rates during mid-afternoon hours (14:00-16:00). Females exhibit pronounced host-plant selection behavior prior to oviposition, utilizing chemosensory antennae and gustatory receptors.

Population growth potential (λ) estimates yield values exceeding 2.0 under optimal conditions, indicating rapid population expansion when natural enemies are suppressed or chemical control is absent. Life-stage survivorship analyses demonstrate highest mortality during late-nymphal and early-adult stages; egg and early-nymphal stages exhibit relatively high viability (>80%) under favorable conditions.

Economic Injury Level And Economic Threshold Level

Definition and Quantification

Economic Injury Level (EIL) represents the lowest pest population density producing economic loss equivalent to management costs. Economic Threshold Level (ETL)—also designated as Action Threshold—represents the population density at which pest management interventions should be initiated to prevent pest populations from exceeding EIL, accounting for management implementation lag-time.

Recommended Thresholds for *Dysdercus* spp. in Cotton

Based on comprehensive field studies conducted across Indian cotton zones (NIPHM, 2014; ICAR-CICR regional protocols):

ETL for Red Cotton Bug: 10-15 bugs per 100 plants OR 1 bug per m² canopy area

This threshold applies to reproductive crop stages (flowering through boll maturation). The threshold reflects cotton's capacity to tolerate early-season pest pressure without significant yield reduction; late-season infestations at lower population densities may warrant intervention due to inability to compensate for seed/boll damage during critical reproductive windows.

Factors Influencing Economic Thresholds

Economic thresholds exhibit dynamic variation based on:

Cotton commodity price: Higher market prices justify lower treatment thresholds

Cost of pest management intervention: Expensive interventions necessitate higher thresholds to justify economic justification

Cotton cultivar compensatory capacity: Modern Bt cotton hybrids demonstrate reduced compensatory capacity compared to conventional cotton, potentially lowering applicable thresholds

Pest population growth rate: Rapidly expanding populations warrant preemptive intervention below stated ETL

Natural enemy complex abundance: High predator/parasitoid densities may justify delayed intervention (raising de facto threshold)

Crop developmental stage: Early-season pest pressure on vegetative plants typically warrants lower treatment thresholds than equivalent population densities on fruiting plants [Anto Claver & Yadav (2024)]

Damage symptoms and economic consequences

Primary Damage Symptoms

Direct Sap-Extraction Injury: Both nymphs and adults possess specialized piercing-sucking mouthparts (rostrum) adapted for penetrating cotton boll walls and extracting cellular contents from developing seeds and floral tissues. Feeding injury manifests as:

- Water-soaked spots on boll surface progressing to necrotic lesions
- Premature seed abortion and loss of seed viability
- Reduced oil content (up to 15-20% reduction in severe infestations)
- Characteristic dark stains on lint at feeding puncture sites

Secondary Pathogenic Contamination: Red cotton bug feeding creates entry portals for the entomopathogenic ascomycete fungus *Nematospora gossypii* (previously classified as *Nematospora coryli*). Fungal establishment within boll tissues induces:

- Brown-to-black staining of developing lint
- Boll-tissue maceration and accelerated boll rot
- Complete seed destruction in severely infected bolls
- Lint discoloration persisting through ginning and processing

Secondary Symptoms and Plant Response

Systemic plant responses to red cotton bug infestation include:

- Reduced photosynthetic efficiency in foliage proximal to feeding sites (localized chlorosis not typical; systemic decline associated with high population densities)
- Premature boll-drop and abscission under high-pest-pressure conditions
- Reduced plant vigor during critical growth stages
- Delayed crop maturity in late-season infestations

Economic damage and crop loss estimation

Quantified Yield and Quality Losses

Field surveys conducted in cotton-growing regions of India document the following economic impacts:

Yield Losses: Direct yield reduction attributable to red cotton bug infestation ranges 8-15% in moderate infestations (10-20 bugs/100 plants) to 25-40% in severe infestations (>50 bugs/100 plants). Economic losses reflect both reduced boll production and decreased seed viability.

Lint Quality Deterioration: Red cotton bug damage significantly reduces lint quality grades, resulting in:

- Downgrading from premium quality cotton (white/cream) to lower commercial grades
- Price discounts of 15-25% for stained cotton bales
- Reduced market access for export-oriented cotton cultivation
- Processing complications in textile mills (increased rejections, additional cleaning costs)

Seed Oil Degradation: Red cotton bug feeding reduces cottonseed oil content by 10-20%, with particular impact on oleic and linoleic acid composition, diminishing seed value for oil extraction and animal feed applications.

Estimated Annual Loss in India: Conservative estimates place annual economic losses attributable to red cotton bug in India at INR 800-1200 crore (USD 96-144 million) based on area-wide infestation data, commodity prices, and management costs.

Integrated Pest Management strategies

Legal and Regulatory Methods Quarantine and Phytosanitary Regulations:

- Prohibition on inter-state movement of infested cotton plant material and seeds lacking phytosanitary certification
- Mandatory inspection protocols for cotton seed and planting material imported from red cotton bug-endemic regions
- State-level regulations restricting cultivation of highly-susceptible cultivars in endemic regions (e.g., certain desi cotton landraces)

Registrations and Approval Requirements:

- Use of only government-approved insecticides and biopesticides registered for red cotton bug management under Ministry of Agriculture protocols
- Adherence to established Maximum Residue Limits (MRL) for pesticide residues in cotton

fiber and seeds

- Compliance with Insecticide Act (1968) and Rules (1971) governing pesticide formulation, labeling, and sale.

1.1 Mechanical Management Methods

Hand-Picking and Visual Monitoring:

During early infestation phases (pest density <5 bugs/100 plants), hand-collection of adult insects and egg clusters from cotton plants and soil surface reduces pest population by 30-40%. This labor-intensive approach proves economically viable in small-holder and organic farming systems.

Pheromone and Yellow Sticky Traps:

While functional pheromone traps for *Dysdercus spp.* are not commercially available (unlike *Helicoverpa* pheromone systems), yellow sticky traps (11cm × 28cm) capture adults and nymphs during field movement, providing population monitoring and modest population reduction (10- 15% pest suppression). Trap placement: 4-6 traps per acre at cotton canopy height.

Bird Perches and Avian Predation:

Installation of elevated perches (bamboo/wooden structures; 1.5-2.0m height) at density of 8-10 per hectare facilitates predation by insectivorous birds (primarily weaverbirds, drongos, bulbuls), achieving 15-25% nymphal and adult predation rates.

Crop Sanitation:

- Destruction of crop residues post-harvest within 10-15 days, eliminating diapausing nymphs and adults overwintering in plant debris
- Removal of alternate host plants (wild malvaceous species, volunteer cotton plants) from field margins and adjacent areas
- Thorough field cleaning of dropped bolls and plant material during boll-opening phase

Cultural Management Practices

Crop Rotation: Implementation of 2-3 year cotton-free intervals utilizing non-host crops (legumes, cereals, oilseeds) significantly reduces carry-over populations. Rotation with pigeon pea, groundnut, or rice demonstrated 60-70% reduction in pest population during subsequent

cotton season.

Timing of Planting:

- Early planting (first fortnight of May in North zone; June-July in Central/South zones) allows cotton phenological escape, with plants reaching reproductive maturity prior to peak red cotton bug population buildup in August-September
- Synchronous sowing across contiguous cultivated areas prevents localized population refuges and facilitates integrated population suppression

Host-Plant Resistance Germplasm:

While no complete immunity exists, certain cotton germplasm demonstrates reduced susceptibility:

- Desi cotton (*G. arboreum*) lines display higher tolerance compared to Upland cotton (*G. hirsutum*)
- *Gossypium* lines possessing elevated densities of glandular trichomes and secondary metabolites (gossypol, flavonoids) exhibit slight deterrence to pest feeding (20-30% reduced oviposition)
- Ongoing breeding programs in ICAR-CICR institutions focus on pyramiding pest-resistance traits with agronomic performance

Intercropping and Trap Cropping:

- Intercropping cotton with pigeon pea (1:2 ratio cotton:pigeon pea) or groundnut reduces pest population densities by 25-35%
- Okra and hibiscus utilized as trap crops planted in field borders attract and concentrate *Dysdercus* populations for targeted management intervention

Nutrient Management:

Balanced fertilizer application (avoiding excessive nitrogenous fertilization) reduces plant stress-induced pest susceptibility. Nitrogen application exceeding 120 kg/ha correlates with increased pest population densities and reproductive output.

Biological Control Methods

Predatory Enemies

Reduviid Predators (Assassin Bugs):

Rhynocoris fuscipes (F.) and related reduviid species emerge as principal natural enemies in cotton ecosystems. Laboratory functional response experiments document predation rates:

- Fourth-instar *R. fuscipes* consumed 1.0-3.9 *Dysdercus koenigii* nymphs/predator/day across prey densities of 1-16 bugs
- Attack efficiency and searching time inversely correlate with prey density (typical Type II functional response)
- Nymphal stages of *D. koenigii* preferred over adult stages
- *R. fuscipes* demonstrates 40-60% field parasitism under natural conditions

Conservation of reduviid populations through judicious pesticide avoidance yields 15-25% biological suppression of red cotton bug. Densities of 2-4 reduviid individuals per 100 plants represent target conservation goals.

Ladybird Beetles and Spiders:

While not obligate *Dysdercus* predators, generalist predators (Coccinellidae: *Coccinella septempunctata*, *Menochilus sexmaculatus*; Salticidae: jumping spiders) contribute supplementary predation pressure, particularly on nymphal stages. Combined predator complex achieves 20-30% mortality of *Dysdercus* nymphs under field conditions.

Parasitoid Enemies

Dipteran Parasitoids (Tachinidae):

Limited research documents parasitoid associations with *Dysdercus spp.* Tachinid flies (family Tachinidae), particularly *Phasia varicolor* and related species, demonstrate potential as secondary mortality agents. Parasitism rates typically remain <10% in field populations, suggesting supplementary rather than primary parasitoid role. Endoparasitoid wasps (Hymenoptera) of *Dysdercus* remain poorly documented in Indian scientific literature.

Botanical Pesticides and Plant-Derived Compounds

Neem-Based Formulations:

Azadirachtin extracts (3000-10000 ppm concentrations) demonstrate antifeedant and reproductive disruption effects:

- Neem Seed Kernel Extract (NSKE) at 5% concentration: reduced *Dysdercus* nymphal survival by 35-45%
- Neem oil (3-5% formulation): ovicidal and antifeedant properties; 2-3 foliar sprays at 7-day intervals achieve 40-50% population reduction
- Mechanism: Azadirachtin inhibits molting hormone (ecdysone) synthesis; disrupts reproductive hormone (juvenile hormone) signaling
- Application rates: 2.5-5 L/ha NSKE; 1-2 ml/L neem oil formulation

Garlic and Chili Extracts:

Empirical field trials document modest efficacy:

- Garlic extract spray (10% v/v aqueous suspension): 25-30% nymphal mortality; antifeedant effects reduce feeding damage
- Chili-based repellent sprays: primarily serve as feeding deterrents rather than mortality agents; 30-40% reduction in pest settling behavior

Botanical Insecticide Formulations:

Commercial products combining botanical extracts (Control TRM, Vedagna Nobor) demonstrate variable efficacy (20-40% pest suppression) and represent acceptable alternatives in organic production systems. Cost-benefit analysis indicates marginally acceptable economics in smallholder farming.

Microbial Insecticides and Entomopathogenic Organisms

Beauveria bassiana (Bals.) Vuill. (Hypocreales: Cordycipitaceae):

An entomopathogenic fungus with demonstrated virulence against *Dysdercus koenigii*:

- Spore concentrations: 10^8 to 10^9 CFU/ml
- Infection mechanism: Spore attachment → cuticle penetration → hyphal ramification through

hemocoel → sporulation on cadaver surface

- Field efficacy: 2-2.5 kg/ha application ($0.5-2.0 \times 10^9$ CFU/g formulation) achieves 35-50% mortality 7-10 days post-application
- Optimal conditions: 70-85% relative humidity; temperatures 18-28°C; shade application reduces UV inactivation

***Metarhizium anisopliae* (Metschn.) Sorokin:**

Alternative entomopathogenic fungal species:

- Virulence comparable to *B. bassiana* against *Dysdercus* nymphs
- Similar humidity/temperature requirements
- Application rate: $1-2 \times 10^8$ CFU/ml suspension; 2 L/ha
- Integration with other biological controls feasible

Entomopathogenic Nematodes:

Field efficacy against *Dysdercus spp.* remains limited due to requirement for soil-moisture conditions during diapausing nymphal stages. Laboratory studies demonstrate parasitism, but field adoption remains minimal.

Chemical Management and Insecticide Options

Chemical management should follow strict ETL-based decision protocols, with application timing optimized to pest lifecycle susceptibility. Insecticide rotation (alternating chemical groups) mandatory to delay resistance development.\

Recommended Chemical Options:

Organophosphates:

- Acephate 75% SP: 1.0-1.5 gm/L water; broad-spectrum activity; neuromotor disruption (acetylcholinesterase inhibition); moderate persistence (5-7 days)
- Chlorpyrifos 50% + Cypermethrin 5% EC: 2 ml/L water; combination of organophosphate and pyrethroid; extended spectrum efficacy
- Profenofos 50% EC: 1.5-2 ml/L water; delayed toxicity profile suitable for adult control

Neonicotinoid Insecticides:

- Imidacloprid 17.8-20% SL: 0.25-0.5 ml/L water; systemic activity; phloem translocation provides internal protection; excellent control of nymphs
- Thiamethoxam 25% WG: 0.3-0.5 gm/L water; neonicotinoid with enhanced systemic activity
- Acetamiprid 20% SP: 0.5 gm/L water; lower mammalian toxicity profile

Biological Insecticides:

- Spinosad 44.03% SC (Spinetoram 11.7% SC): 0.5-1.0 ml/L water; secondary metabolites from *Saccharopolyspora spinosa*; neurological paralysis; low persistence (3-5 days); acceptable for organic systems
- Emamectin benzoate 5% SG: 0.4-0.5 gm/L water; semi-synthetic avermectin; larval and nymphal activity

Diamide Insecticides:

- Cyantraniliprole 10.26% OD: 1.5 ml/L water; ryanodine receptor antagonist; moderate persistence
- Chlorantraniliprole 18.5% SC: 0.3 ml/L water; rapid knockdown; systemic characteristics

Application Protocols:

- Spray volume: 1000 L/hectare
- Timing: Early morning (05:00-08:00) or late afternoon (16:00-19:00) to maximize spray coverage on lower plant canopy where *Dysdercus* aggregates
- Application interval: 10-14 days depending on pest pressure and product persistence
- Maximum 2-3 sprays per season to minimize resistance development

Resistance Management:

- Mandatory rotation among insecticide chemical groups (alternating organophosphate ↔ neonicotinoid ↔ diamide cycles)
- Avoid consecutive applications of chemically-similar products

- Integrate with biological control methods and cultural practices to reduce selection pressure

Host-Plant Resistance and Genetic Breeding Bt

Transgenic Cotton:

Commercialized Bt cotton hybrids (expressing Cry1Ac, Cry2Ab, or stacked Cry1Ac + Cry2Ab proteins from *Bacillus thuringiensis*) provide effective control of lepidopteran pests (bollworms) but offer no inherent protection against hemipteran pests including *Dysdercus spp.* Red cotton bug continues as significant pest in Bt cotton cultivation, requiring additional management interventions.

Gossypol and Glandular Trichome-Enriched Germplasm:

- High-gossypol cotton lines display 15-25% reduced *Dysdercus* oviposition compared to low-gossypol varieties
- Enhanced glandular trichome density (trichomes possessing sesquiterpene-producing glands) provides modest pest deterrence through allelochemical production
- Ongoing ICAR-CICR breeding programs introgress resistance traits into agronomically elite backgrounds; pending multi-location evaluation and release

Molecular Resistance Mechanisms:

- Enhanced expression of proteinase inhibitors in developing seeds
- Elevated production of secondary metabolites (flavonoids, stilbenes) in seed coat tissues
- Reduced nutritional quality (protein, lipid composition) in seeds of resistant germplasm rendering them unsuitable for pest population growth

Future Research Directions and Emerging Challenges

Genomic and Molecular Research:

- Whole-genome sequencing of *Dysdercus spp.* to identify genes controlling host-plant recognition, digestive physiology, and reproductive biology
- Transcriptomic profiling during different developmental stages and feeding conditions
- Functional genomics approaches to validate candidate genes controlling pest-plant interactions

Resistance Management:

- Baseline susceptibility monitoring of field populations to diverse insecticide classes using molecular resistance markers
- Development of resistance management protocols for extended Bt cotton deployment in red cotton bug-endemic regions

Climate-Pest Interactions:

- Population dynamics modeling incorporating projected temperature and precipitation changes under climate-change scenarios
- Geographic redistribution predictions of *Dysdercus spp.* based on bioclimatic envelope modeling

Biological Control Enhancement:

- Mass-rearing protocols for reduviid predators and parasitoids for augmentative release programs
- Genetic improvement of natural enemies for enhanced pest suppression capacity
- Inundative releases of entomopathogenic fungi in high-pest-incidence regions

Integrated Approach Optimization:

- Farmer field schools implementing participatory IPM protocols in cotton clusters
- Decision-support systems integrating pest monitoring data, weather information, and ETL-based recommendations for real-time management decisions

Conclusion

Red cotton bug (*Dysdercus spp.*) represents an economically significant constraint to sustainable cotton production in India and tropical regions globally. The pest's capacity for rapid population multiplication, lint-staining damage through direct feeding and secondary pathogenic contamination, and threat to cotton seed quality necessitate comprehensive integrated pest management approaches. Contemporary management paradigms must balance

productivity imperatives with environmental stewardship and farmer economic viability. Successful *Dysdercus* management requires hierarchical implementation of cultural practices (crop rotation, resistant varieties, optimal sowing time), mechanical interventions (field sanitation, trap deployment), and biological control strategies emphasizing predator conservation and parasitoid augmentation. Chemical interventions should follow strict economic threshold protocols, with insecticide rotation mandatory to delay resistance evolution. Synergistic integration of diverse management tactics within IPM frameworks consistently outperforms single-tactic approaches in field efficacy and economic cost-benefit analyses. Future research priorities must address genomic characterization of pest biology, validation of host-plant resistance germplasm, and development of decision-support systems for precision pest management. Extension of collaborative research networks among ICAR institutes, State Agricultural Universities, and international research organizations will accelerate technology adoption and foster farmer capacity-building in cotton pest management.

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Chapter 6: Precision IPM and Economic Threshold-Based Decision Making for Pigeonpea Pod Borer Management

Abstract

Pigeonpea (*Cajanus cajan* L.) is an important grain legume that promotes soil fertility, protein security, and livelihood resilience in tropical and subtropical regions, particularly in India, Africa, and Southeast Asia. *Helicoverpa armigera*, *Etiella zinckenella*, *Maruca vitrata*, and *Cydia* spp. dominate the pod borer complex, a persistent biotic constraint that poses a threat to production sustainability and results in significant yield losses. Economic threshold-based decision-making and integrated pest management (IPM) are required because traditional pesticide-centric management has led to resistance development, non-target effects, and ecological imbalance. Using digital tools, pheromone-based monitoring, biological control, host plant resistance, and climate-informed forecasting, this review explores the transition to precision IPM. Additionally, it summarizes research on the biology, damage dynamics, and economic thresholds of pigeonpea pod borers from India and around the world and critically evaluates threshold-based decision frameworks. The focus is on matching pest population dynamics with real-time decision support systems to reduce chemical inputs while boosting sustainability and productivity.

Keywords: Decision support systems, Economic threshold level, Pod borer complex, *Cajanus cajan* and precision IPM.

Introduction

India accounts for almost 70% of the world's pigeonpea production, which is grown on more than 7 million hectares (FAOSTAT, 2024; ICAR-IIPR, 2023). Despite its significance, productivity is still low (700–900 kg ha⁻¹), mostly because of insect pests, the most damaging of

which is the pod borer complex (Sharma *et al.*, 2016; Saxena *et al.*, 2021). Depending on crop stage, management techniques, and infestation intensity, pod borers can cause yield losses ranging from 30 to 80% (Patil *et al.*, 2021). Calendar-based insecticide applications, which frequently surpass 6–8 sprays per season, are a major component of conventional management (Kranthi *et al.*, 2022). As a result, *H. armigera* resistance has increased, natural enemy populations have been disturbed, and production costs have gone up (Armes *et al.*,

2019). As a result, pest management paradigms have changed to emphasize economic threshold-based decision-making, in which interventions are only initiated when pest populations pose a threat to financial gain (Pedigo & Rice, 2014). The use of threshold-driven IPM in pigeonpea ecosystems is further improved by recent developments in digital advisory systems and precision agriculture (Prasanna *et al.*, 2023).

Pigeonpea Pod Borer Complex: Species Composition and Biology

Major Pod Borer Species

The pigeonpea pod borer complex consists of several lepidopteran pests with overlapping feeding habits:

- a. ***Helicoverpa armigera* (Hübner):** The most dominant species, characterized by polyphagy, high fecundity, migratory behavior, and insecticide resistance (Fitt, 2018; Kranthi *et al.*, 2022).
- b. ***Etiella zinckenella* (Treitschke):** An internal pod feeder causing concealed seed damage, particularly prevalent in semi-arid regions (Yadava *et al.*, 2017).
- c. ***Maruca vitrata* (Fabricius):** A serious pest in humid tropics, attacking flowers and young pods (Sharma & Gaur, 2020).
- d. ***Cydia spp.*:** Region-specific pests contributing to localized yield losses (Patil *et al.*, 2021).

Biology and Population Dynamic

The population dynamics of the pigeon pea pod borer complex are significantly influenced by the biological traits, host plant phenology, and current agroclimatic conditions. *Helicoverpa armigera* is the most dominant species in the complex due to its high fecundity, polyphagous feeding habits, strong migratory capacity, and remarkable adaptive potential (Fitt, 2018; Kranthi *et al.*, 2022). Up to 1,000–1,500 eggs can be laid by females over the course of their lifetime. These

eggs are laid singly on flower buds, leaves, and young pods. As a result, during the pigeonpea's reproductive stage, the population can expand rapidly (Sharma *et al.*, 2016). The most harmful stage that directly harms flowers and pods is the larval stage, which lasts 14–21 days and consists of five to six instars. The egg incubation period lasts two to four days (Patil *et al.*, 2021).

During the flowering and pod formation stages, when host tissue availability and nutritional quality are at their peak, pod borer populations typically peak (Sithanantham *et al.*, 2018). Temperature and relative humidity have a major impact on development rate, survival, and voltinism. Optimal temperatures (25–30 °C) significantly boost larval survival and adult fecundity, while excessive rainfall can reduce early instar survival but encourage later outbreaks under humid conditions (Sharma & Gaur, 2020). *Maruca vitrata*, on the other hand, is more prevalent in humid and sub-humid settings, where it completes multiple overlapping generations and exhibits cryptic feeding behavior within webbed flowers and pods, making detection and management more challenging (Srinivasan *et al.*, 2021).

By causing more generations to occur each season, causing infestations to begin earlier, and causing them to spread over greater areas, climate change has altered the way pod borer populations grow (Deutsch *et al.*, 2018). Warmer temperatures have been shown to accelerate insect development and metabolism, which frequently results in earlier economic threshold crossing and longer crop vulnerability periods (Prasanna *et al.*, 2023). These changing population trends that are affected by the weather show how static threshold values don't work and how important it is to monitor them in real time and make decisions based on biology when managing pigeonpea pod borers.

Damage Mechanisms and Yield Loss Assessment

The primary cause of the damage caused by the pigeonpea pod borer complex is the larvae's consumption of reproductive structures, which results in yield losses that are both quantitative and qualitative. Too many flowers fall off because early instar larvae consume flower buds and open flowers. Conversely, later instars eat immature seeds and bore into developing pods, which can harm several pods during their growth (Sharma *et al.*, 2016; Patil *et al.*, 2021). The primary cause of the damage caused by the pigeonpea pod borer complex is the larvae's consumption of reproductive structures, which results in yield losses that are both quantitative and qualitative. Too many flowers fall off because early instar larvae consume flower buds and open flowers. Conversely, later instars eat immature seeds and bore into developing pods, which can harm several pods during their growth (Sharma *et al.*, 2016; Patil *et al.*, 2021).

Pigeonpea yield loss can be measured in a number of ways, including the number of larvae per plant, the percentage of pod damage, and the loss of grain weight and seed quality (Sharma *et al.*, 2016). According to research conducted in important pigeonpea-growing regions of India, yield reductions under moderate infestations range from 30 to 60%, and

during severe outbreaks, they can reach over 80% in unmanaged fields (Patil *et al.*, 2021; Saxena *et al.*, 2021). The number of larvae present during the pod formation stage is strongly positively correlated with the final yield reduction, according to quantitative loss models. As a result, threshold-based intervention strategies and economic injury levels were developed (Pedigo & Rice, 2014). Pod borer damage also makes pods more likely to get secondary fungal and bacterial infections, which lowers the quality and market value of the grain even more, leading to even bigger economic losses than just lower yields (Sharma & Gaur, 2020).

Economic Thresholds and Action Levels

Conceptual Framework

The Economic Threshold Level (ETL) is the number of pests at which management steps should be taken to keep populations from reaching the Economic Injury Level (Pedigo & Rice, 2014). ETLs are the scientific basis for IPM that is based on decisions.

Levels for Pod Borers

Reported ETLs for pigeonpea are:

- 1 to 2 larvae per plant during the flowering and podding stages (Sharma *et al.*, 2016)
- 5–10% of the pods are damaged (ICAR-IIPR, 2023)
- 8 to 10 moths trap⁻¹ night⁻¹ in pheromone traps for *H. armigera* (Patil *et al.*, 2021)
- Variations in thresholds across regions show that different cultivars are more or less resistant, that input costs are different, and that market prices are different (Pedigo & Rice, 2014).

Restrictions

Limitations of Economic Threshold–Based Decision-Making

Even though economic threshold levels (ETLs) are the scientific basis for integrated pest management, they can't be used in pigeonpea pod borer management because of a number of biological, environmental, and socio-economic factors. One of the main problems with static thresholds is that they don't take into account how pest populations change over time and space due to changes in the weather. Temperature, precipitation, and relative humidity substantially affect the developmental rate, survival, fecundity, and voltinism of

significant pod borer species, including *Helicoverpa armigera* and *Maruca vitrata*. This results in swift population increases that can surpass established thresholds prior to the implementation of management strategies (Deutsch *et al.*, 2018; Prasanna *et al.*, 2023). Consequently, static ETLs formulated under historical climatic conditions may understate risk in warming scenarios, thereby heightening the potential for economic harm.

Another important limitation comes from the fact that the pigeonpea pod borer complex is made up of many different species. Economic thresholds are typically established for specific pest species under controlled conditions; however, in agricultural fields, multiple pod borer species often coexist and interact synergistically, leading to increased crop damage (Patil *et al.*, 2021). Mixed infestations with *H. armigera*, *Etiella zinckenella*, and *Maruca vitrata* make it harder to get an accurate count of pests and apply thresholds because the damage potential varies between species and life stages (Sharma *et al.*, 2016). Moreover, cryptic feeders like *M. vitrata* and *E. zinckenella* inflict hidden damage in flowers and pods, resulting in an underestimation of infestation levels during regular scouting (Sithanantham *et al.*, 2018).

Operational limitations further restrict the implementation of threshold-based decision-making. Field scouting to figure out how many larvae there are or how much damage has been done to the pods takes a lot of work, time, and technical skills that many smallholder farmers don't have (Saxena, 2020). In rainfed pigeonpea systems, where labor is only available at certain times of the year and farms are small, regular monitoring is not common. This means that interventions are often delayed or missed (ICAR-IIPR, 2023). This problem gets worse because there isn't enough extension support and it's hard to get reliable pest surveillance tools, especially in remote and resource-poor areas.

Socio-economic factors have a big impact on how well ETL works. Threshold values are naturally affected by market prices, the cost of control measures, and how farmers see risk (Pedigo & Rice, 2014). Farmers often use preventive insecticide applications even when there aren't many pests in areas where market prices are unstable or pest pressure is high. This is to avoid perceived yield losses, which defeats the purpose of threshold-based IPM (Kranthi *et al.*, 2022). Moreover, differences in cultivar susceptibility, input costs, and availability of biocontrol agents render uniform threshold recommendations unfeasible across various agro-ecological zones (Sharma *et al.*, 2016).

Finally, the changing effects of climate change make static thresholds even less useful. Rising temperatures and changing rainfall patterns are making pests more likely to reproduce, spreading their ranges, and starting infestations earlier. This often leads to crop-pest

interactions that happen at different times (Deutsch *et al.*, 2018). These changes require a move away from fixed thresholds and toward adaptive, real-time decision-making systems that take into account pest biology, weather data, and economic factors (Prasanna *et al.*, 2023). If these changes aren't made, relying on static ETLs could mean that interventions are delayed, which could lead to crop loss, or that pesticides are used when they aren't needed, which would hurt both the economy and the environment.

Integrated Decision-Making in Pod Borer IPM

Cultural Practices

Cultural practices create an environment that is not good for pests to settle, survive, and reproduce, which is the first line of defense in integrated pest management of pigeonpea pod borers. The main goals of these practices are to break up the life cycles of pests, lower the number of pests that first show up, and make crops more resistant to pests, which will delay or stop the crossing of economic thresholds (Sharma *et al.*, 2016; Saxena *et al.*, 2021). Early and synchronized sowing of pigeonpea has consistently demonstrated efficacy in diminishing pod borer incidence by allowing the crop to evade periods of peak pest activity. Early-sown crops frequently finish flowering and forming pods before pod borer populations get high enough to cause damage. This means that there are fewer larvae and less damage to pods than in late-sown crops (Patil *et al.*, 2021).

Another good way to keep pod borer numbers down is to plant pigeonpea with cereal crops that aren't hosts or aren't as popular, like sorghum, pearl millet, or maize. Intercropping changes the structure of the crop canopy, the microclimate, and the visibility of the host plant, which makes it harder for *Helicoverpa armigera* to lay eggs and for larvae to move (Saxena *et al.*, 2021). Multiple field studies in India have shown that intercropping systems that include pigeonpea can cut pod borer damage by 20–40% compared to growing only pigeonpea, and they can also increase the number of natural enemies (Sharma & Gaur, 2020). Taking out and destroying alternate and volunteer host plants is very important for keeping pests from building up early in the season. *H. armigera* lives on other plants, like chickpeas, tomatoes, and weeds, between cropping seasons. This means that pigeonpea crops are always at risk of getting infested (Fitt, 2018). Sanitation practices, such as removing crop residues and volunteer plants, lower the number of pests that can survive and make it easier to start a new crop (Sithanantham *et al.*, 2018). Also, it is important to manage nutrients in a balanced way, especially by not using too much nitrogen fertilizer. This is because plants with a lot of nitrogen are more appealing and nutritious for pod borer larvae, which leads to higher levels

of infestation (Prasanna *et al.*, 2023).

All of these cultural practices work together to lower the number of pests at the start, make other parts of IPM work better, and make economic threshold-based decision-making more reliable when it comes to managing pigeonpea pod borer.

Host Plant Resistance

Host plant resistance (HPR) is a key part of sustainable integrated pest management in pigeonpea. It is a cost-effective and eco-friendly way to reduce damage from pod borers. Resistant and tolerant pigeonpea genotypes negatively influence pest behavior, survival, development, and fecundity, consequently diminishing pest pressure and effectively elevating economic threshold levels (ETLs) (Sharma *et al.*, 2016; Varshney *et al.*, 2017). Host plant resistance delays the point at which pest populations reach levels that are harmful to the economy by lowering the baseline infestation and slowing the growth of the population. This makes threshold-based decision-making more effective.

Pigeonpea has three ways to fight pod borers: antibiosis, antixenosis, and tolerance. Antibiosis entails detrimental impacts on insect biology, including diminished larval survival, extended developmental periods, and decreased pupal weight, as evidenced in various resistant pigeonpea genotypes against *Helicoverpa armigera* (Sharma *et al.*, 2016). Antixenosis, or non-preference, diminishes oviposition and feeding via morphological and biochemical characteristics, including thicker pod walls, trichome density, and secondary metabolites such as phenolics and flavonoids (Saxena *et al.*, 2021). Tolerant genotypes, despite sustaining some damage, preserve yield through compensatory growth and enhanced pod retention, thereby mitigating economic loss in the presence of pests.

Significant progress has been made in identifying pod borer-resistant sources from cultivated germplasm and wild relatives of pigeonpea. Wild species such as *Cajanus scarabaeoides* and *C. platycarpus* have shown high levels of resistance to *H. armigera* and *Maruca vitrata* and are being utilized in breeding programs (Varshney *et al.*, 2017). Advances in genomics-assisted breeding, quantitative trait loci (QTL) mapping, and marker-assisted selection have accelerated the development of improved pigeonpea cultivars with enhanced resistance traits (Varshney *et al.*, 2017; Saxena, 2020).

Integration of host plant resistance with other IPM components, such as biological control and need-based chemical interventions, provides additive and synergistic effects. Resistant cultivars also reduce selection pressure for insecticide resistance by minimizing pesticide use, contributing to long-term sustainability of pod borer management strategies

(Kranthi *et al.*, 2022). Consequently, host plant resistance remains a key driver of resilient, threshold-based decision-making frameworks in pigeonpea pod borer IPM.

Biological Control

Biological control is an important part of integrated pest management (IPM) for pigeonpea pod borers because it naturally keeps pest populations down and slows their growth toward economic threshold levels. Egg parasitoids like *Trichogramma chilonis* are commonly employed in pigeonpea ecosystems and effectively parasitize the eggs of *Helicoverpa armigera* and *Maruca vitrata*, thereby inhibiting larval emergence and mitigating subsequent crop damage (Sithanantham *et al.*, 2018; Sharma *et al.*, 2016). Augmentative releases of *T. chilonis* during flowering and early podding stages have been demonstrated to substantially decrease larval density and pod damage, particularly when integrated with cultural and host plant resistance strategies (Patil *et al.*, 2021).

Under field conditions, larval parasitoids, especially *Campoletis chlorideae*, play a big role in keeping *H. armigera* populations in check. This parasitoid preys on early instar larvae, which lowers their chances of survival and slows down the growth of the population. This makes economic threshold-based interventions more effective (Sharma *et al.*, 2016). Predators like spiders, ladybird beetles, lacewings, and insectivorous birds also help parasitoids by constantly eating eggs and larvae, especially in fields that haven't been sprayed or have only been lightly treated (Sithanantham *et al.*, 2018).

Campoletis chlorideae and other larval parasitoids play a big role in keeping *H. armigera* populations in check in the field. These parasitoid attacks early instar larvae, which makes it harder for the larvae to survive and slows down the growth of the population. This makes economic threshold-based interventions work better (Sharma *et al.*, 2016). Predators like spiders, ladybird beetles, lacewings, and insect-eating birds also help parasitoids by constantly eating eggs and larvae, especially in fields that haven't been sprayed or have only been lightly treated (Sithanantham *et al.*, 2018).

Microbial control agents are an important and safe choice for the environment in threshold-based IPM. *Helicoverpa armigera* nucleopolyhedrovirus (HaNPV) offers precise control of *H. armigera* larvae, demonstrating optimal efficacy when administered during the early larval stages at threshold concentrations (Kranthi *et al.*, 2022). *Bacillus thuringiensis* formulations also kill larvae by damaging their guts, and they work well with natural enemies and other IPM parts (Srinivasan *et al.*, 2021). Combining these biological agents with decision-making based on economic thresholds makes pigeonpea pod borer management

systems more sustainable and stronger.

Chemical Interventions

Chemical control is still an important part of controlling pigeonpea pod borers, but it should only be used when pest populations are above the economic threshold levels (ETLs). When used carefully, selective insecticides quickly kill off harmful larval populations while having the least negative effects on natural enemies and the health of the agroecosystem (Kranthi *et al.*, 2022). Historically, indiscriminate and calendar-based spraying, especially of broad-spectrum insecticides, has led to the development of resistance in *Helicoverpa armigera*, the return of secondary pests, and an imbalance in the ecosystem in pigeonpea (Armes *et al.*, 2019).

Threshold-guided chemical interventions stress the use of newer insecticide molecules with new ways of working, like diamides, spinosyns, oxadiazines, and insect growth regulators. These chemicals are more selective and less toxic to non-target organisms (Kranthi *et al.*, 2022). It is important to rotate insecticides based on how they work in order to slow down the development of resistance and keep them working for a long time. Timing of application is also very important. Targeting early larval instars near ETLs makes control more effective and cuts down on the need

for repeated sprays (Sharma *et al.*, 2016). Combining chemical control with biological agents like parasitoids and microbial insecticides makes things even more sustainable. For example, HaNPV and *Bacillus thuringiensis* can be used before or in between selective insecticides to lower the amount of chemicals while still keeping pests under control (Sithanantham *et al.*, 2018). So, chemical interventions work best as a supporting part of integrated decision-making frameworks, which supports the ideas of precision IPM in managing pigeon pea pod borers.

Digital Decision Support Systems and Precision IPM

Precision integrated pest management (IPM) signifies a transformative shift from reactive pest control to proactive, data-informed decision-making. In managing the pigeonpea pod borer, precision IPM combines real-time pest monitoring, economic thresholds, weather data, and predictive analytics to find the best time and type of action to take (Prasanna *et al.*, 2023). This method makes decisions more accurate, cuts down on unnecessary pesticide use, and makes things better for the economy and the environment. Digital decision support

systems (DSS) allow for a dynamic evaluation of pest risk by integrating field observations with regional climatic and agronomic information. These systems go beyond static threshold ideas by taking into account how pest populations, crop phenology, and input costs change over time (Pedigo & Rice, 2014). Precision IPM tools are especially useful for pigeonpea because temperature, rainfall patterns, and crop stage have a big effect on pod borer infestations (Sharma *et al.*, 2016). Recent progress in sensors, artificial intelligence (AI), and mobile-based advisory platforms has sped up the use of precision IPM in developing agricultural systems. In India, public-sector programs led by ICAR and state agricultural departments are increasingly adding digital surveillance and advisory services to national pest management programs (ICAR-IIPR, 2023). When done right, precision IPM makes decision-making based on thresholds stronger, makes better use of resources, and helps pigeon pea production systems that can handle climate change.

Intelligent Monitoring Instruments

Smart monitoring tools are the basis of precision IPM because they let you keep an eye on pod borer populations all the time, accurately, and in real time. More and more, automated pheromone traps with optical sensors and wireless data transmission are being used to keep an eye on adult *Helicoverpa armigera* activity. These traps can give early warning signs of infestations (Prasanna *et al.*, 2023). These systems get around the problems that come with manual scouting, like being hard to do, being biased by the observer, and taking too long to respond. IoT-enabled field sensors that measure temperature, humidity, and rainfall improve pest monitoring by connecting environmental factors with pest life cycles. Because pod borer growth and voltinism are very dependent on the weather, adding microclimatic data makes predictions more accurate and relevant to the threshold (Deutsch *et al.*, 2018). Stakeholders can see pest trends across different areas and times with real-time dashboards and cloud-based platforms. This makes it easier to make decisions that are specific to a certain area.

Smart monitoring tools have shown a lot of promise in pigeon pea ecosystems for improving the timing of interventions, cutting down on prophylactic spraying, and protecting biological control (Patil *et al.*, 2021). But for them to work, they need to be properly calibrated, easy for farmers to use, and linked to advisory services. As digital infrastructure expands in rural areas, smart monitoring is expected to play an increasingly central role in threshold-based IPM frameworks.

AI and Making Predictions

Because they enable you to anticipate when pests will appear rather than merely respond to them, artificial intelligence (AI) and predictive modelling are revolutionary tools for pest control. The population dynamics and outbreak risks of pod borers are predicted by machine learning algorithms using historical pest data, weather data, crop phenology, and landscape features (Deutsch *et al.*, 2018). These models aid in the development of dynamic economic thresholds that adapt to changes in the environment or the economy. By providing timely guidance on how to monitor pests, when to release biological controls, and when to use chemicals, digital advisories encourage people to use IPM more. Research in India indicates that farmers who receive mobile advisories implement ETL-based spraying more consistently, resulting in a 20–30% reduction in pesticide usage without affecting yield (Prasanna *et al.*, 2023). Combining pest surveillance data with advisory platforms makes them even more useful and helps people make better decisions. But there are still problems with making sure that digital recommendations are trustworthy, accessible in different languages, and localized (Saxena, 2020). To make mobile advisory services bigger and make precision IPM a normal part of pigeonpea production, it will be important to strengthen public-private partnerships and add ways for people to give feedback.

Climate Change and Adaptable Limits

Climate change is having a big effect on the ecology and management of pigeonpea pod borers by changing where they live, when they reproduce, and how quickly their populations grow. Higher temperatures and unpredictable rainfall patterns have made *H. armigera* more likely to reproduce multiple times in a season, lengthened the time it takes for an infestation to happen, and made it easier for the pest to spread to areas where it was not previously able to thrive (Deutsch *et al.*, 2018). These changes make it less likely that static economic thresholds based on past climate conditions will be accurate. Adaptive threshold concepts take into account changes in climate by using weather-based risk indices and crop growth models in decision-making frameworks (Prasanna *et al.*, 2023). Climate-responsive thresholds allow for earlier actions during times of high risk and stop yield losses during extreme weather events. So, combining climate forecasting with pest monitoring is very important for IPM strategies that work. To create adaptive thresholds, you need long-term datasets, people from different fields to work together, and constant testing. As climate variability increases, incorporating climate intelligence into precision IPM will be crucial for maintaining pigeonpea productivity and reducing ecological

disruption.

Challenges

Even though IPM and digital agriculture have come a long way, there are still a lot of problems that make it hard to make good decisions about how to deal with pigeonpea pod borers. Smallholders have trouble adopting because there aren't enough region-specific economic thresholds, predictive models aren't validated well enough, and smallholders don't have easy access to digital tools (Saxena, 2020). The implementation of threshold-based strategies is further limited by fragmented extension systems and a lack of awareness.

Future research should focus on creating dynamic, climate-smart thresholds that are specific to local agroecologies. It is important to strengthen participatory research, improve digital infrastructure, and add farmer feedback to DSS platforms. Policy support and investment in institutions.

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To create adaptive thresholds, you need long-term datasets, people from different fields to work together, and constant testing. As climate variability increases, incorporating climate intelligence into precision IPM will be crucial for maintaining pigeonpea productivity and reducing ecological disruption.

Conclusion

Effective management of the pigeonpea pod borer complex requires a shift from calendar-based pesticide use to science-driven, threshold-based decision-making within integrated pest management (IPM) frameworks. Evidence from India and other pigeonpea-growing regions confirms that economic threshold levels (ETLs), grounded in pest biology and crop phenology, reduce unnecessary interventions while improving control efficiency. The integration of cultural practices, host plant resistance, and biological control lowers baseline pest pressure and enhances the reliability of threshold-based actions. Judicious use of selective insecticides at early larval stages, following threshold attainment, ensures effective control of *Helicoverpa armigera* while conserving natural enemies and minimizing resistance

risks. Advances in precision IPM— including real-time monitoring, digital decision-support tools, and climate-informed predictive models—further strengthen adaptive pest management under changing agro-climatic conditions. Continued investment in adaptive thresholds, digital advisory systems, and policy-supported IPM adoption is essential for sustainable, productive, and economically viable pigeonpea cultivation.

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Chapter 7: Wheat Aphids (Hemiptera: Aphididae): Biology, Ecology, Economic Impact and Integrated Management

Abstract

Wheat (*Triticum aestivum* L.) – is one of the most important cereal crops at the global level with its productivity greatly affected by insect pests among which aphids (Hemiptera: Aphididae) are the most harmful sap-suckers. Wheat aphids cause direct damage through removal of phloem sap and indirect damage through transmission of viral diseases, in particular Barley Yellow Dwarf Virus (BYDV). In India and other wheat growing regions, aphids have evolved from sporadic to regular and economically important pests as a result of climate change, intensified cropping systems and application of nitrogenous fertilizers. The aphid complex in wheat is mainly comprised by *Sitobion avenae*, *Sitobion miscanthi*, *Rhopalosiphumpadi* and *Rhopalosiphum maidis* that differ on their ecology, feeding behaviour and potential for damage. This review provides an overview on updated information on history, hosts range taxonomy life cycle seasonal dynamics economic threshold levels symptomology and yield losses caused by wheat aphids. Emphasis is given to IPM strategies including cultural mechanical biological botanical microbial chemical control measures. Upcoming challenges like insecticide resistance climate variability declining natural enemy populations are brought into notice. Review throws light on future research needs for development of sustainable climate resilient management practices against wheat aphids in wheat ecosystems.

Keywords: Wheat aphids; *Sitobion avenae*; *Rhopalosiphum padi*; Economic threshold level; Integrated pest management; Barley Yellow Dwarf Virus; India

Introduction

Wheat (*Triticum aestivum* L.) is among the main staple foods in the world and contributes about 20 per cent of the total caloric requirement of humans. In India, wheat is grown on an area of approximately 31 million hectares with the overall production exceeding 110 million tonnes thus making India the second largest wheat producing country in the world. However, despite all these efforts made in genetic transformation and agronomic practices, insect pests remain one of the major constraints towards realization of optimal wheat yield level. Under this category aphids are identified as principal sap-sucking pests which attack wheat crop as was highlighted by earlier global syntheses done by Blackman And Eastop (2000) cited on Indian context about Aheer *et al.* (2007) and Agarwal *et al.* (2012). It has become clear that aphids (Hemiptera:

Aphididae) play a critical role in wheat production affecting the wheat crop in the various agro ecological regions of India with significant yield losses-direct and indirect, since then. Singh *et al.* (2013) reported that aphids on wheat attack crops by feeding on phloem sap continuously which causes decrease of plant vigor, chlorosis, leaf curling, and black grain development. Apart from direct feeding damage aphids are responsible for sap honey dew loss and virus diseases spreading which represents an overall serious challenge to sustainable systems of wheat cultivation ((Blackman and Eastop, 2000; Singh S.; Malik R., 2020).

Wheat aphids are not a single species rather they are a complex of species which colonize the crop at different growth stages ranging from tillering to grain filling. Agarwal *et al.* (2012), Singh *et al.* (2013), and Verma *et al.* (2016) did the surveys in almost all wheat growing regions of India and concluded that *Sitobion avenae* (Fabricius), *Sitobion miscanthi* (Takahashi), *Rhopalosiphum padi* (Linnaeus), and *Rhopalosiphum maidis* (Fitch) were the dominant aphid species on wheat. The incidence and prevalence of these species change with host development stages, climatic conditions and location, affecting the severity and type of damage caused by pests on the crop plants (Choudhary *et al.*, 2018; Singh and Malik, 2020).

In recent years, wheat aphids have shifted from being sporadic or minor pests to regular and occasionally severe constraints in major wheat-growing regions of India. Aheer *et al.* (2007) and Singh and Singh (2015) reported that changes in climatic conditions, particularly warmer winters and prolonged cool periods during the Rabi season, have favoured aphid survival and rapid population build-up. Agronomic modifications, such as greater HWNR cultivar adoption, N- responsive varieties selection, high fertilizer amounts application, residue retention and reduced- tillage approaches in particular have continued to shape the agro-ecosystem by making them more aphid facilitating ooser reproduction (Singh *et al.* (2013) and Agarwal *et al.* (2012). The reduced genetic diversity in cultivated wheat has made crop more susceptible to aphid attack as well (Verma *et al.*, 2016).

Wheat aphid species and distribution

Wheat in India faces attacks from a mix of aphid species in the family Aphididae (Hemiptera). This group is often called the wheat aphid complex. This has been termed the wheat aphid complex, Blackman and Eastop (2000) have further expounded the existence of various species of aphids with various ecology, season and feeding location and damages potentials in wheat. Agarwal *et al.* (2012) and Singh *et al.* (2013) subsequently proved these findings in the Indian farming conditions. As it is stated by Singh and Singh (2015), these species may co-exist on the same crop, but the level of abundance of these species depends on the region and climate along with the age of the crop and agriculture practices. One of them is one of the most harmful species of the wheat aphid complex, *Sitobion avenae* (Fabricius) or English grain aphid. The studies of Agarwal *et al.* (2012) and Singh *et al.* (2013) were carried out in the Indo-Gangetic Plains and found out that the species mainly colonized the top leaves and wheat spikes during the heading to grain-filling stages. Their feeding determines significantly the size of the grain, the weight and yield of a thousand grains. An extremely close sps of *s.avenae* is the Indian grain aphid *iis*. A field survey performed by Verma *et al.* (2016) and Choudhary *et al.* (2018) showed that it is better adapted to local weather and occurs at a high rate in the main wheat-producing states, including Punjab, Haryana, Uttar Pradesh, Bihar, and some part of Rajasthan. It can be explained by its long period of existence and high reproductive rate which ensures active activity in these areas.

Another important species that occurs in the Indian wheat fields is the bird cherry oat aphid *Rhopalosiphum padi* (Linnaeus). According to Aheer *et al.* (2007) and Singh and Malik (2020), this species is more likely to infect wheat in its early stages of growth, with leaves and stems being the main food sources. Its economic importance is enhanced by the fact that it acts as a carrier of Barley Yellow Dwarf Virus (BYDV) that has the potential to cause severe consequences to the yield despite moderate levels of aphid populations as reported by Blackman and Eastop (2000). Though *Rhopalosiphum maidis* (Fitch) is commonly associated with maize and other cereals it has been common in wheat in India. This species was also found in mixed cereal cropping as observed in studies by Agarwal *et al.* (2012) and Singh *et al.* (2013). The wheat aphids occur in all the significant wheat-producing areas in India such as the north-western plains, north-eastern plains, central India and a portion of the hilly north. Aheer *et al.* (2007), Singh and Singh (2015), and Choudhary *et al.* (2018) reported that warmer winters and longer cool winters during the Rabi season would allow aphids to survive, colonize early, and increase their population in a very short time. This causes

increased periods of infestation. Furthermore, Blackman and Eastop (2000) have explicitly indicated the way alternative host plants, volunteer cereals and grassy weeds maintain aphid populations during the various seasons. Later this was verified in Indian wheat systems.

Geographical occurrence of wheat aphids

In India, there are a lot of places where aphids of wheat can be found. They are able to grow in different agro-climatic conditions. They are associated with the winter temperatures, crop growth phases and the farming activities in the area.

Punjab

According to Singh and Verma (2012) and Sharma *et al.* (2016), Punjab demonstrates a high aphid occurrence regularly because of the high concentration of wheat farming and appropriate winter temperatures. The chief ones are *Sitobion miscanthi* and *Sitobion avenae*. The highest population of aphids normally occurs between February and early March. Frequent infestation occurs with the use of high levels of nitrogen and monocropping.

Bihar

The aphids are regularly found in Bihar, particularly in the central parts and North areas. The predominant one is *S. miscanthi*, and also *R. padi* and *R. maidis*. The conditions are usually cool and humid, thereby prolonging aphid populations, and causing crops to become susceptible to grain filling.

Madhya Pradesh

Wheat aphids are found sporadically in Madhya Pradesh. The warmer climate and shorter winters limit how quickly aphids can multiply. However, delayed planting or extended cool periods can lead to significant infestations, mainly caused by *S. avenae*. Overall, aphid pressure is lower than in the Indo-Gangetic Plains.

West Bengal

In West Bengal, aphids mainly appear in the wheat-growing areas of the Gangetic plains. *S. miscanthi* and *R. padi* are common species, and infestations often begin early because of mild winters. The continuous presence of alternate hosts and grassy weeds helps aphids survive.

Hill States (Himachal Pradesh, Uttarakhand, Jammu & Kashmir)

The hill regions usually have less aphid pressure because of cooler temperatures and shorter crop cycles. However, warmer winters have caused occasional aphid outbreaks in recent years, especially at lower altitudes. *R. padi* is reported more often during the early stages of crops. Overall, the distribution of wheat aphids in India shows that Sitobion species are most common in the Indo-Gangetic Plains, and local climate affects pest severity.

Host plant and feeding ecology of wheat aphids

Wheat aphids have a close relationship with cereal plants, with wheat (*Triticum aestivum* L.) being the main host during the Rabi season in India. Blackman and Eastop (2000) extensively described the strong preference of cereal aphids for wheat. Aheer *et al.* (2007) and Agarwal *et al.* (2012). Nevertheless, the wheat aphids do not only feed on cultivated wheat since they also have a broader host range that includes other cereals, wild grasses, and volunteer plants, as described by Singh *et al.* (2013) and Verma *et al.* (2016). *Sitobion miscanthi*, *Sitobion avenae* and *Rhopalosiphum padi* and *Rhopalosiphum maidis* are the main species of aphids that infest wheat, and they vary greatly in terms of their preferences, colonization behaviour, and location of feeding on the plant (Singh and Singh, 2015).

Wheat is reported to be the most appropriate and desired host to Sitobion species especially at the reproductive stage of crop growth. Agarwal *et al.* (2012), and Singh *et al.* (2013) carried out field observations that revealed Sitobion aphids mainly colonise the upper leaves, peduncle and earheads, whereby nutrient-enriched phloem sap is readily accessible. On the other hand, *Rhopalosiphum padi* and *R. maidis* are known to infest the low leaves and stems at the tender stages of development and slowly transferred to the higher parts of the plant as the crop grows. This stratification in the wheat canopy previously suggested by Blackman and Eastop (2000) and confirmed by Verma *et al.* (2016) ensures that there is less interspecific competition and leads to coexistence of several aphid species on the same host.

Besides wheat, aphids feed on a large variety of alternate hosts such as barley (*Hordeum vulgare*), oats (*Avena sativa*), maize (*Zea mays*) and a variety of grassy weeds. Blackman and Eastop (2000) have highlighted the reservoir host importance of grasses like *Phalaris minor*, *Avena fatua*, and *Cynodon dactylon* and Aheer *et al.* (2007) and Choudhary *et al.* (2018) have further reported them under Indian circumstances. These alternative hosts

help the aphids to survive in the non-season and early colonize the wheat fields which has a powerful impact on population dynamics and outbreak potential.

Aphids feed on the phloem tissues inserting the fine stylets that suck the phloem tissues to obtain the sugars and amino acid-rich sap. Blackman and Eastop (2000) then first described phloem- feeding mechanism and its ecological implication and was later verified by Singh *et al.* (2013). In this feeding method, it allows the unlimited extraction of nutrients with only slight evidences of tissue loss during the very early stages of infestation. However, the prolonged feeding has resulted in physiological symptoms of stress such as chlorosis, leaf curling, reduced tillering, and stunted growth of plant growth that are confirmed by Verma *et al.* (2016). Earheading during grain-filling stage is particularly detrimental, and it reduces the size of the grain, the weight of the grain, and the quality of the grain directly (Agarwal *et al.*, 2012; Singh *et al.*, 2013).

The wheat genotype, nutritional condition of plants and environmental conditions have a strong effect in terms of feeding efficiency and host suitability. The results of the studies summarized by Singh *et al.* (2013) and Singh and Singh (2015) showed that high nitrogen fertilization increases the concentration of amino acids in the phloem, which causes an increase in the reproduction and survival of aphids. On the other hand, some types of wheat are partially resistant, e.g., antixenosis and antibiosis, which minimize aphid feeding and growth (Agarwal *et al.*, 2012; Verma *et al.*, 2016).

Life cycle

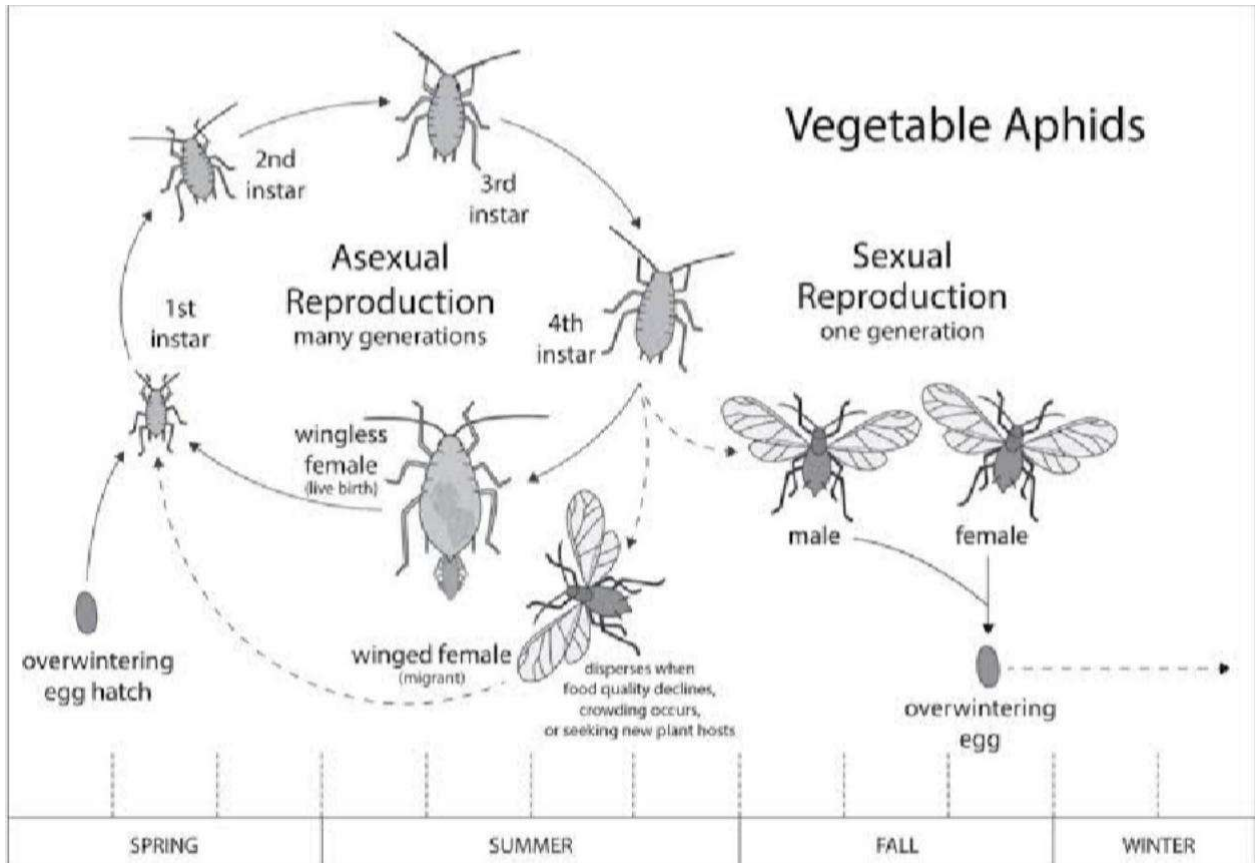
The life cycle of wheat aphids (Hemiptera: Aphididae) is fast paced, flexible and highly adaptable to allow the aphids to reach large population densities in a short time with cry of favourable environmental conditions, as initially outlined by Dixon (1985) and subsequently synthesized by Blackman and Eastop (2000). *Sitobion avenae*, *Sitobion miscanthi*, *Rhopalosiphum padi* and *Rhopalosiphum maidis* are significant aphid species that infest wheat in India, and the similarities in the patterns of their development are quite general, though Singh *et al.* (2009) and Remaudiere and Remaudiere (1997) have observed some differences in host preference and seasonality, and also in dispersal patterns.

Wheat growing seasons in India are the periods where aphids reproduce mainly by parthenogenesis and viviparity where females bear live nymphs without copulation. This is a reproductive strategy, which provides the opportunity to generate numerous overlapping generations and high rate of population escalation. Adult females start reproducing shortly

after the emergence, and may give birth to 30-80 nymphs in a lifetime, which is determined by the temperature, the quality of host plants, and nutritional conditions of the crop.

A life cycle of an aphid has four nymphal instar stages after which it becomes an adult. As Blackman (1974) explains, Nymphs are morphologically similar to their adult counterparts but smaller and wingless. In ideal situations, the nymphal stage is over in a period of 7-10 days with each instar stage taking about 1-2 days (Dixon, 1985; Singh and Verma, 1991). Levels of continuous feeding on phloem sap during nymphal life cause persistent physiological stress on wheat plants (Auclair, 1963; Miles, 1999). Aphids become wingless (apterous) and winged (alate) morphs depending on the level of population density, host deterioration and environmental signals, a process widely researched by Johnson (1963) and Mueller *et al* (2001).

Alate forms are very important in dispersion and colonization of new fields of wheat. The density of aphids and the deterioration in the quality of the hosts promote the production of alates, which allows them to migrate to other wheat crops and other cereal hosts (Kennedy *et al.*, 1961; Irwin and Thresh, 1988). This mechanism of dispersal helps spread infestations and colonize newly planted wheat fields in the Indo-Gangetic plains through the mechanism of rapid spread (Singh *et al.*, 2009; ICAR, 2018).



In cool climates, the aphids of wheat tend to go through a holocyclic life cycle, which includes sexual reproduction and eggs overwintering, in accordance with Dedryver *et al.* (2010). But in majority of the wheat-producing areas of India, the aphids have been found to have anholocyclic life cycle and reproduce asexually throughout the season (Singh and Sachan, 1993; Bindra and Singh, 2002). The survival of off-season takes place on alternate crop varieties, and on grassy weeds, and volunteer wheat plants, and on surrounding plants like maize and barley (Parry, 2013). Less sexual reproduction and overwintering of the egg is possible in hilly ecosystems but is rare in the plains (Verma *et al.*, 2004).

Ideal temperatures of 15 to 25 °C enhance fast growth and high reproducing rates. Nevertheless, extreme temperatures, rainfall, or frost may have a detrimental impact on survival (Campbell *et al.*, 1974; Bale *et al.*, 2002). Aphids may also have multiple generations in one crop year in India, and it will result in the rapid increase of the population (Singh *et al.*, 2015).

Aphids of wheat in India have a rapid and continuous life cycle, and this poses great challenges when controlling them. Dixon (1998) and ICAR (2018) emphasize the importance of knowing the aphid development, reproduction, and movement to successfully monitor them, establish the level of economic threshold and the timely application of management strategies to control them.

Seasonal dynamics of wheat aphids

The aphids of wheat in India exhibit seasonal trends that are associated with the growth of wheat, temperatures, and weather patterns of Rabi season. This was reported by Aheer *et al.* (2007) and confirmed by Singh and Singh (2015) in the Indian settings. According to Agarwal *et al.* (2012), the infestation of aphids normally begins immediately the crops are planted. The populations are usually observed at the end of December or the beginning of January, with the time of sowing and the climate of the region. Winged forms of the aphids typically form the initial presence of wheat aphids in fields, which have migrated to other plants, volunteer cereals and grassy weeds.

Research undertaken by Singh *et al.* (2013) has indicated that the population of aphids gradually rises during the vegetative phase. They reproduce and grow very fast during the tillering stage to the heading stage when the weather is good. The significance of cool and dry weather, between 15 and 25 °C, in enhancing aphid reproduction and survival was first reported by Saxena and Barrion (1987). These findings were later verified by Aheer *et al.* (2007).

Rhopalosiphum padi prevails at early vegetative stages. On the other hand, *Sitobion miscanthi* and *Sitobion avenae* increase in prevalence in booting, heading, and grain-filling. Verma *et al.* (2016) and Singh and Malik (2020) report this especially with regard to earheads and upper leaves. The maximum aphid density in key wheat-producing areas in India normally occurs during the months of February-March. Agarwal *et al.* (2012) and Choudhary *et al.* (2018) have consistently reported this. Singh *et al.* (2013) noted that later the wheat crops are sown, the more susceptible they are to aphid infestation. This can be attributed to the

fact that the reproductive stages coincide with the apex activity of aphids. Conversely, crops sown earlier on can also escape serious harm due to temporal asynchrony as Aheer *et al.* (2007) reported.

The declining numbers of aphids throughout the season during the growth of crops are primarily caused by the effects of hot temperatures, decreasing host preference, natural enemies becoming more active, and occasional rainfall, as described by Saxena and Barrion (1987) and Verma *et al.* (2016). In addition, Singh and Singh (2015) noted that weather variations have a strong influence on the changes in the number of aphids on an annual basis. Gentle winters favor the increase of populations and the aphids are suppressed by extreme weather. Such seasonal trends are still significant to know to monitor, predict, and manage the crucial stages of crop growth in a timely manner.

Economic Importance and Economic Threshold Levels of Wheat Aphids

There are also indirect economic losses attributed to wheat aphids. Aphids produce honeydew that multiplication of the sooty mold fungi on the leaf surfaces. This also restricts photosynthesis as mentioned by Saxena and Barrion (1987). More to the point, there are aphid species that are particularly known to transmit Barley Yellow Dwarf Virus (BYDV), among others: *Rhopalosiphum padi*. Blackman and Eastop (2000) were the first to report the role of aphids in the reproduction of BYDV and subsequent confirmation in the Indian wheat by Singh and Malik (2020). Even in cases where there are low aphids, the virus infection at the initial stages of crop development can result in extreme losses of yields.

Phloem sap is continuously sucked by aphids thus making the plants weak and less effective in photosynthetic processes. This brings direct costs to an economy. Verma *et al.* (2016) have included Indian wheat ecosystems, which are associated with chlorosis, curling of leaves, stunted growth, reduced tillering, and inappropriate grain filling. The consumption of earheads at the grain-filling stage is especially harmful, as shown by Singh *et al.* (2013) since it leads directly to the reduction of the grain size, the weight of the thousand grains, and the total yield. The worst cases have been attributed to the death of grains and reduction of the quality of grain, which damages the market price as well as the reasonable survival of the seeds (Agarwal *et al.*, 2012).

This makes photosynthesis even harder, as Saxena and Barrion (1987) point out. More importantly, some types of aphids, especially *Rhopalosiphum padi*, have been found to be good carriers of Barley Yellow Dwarf Virus (BYDV). Blackman and Eastop (2000) were the first to show that aphids play a role in the spread of BYDV, and Singh and Malik (2020) later confirmed this in Indian wheat. Virus infection during the early stages of crop growth can cause huge losses in yield, even when there aren't many aphids. This shows how important it is to find and treat the problem quickly.

Studies have found that moderate to heavy infestations of aphids can result in yield losses of 5- 30% across the span of areas in India that are suitable for wheat production as well as other areas of the world. Estimates of yield loss due to infestation have been shown by Aheer *et al.*, (2007) and Agarwal *et al.*, (2012). In addition, due to the timing of when infestations occur with regard to the reproductive stages when plants are growing (boot to grain fill), it was shown that the amount of damage to the economy will be greater when infestations coincide with these reproductive stages. Economic damage from aphid infestations also depends on the agronomic practices employed when producing wheat, for example, Singh *et al.* (2013) showed that high levels of nitrogen fertilization increased the rate at which aphids reproduce as well as increased the degree of susceptibility of wheat crops to aphid infestations. Additionally, timing of wheat plantings, such as that presented by Aheer *et al.* (2007), found that planting later in the season makes crops more susceptible to aphids since sensitive reproductive stages are occurring when aphid populations are highest.

The Economic Threshold Level (ETL) is extremely important for determining when it is financially worthwhile to take action against an insect. The ETL is based on pest density and the cost of control. In the production of wheat in India, the recommended ETL is five aphids per earhead, which was developed from a large number of field observations and cost-benefit analyses (Singh, *et al.* 2013) and adopted by all of the Indian Council of Agricultural Research (ICAR) advisory schedules. There are additional studies (Agarwal, *et al.* 2012) that identified intervention thresholds of 10 to 15 aphids per tiller in the vegetative growth stages, especially in late-sown wheat.

As a result of the wide range of factors that determine what constitutes an economic threshold for insect pests (e.g., variety of wheat grown, growth stage of the crop, and weather conditions), the determination of economic thresholds is not fixed. This has been documented by Singh and Singh (2015). The need for developing economic thresholds according to specific growth stages and particular regions has been reported by authors such as Choudhary *et al.* (2018). Particularly in the light of changing climates, the authors also emphasize the need for developing economic thresholds based upon the role of natural enemies as natural pest control agents (e.g., predators, parasitoids) as a method to increase the sustainability of the growing system (i.e., to decrease the amount of chemicals applied) while also decreasing the number of unnecessary insecticides applied to crops. Therefore, continued refinement of economic thresholds through long-term, regionally localized (multi-site) research is essential to ensure that integrated pest management (IPM) strategies remain as effective as possible in the wheat-growing region.

Table 1. Economic Threshold Levels (ETLs) of Wheat Aphids

Crop stage	Aphid density (ETL)	Sampling unit
Vegetative (tillering)	10–15 aphids	Per tiller
Booting to heading	5 aphids	Per earhead
Grain filling	5 aphids	Per earhead
Late-sown wheat (any stage)	Lower ETL applicable	Tiller / earhead



Healthy plant of wheat



Infested plant of wheat aphids

The current challenge for wheat aphids

The Current Situation For Wheat Aphids Has Become More Difficult To Control. Many studies Have Been Conducted To Show That As Time Goes On, India Will Experience Increased Difficulties With Managing Wheat Aphids Due To Many Different Technical And Operational Issues. From All These Studies And The Daily Experiences People Are Having In The Field There Are Many Ongoing Problems That Will Continue To Cause Problems In The Future Regarding The Control Of Wheat Aphids. An Increasing Number Of Farmers Are Relying On Chemical Use For Manage And Suppress Aphids. The Earlier Published Synthesis Of The Available Literature Regarding Wheat Aphids By Blackman And Eastop(2000), And The Indian Field Studies By Aheer Etc., 2007, And Agarwal 2012, Indicated That Continued Use Of High Levels Of Broad- spectrum Chemicals On The Same Product Will Accelerate The Development Of Resistance To Wheat Aphids. Although There Is Limited Information About The Systematic Resistance Monitoring Data Under The Conditions Of India; Singh Etal. (2013) Reported That There Were Areas In Some Parts Of India Where The Field Efficacy Of The Chemicals Recommended As Validated For Consumption, Were Decreasing Over Time. Therefore, Application Of Selective

Use Of Chemicals And A Comprehensive Resistance Management Program Must Be Put In Place and Maintain A Multi-divisional Plan (MDP) To Manage Resistance To Wheat Aphids.

One of the primary limiting factors that has been identified for the effective management of wheat aphids is the non-specific nature of pesticide use that has affected the balance within natural predator and parasite communities. The wide-ranging complexity of wheat aphids in India includes a variety of predatory and parasitic species, which have been documented by Saxena and Barrion (1987) and later verified by Verma *et al.* (2016) to be beneficial and important in keeping the population of aphids under control. The high populations of these useful species, such as coccinellid beetles, syrphid larval, chrysopidae, and parasitic wasps are also useful in the overall success of a chemical control of wheat aphids. However, the use of repeated insecticides has led to a marked decrease in their populations, creating conditions for an increase in aphid populations and, at times, creating additional pest problems due, in part, to the creation of an ecological deficit, as noted by Singh and Singh (2015). The existence of this ecological imbalance also creates a challenge for the long-term integrity and effectiveness of chemical control methods used for aphid control.

Integrated management strategies for wheat aphids

The most effective way to control wheat aphids is through a comprehensive approach known as Integrated Pest Management (IPM). This integrated approach involves the combination of cultural, genetic, biological, chemical and monitoring techniques. The primary strategies for controlling wheat aphids are these:

Cultural control techniques

- If possible, sowing wheat as early as possible in order to avoid the α peak population levels of wheat aphids (i.e. mid to late Feb.-Mar.)
- Keep wheat rows well spaced to reduce the humidity and microclimate conditions that favour high aphid reproduction rates.
- Apply nitrogen fertilisers at rates that allow for optimal equalisation of phloem nutrients so that there will be lower concentrations of phloem nitrogen available for aphid reproduction.

- Eliminating all other possible host plants such as wild forms and natural grasses (e.g. volunteer wheat/rye plants) inside fields and adjacent areas will reduce the amount of overwintering sites and provide early-season 'reservoirs' from which to establish aphid populations in a new wheat planting.
- Use crop rotation, with non-host plants, to break the aphids' lifecycles on previously planted crops and decrease their seasonal population increases.

Resistant varieties

- RSP 561 - Identified as having resistance against *Sitobion avenae* from the field trials of variety screening studies; other tested varieties of wheat had moderate and susceptible levels of resistance.
- HI 1454, HI 1544, PBW 373, JAUW 584, PBW 343, DBW 17, RAJ 3765 - These varieties had moderate levels of resistance against *Sitobion avenae* based on screening studies performed.
- Wheat breeders' lines (MACS 6774, PBW 873) - Some of the more advanced breeding lines were found to have moderate levels of resistance to foliar aphids from the screening studies.
- The wild/ancestral lines of *Triticum monococcum* contain genotypes (MDR045 and MDR049) that had fewer aphid populations than the susceptible controls, suggesting that they may provide sources of resistance.

Host plant resistance

- To help reduce reliance on chemicals, plant breeders have developed wheat varieties that show partial resistance to the wheat aphid through antibiosis (less aphid survival), antixenosis (less preference for the host plant) and tolerance (less yield loss). In high-risk areas, using resistant cultivars in combination with existing control methods can have a significant impact on reducing dependence on the use of chemical controls.
- Breeding programs should also focus on developing durable resistance against multiple aphid biotypes and the environmental stresses that affect plants' survival and growth.

Biological control

Predators

The ladybird beetles (Coccinellidae) such as *C. septempunctata*, *C. transversalis*, and *H. axyridis* are among the most effective predators of aphids. Ladybird beetles feed upon large numbers of aphids throughout their life cycle, with a single adult ladybug able to consume between 30 and 50 aphids per day. The larvae and adults of hover flies (Syrphidae) and green lacewings (*Chrysoperla carnea*) are also important aphid predators that can eat between 20 and 100 aphids per larva per day, depending on the stage of development. By conserving these natural enemy species by minimising the use of broad-spectrum insecticides and by keeping field edges with flowering plants that produce flowers that provide nectar and pollen, you can keep many of these predators active.

Recommended density

For augmentative releases, 2-3g of *C. carnea* eggs or 500-1,000 larvae per acre can be applied at the initial infestation stage. In high-pressure situations, ladybug beetles can be released at rates of 500-1,000 adults per acre.

Parasitoids

Aphid parasitoids are primarily the three species: *Aphidius colemani*, *Aphidius ervi* and *Aphelinus abdominalis*. They play an important role in limiting aphid populations in the environment. When aphid parasitoids lay their eggs inside aphid hosts, the resulting mummified aphids will die and become mummies. Typically, the rate of parasitism of aphids in Indian wheat fields is found between 20% and 60%, based upon the density of the aphids and the environmental conditions at that time.

Recommended density:

The augmentative release of parasitoids is generally recommended, at a rate of 5,000-10,000 adults per acre of wheat, during the early tiller-to-boot stage of the wheat plant. Releases should continue every week for 2-3 weeks if the aphid problem persists.

Pathogen types

The fungal pathogens *Beauveria bassiana* and *Lecanicillium lecanii* can result in epizootics of aphids in favorable growing conditions (eg, high humidity and moderate temperature). Application of these products as water-soluble sprays may enhance the performance of their natural enemies (predators & parasitoids) in controlling aphid populations.

Recommended density :

Rate of 1-2 Kg/acre folded with water to a manufacturer's label, and sprayed on the foliage with a conventional sprayer during the cool hours of the day (early morning or late afternoon) when UV light is at its lowest.

Chemical control

Insecticides used for the control of wheat aphid populations should be utilized only when the number of aphids exceeds the Economic Threshold Levels (ETLs), e.g., 5 aphids per ear but or 10- 15 per tiller depending on the growth stage of the crop. The best timing for applying insecticides to control wheat aphids is at the early stage of infestation (generally after 25-45 days from sowing) during tillering and if needed again around 55-65 days from sowing during booting to ear- emergence. Systemic neonicotinoid insecticides, such as imidacloprid 17.8% SL (0.3-0.5 ml/litre of water) and thiamethoxam 25% WG (0.25-0.5 g/litre of water) may be used as seed treatments or foliar applications and are very effective for controlling early colonising aphid nymphs. Some examples of pyrethroid insecticides, such as lambda-cyhalothrin 5% (0.5-0.6 ml/litre) and deltamethrin 2.8% (0.5 ml/litre), will provide fast action (knockdown) and a short period of residual control, but they can have a negative impact on natural enemies. Organophosphate insecticides, including chlorpyrifos 20% (1.5 ml/litre) and quinalphos 25% (1.0-1.5 ml/litre), should be used in extreme cases when infestations are of an extremely high density, and should only be used after careful consideration because of their greater potential risks to the environment and human health. It is at its lowest.

New monitoring and forecasting techniques

Field scouting routinely for aphid density and population trends; Monitoring/modeling (using available forecasting models) to time interventions based on the growth stage of crops, weather conditions, and aphid migration; and Make pest control decisions based on Economic Threshold Levels (ETL) rather than simply based on calendar dates.

Integrated methods

Use an IPM approach that uses a combination of cultural control (crop rotation), host plant resistance, natural enemies (predators, parasites and pathogens), and chemical pesticides in a coordinated manner; and Each producer should adjust crop management practices based on his/her own climatic and geographical locations, variety of wheat and stage of growth of the crop.

Training of Producers to Timely Decision-Making and Minimizing Unnecessary Chemical Use will also help keep aphid populations to the level of economic injury and preserve beneficial insects and reduce the environmental impact of wheat production. The Investigation of the Developing Resistant Varieties, Enhancing Natural Enemies and Climate-Adaptation of Strategies is Ultimately Crucial to the Long-Term Sustainability of Wheat Production in India.

Future directions

Since their introduction to India, wheat aphids have placed great pressure on the productivity of wheat. Challenges associated with climate, agronomy, and ecology impact the management of wheat aphids. Future research on developing management practices that are climate-resilient and tailored to regions for which they are developed should include the consideration of changing distribution, population dynamics, and phenology.

The development of tools based on predictive models formed from rainfall, temperature, and the growth stage of crops will allow for more precise timing when applying management interventions, increasing the efficiency and effectiveness of those interventions and providing more information to support the continued use of integrated pest management (IPM) practices. Research on the use of genetically resistant wheat varieties should receive priority;

breeding programs should focus on improving the durability of the resistance genes and developing varieties that contain multiple resistance genes to provide durable resistance to evolving biotypes of aphids. Utilisation of biological control, including the conservation and augmentation of natural enemies of aphids (e.g., parasitic wasps, predators, etc.) provides an opportunity for sustainable alternatives to chemical control for aphids and should be implemented in combination with other ecological engineering methods, such as the establishment of flowering strips and trap crops.

The advancement of remote sensing technology and precision farming will allow for greater access to data and information that can aid in locating and identifying aphid infestations during the early stages of an infestation, and also aid in monitoring aphid infestations in real-time; therefore, farmers can act quickly after the first sign of aphids. The use of insecticides judiciously and selectively, with due consideration of economic thresholds and through the practice of rotating active ingredients, will remain essential for delaying the development of resistance to insecticides and for protecting beneficial insect populations.

Conclusion

Wheat aphids can be managed through an Integrated Pest Management approach by using a combination of Cultural, Genetic, Biological and Chemical Methods. Following IPM practices that are supported by research, farmer education and Climate Adapting Methods leads to sustainable agricultural practices and food security for future generations. Increasing the awareness of regional growers about wheat aphids, developing stronger programs for regional monitoring and enhancing collaborative research will be necessary to reduce the economic impact of wheat aphids in India.

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Chapter 8: Sugarcane Internode Borer: Bionomics and Sustainable Management Strategies

Introduction

Sugarcane (*Saccharum* spp.) is one of the most economically important commercial crops globally, serving as a major source of sugar, bioethanol, jaggery, and several industrial by-products (Alexander, 1973; Moore *et al.*, 2013). In India, sugarcane occupies more than 5 million hectares and plays a vital role in the agricultural economy by supporting millions of farmers and workers engaged in cultivation and the sugar industry (Solomon, 2011). However, sugarcane productivity is severely constrained by various biotic stresses, among which insect pests are the most important yield-limiting factors (David & Easwaramoorthy, 1990).

More than 200 insect pest species have been reported to infest sugarcane in India at different stages of crop growth (Butani, 1961; Kalra & Sidhu, 1964). Among these, stem borers are considered the most destructive group, causing both quantitative and qualitative losses by damaging the internal tissues of the cane, impairing nutrient translocation, and reducing sucrose content (David *et al.*, 1986; Easwaramoorthy, 2004). The sugarcane internode borer, *Chilo sacchariphagus indicus* (Kapur) (Lepidoptera: Crambidae), has emerged as a major pest in several sugarcane-growing regions of India due to its concealed feeding habit, high fecundity, and ability to adapt to diverse agroecological conditions (Avasthy, 1983; Easwaramoorthy & Nandagopal, 1998).

The internode borer mainly infests the stalks of sugarcane by boring into the internodes and forming larval galleries that interfere with normal cane development (Kalra, 1970). Unlike surface-feeding pests, the cryptic feeding habit of *C. sacchariphagus indicus* makes early detection difficult and limits the effectiveness of contact insecticides (David & Nandagopal, 1990). Larval feeding results in reduced cane weight, deterioration of juice quality, and lower sugar recovery, while the entry holes facilitate secondary infection by fungi and bacteria (Easwaramoorthy, 2004). Yield losses due to internode borer infestation have been reported to range from 8 to 30 per cent under severe incidence (Avasthy, 1983; Rajendra Prasad, 1994).

Although the biology, ecology, and distribution of *C. sacchariphagus indicus* have been studied in detail (Kalra & David, 1971; Easwaramoorthy & Santhalakshmi, 1996), changes in agronomic practices, continuous ratooning, indiscriminate pesticide use, and climate variability have influenced its population dynamics and pest status (Singh *et al.*, 2017). The multivoltine

nature of the pest, characterized by overlapping generations throughout the cropping season, leads to continuous pressure on the crop and complicates management strategies (Easwaramoorthy, 2004).

Increasing concerns over environmental safety and pesticide resistance have reduced reliance on chemical control and emphasized the adoption of Integrated Pest Management (IPM) approaches (Kranthi *et al.*, 2009). Cultural practices, biological control agents such as *Trichogramma* spp. and parasitoids, use of tolerant varieties, and need-based chemical interventions constitute the core components of IPM for sugarcane stem borers (David & Easwaramoorthy, 1990; Easwaramoorthy, 2012). A clear understanding of the pest's life cycle, host preference, seasonal incidence, and economic threshold levels is essential for effective decision-making and sustainable pest management.

This aims to synthesize available information on the distribution, biology, life cycle, host range, economic threshold levels, damage potential, and management strategies of the sugarcane internode borer, *Chilo sacchariphagus indicus*, in India. By integrating classical and recent research findings, the review seeks to provide a comprehensive reference for researchers, extension personnel, and farmers. In addition, emerging challenges such as climate change impacts and the need for precision-based IPM approaches are highlighted to guide future research and policy development.

Taxonomy

Taxonomy The sugarcane internode borer, *Chilo sacchariphagus indicus* (Kapur) is a significant pest of sugarcane, which is a member of the family Crambidae. The taxonomy of the species is as follows: Order: Lepidoptera Family: Crambidae Genus: Chilo This plant is closely related to other sugarcane borers which include *Chilo infuscatellus* and *Chilo partellus*, but can be differentiated with the help of morphological features of the mature moths and the larvae. Adult moths have straw colored forewings and larvae are cream in color having longitudinal stripes across the body. The eggs are deposited in overlapping groups on the cover of the sheaths of leaves and young internodes, which safeguard the eggs against adverse environmental factors and predators. Proper identification at the species level is imperative in crafting effective pest management plans because each of the borer species has a different life cycle, preference of the host and sensitivity to management factors.

Geographic Distribution

The *Chilo sacchariphagus indicus* (Kapur) is a tropical pest that fits the world sugarcane planting areas to an almost perfect fit (Kalra, 1970; Easwaramoorthy, 2004). It is also most commonly reported in South/ Southeast Asia where climatic conditions are suitable to support its survival and reproduction. The pest is very extensive in India being a significant part of the sugarcane stem borer complex in plant and ratoon crop (David and Easwaramoorthy, 1990; Avasthy, 1983). States where sugarcane is grown have reported major infestations in Andhra Pradesh, Tamil Nadu, Karnataka, Maharashtra, Uttar Pradesh and Bihar (Kalra and David, 1971; Easwaramoorthy and Nandagopal, 1998). *C. sacchariphagus indicus* has been reported in a number of sugar producing countries in other continents other than India. The fact that it has been observed in southern and central provinces of China under the sugarcane farming (Li *et al.*, 2011). Thailand, Malaysia, Indonesia, and Vietnam are the countries in Southeast Asia where the pest occurs and is regarded as one of the significant stalk-boring species that influences the quality and yield of cane (Chong and Siti, 1985; Way and Heong, 1994). It has been also reported in locations around the African continent, such as Madagascar, Mozambique and South Africa, and also in the Indian Ocean islands of Mauritius and Re Union where sugarcane is a significant commercial crop (Williams, 1969; Greathead, 1971). Climatic factors like temperature, relative humidity and rainfall are very important geographic determinants of the geographic distribution and abundance of *C. sacchariphagus indicus*, which influence the larval survival, adult emergence, fecundity and the level of annual generation completed (Easwaramoorthy, 2004). In tropical areas and where temperatures are warm and the humidity is moderate to high, several overlapping generations exist and this leads to the constant pest pressure in the crop season (Kalra, 1970). Conversely, the warmer or drier the climate the more likely it is to limit population growth and cause sporadic or localized outbreaks (David *et al.*, 1986). The internode borer is found in most parts of the country and predominantly in the southern sugarcane belt where warm and damp climatic conditions dominate throughout the year (Avasthy, 1983). Population peaks have been observed to be between the mid-season period (June- July) and later stages of crop growth (October-November), at the time of elongation stages of the cane and maturity (Easwaramoorthy and Santhalakshmi, 1996). The flexibility of the pest to a wide range of agroecological habitats and its capacity to live on alternative hosts have added to the gradual invasion of the pest into new sugarcane-producing regions over the last decades (Singh *et al.*, 2017). The knowledge of taxonomy and the geographic distribution of *C. sacchariphagus indicus* is needed to determine the likelihood of infestation, organize region-specific surveillance programs, and apply timely

Integrated Pest Management (IPM) practices. Species identification and understanding of its ecological needs is the basis of effective and sustainable control of this pest that is of economic importance (David and Easwaramoorthy, 1990; Easwaramoorthy, 2012).

Life Cycle and Biology

Knowledge on the biology and life cycle of *Chilo sacchariphagus indicus* (Kapur) will be of interest in coming up with efficient monitoring and management measures given the fact that the insect has a hidden feeding behaviour which is in sugarcane stalks, which restricts early detection and control (Kalra, 1970; David and Easwaramoorthy, 1990). The pest is a complete metamorphic organism which has the egg stage, larval, pupal, and adult stages with the stage mostly depending on the temperature, relative humidity and the condition of the host plant (Easwaramoorthy, 2004).

Egg Stage

The eggs are deposited in hairy masses, which are mostly placed on the under surface of sheaths of leaves, tender internodes, or by the growing points of sugarcane plants (Kalra and David, 1971). The fecundity is between 100 and 300 eggs per female depending on weather conditions and nutritional conditions (Avasthy, 1983). The eggs are smooth, scaly and creamy white and they give good camouflage against the natural predators (David *et al.*, 1986). Eggs hatch in 3-6 days in optimum temperatures of about 28-30 °C (Easwaramoorthy and Santhalakshmi, 1996). The oviposition practice is hidden, which limits the exposure of insecticides and the practice of early monitoring is crucial (David and Nandagopal, 1990).

Larval Stage

The most devastating stage in the life of the pest is the larval one. The young larvae drilled into the sugarcane internodes and fed on the inside tissues creating galleries which obstructed the movement of water and nutrients (Kalra, 1970). The larvae are creamy white in color with longitudinal brown stripes and have a dark brown head capsule used to identify the larval (Avasthy, 1983). Larval period normally runs between 30 and 47 days with 5 to 7 instar stages, which depends on the temperature and the quality of the host (Easwaramoorthy, 2004). Bore holes eliminate frass that is used as the symptomatic sign of infestation (David *et al.*, 1986). The damage to feeding lowers the cane weight, the amount of sucrose and allows the fungi and bacteria to enter into secondary infections, a situation that makes the reduction in yield even worse (Rajendra Prasad, 1994).

Pupal Stage

The pupa is brown, cylindrical, and covered by a silken cocoon which is made of larval secretions (Avasthy, 1983). In good environmental conditions, the pupal stage normally lasts 7-10 days (Easwaramoorthy and Santhalaksmi, 1996). Pupal survival and adult emergence is highly dependent on the temperature and humidity although they are non-feeding and immobile (Easwaramoorthy, 2004). **Adult Stage** The adult moths are nocturnal and are straw coloured and the forewings contain distinct venation and the hind-wings are light (Kalra, 1970). Adults are not prolific feeders and have no direct harmful effect on the crop and their main activity is reproduction and dispersion (David and Easwaramoorthy, 1990). Adults live between 7 and 14 days and during their lifespan, females reproduce eggs in more than one batch so that the overlapping generations during the period of the crop in tropical areas (Easwaramoorthy, 2004).

Male Behavior

The male moths are mostly smaller and more slender than the female and also the wingspan of the male moths is 18-24mm (Avasthy, 1983). They even have filiform to slightly bipectinate antennae, which increase their ability to pick up female sex pheromones (Easwaramoorthy & Nandagopal, 1998). Males are also very mobile at night and during the dusk and also have high degree of dispersion thus spreading the infestations to adjacent fields (David *et al.*, 1986). The argument of pheromone-based monitoring and mass trapping tactics lies on the premise of male peak activity just after the sunset (Kranthi *et al.*, 2009).

Female Behavior

Female moths are relatively bigger, having the wingspan of 22-38 mm and strong abdomen that is capable of producing eggs (Kalra, 1970). The ovipositor is highly formed allowing the females to lay eggs in hidden and secure places like sheaths of leaves and young internodes (Avasthy, 1983). The oviposition behavior of females is selective, they also tend to select sites where there is good probability of survival of the larvae (Easwaramoorthy, 2004). Oviposition is done mainly at night when the risk of predation is minimized and the larvae emerges at the appropriate time when the environment is favorable (David and Easwaramoorthy, 1990).

Host Range

Sugarcane (*Saccharum officinarum* L. and its hybrids) is the principal and most preferred host of *Chilo sacchariphagus indicus* (Kapur), on which the pest completes its entire life cycle (Kalra, 1970; David & Easwaramoorthy, 1990). The pest infests both plant and ratoon crops, although infestation levels are generally higher in ratoon cane due to the presence of weaker

stalks and the carryover of pest populations from the previous crop season (Avasthy, 1983; Easwaramoorthy, 2004).

In addition to cultivated sugarcane, *C. sacchariphagus indicus* is known to survive on several wild and cultivated grasses, which act as alternate hosts during periods when the main crop is absent (Kalra & David, 1971). Wild *Saccharum* species such as *Saccharum spontaneum* and *Saccharum robustum* have been reported as important reservoir hosts, particularly along field bunds and canal banks in sugarcane-growing regions (Williams, 1969; Easwaramoorthy, 2004).

Among cultivated grasses, infestations have been recorded on sorghum (*Sorghum halepense*), pearl millet (*Pennisetum glaucum*), and various fodder grasses grown in proximity to sugarcane fields (Butani, 1961; Kalra, 1970). Occasional infestations on cereal crops such as rice (*Oryza sativa*) and maize (*Zea mays*) have also been reported, especially in areas where these crops are cultivated adjacent to sugarcane fields, although they are considered secondary or incidental hosts (David *et al.*, 1986; Rajendra Prasad, 1994).

The ability of *C. sacchariphagus indicus* to utilize multiple host plants enhances its persistence within the agroecosystem and facilitates early-season infestation of newly planted sugarcane (Easwaramoorthy & Nandagopal, 1998). These alternate hosts play a dual role by serving as reservoirs for pest populations as well as for natural enemies, which can be exploited in conservation and augmentative biological control programs (Greathead, 1971; Easwaramoorthy, 2012).

Symptoms and Damage

Sugarcane internode borer, *Chilo sacchariphagus indicus* (Kapur) is one of the most destructive pests because its larval feeding habit is often hidden in the cane stalk and thus, it may take a long time before the pest is detected and therefore causes a lot of damage (Kalra, 1970; David & Easwaramoorthy, 1990). The knowledge of typical symptoms and damage forms would be vital in monitoring and proper pest management.

First and Second Instars

The initial instar larva is of a cream color, is translucent, and is approximately 12 mm when hatched. Immediately after hatching, larvae dig holes on young internodes or sheaths of leaves and fed on tender parenchymatous internal tissue (Kalra & David, 1971). The second instar larva weighing about 24mm in length moves on with its internal feeding and creates small tunnels in the stem (Avasthy, 1983). Larvae during these initial developmental stages are

relatively more vulnerable to biological control agents (David *et al.*, 1986; Easwaramoorthy, 2004). Early intervention at this phase may help to minimize the later loss.

Third and fourth instar stages.

The third and fourth stages are the most active feeding stages. Larvae are 6-12 mm long and are distinguished by darker head capsule and the stripes which are distinct and longitudinal (Avasthy, 1983). At this stage, the larvae increase the size of galleries through massive feeding on parenchymatous tissues around the vascular bundles which considerably disrupts the translocation of water and nutrients (Kalra, 1970). Frass extrusion through boreholes is significant and a major diagnostic symptom when used in field detection (David and Nandagopal 1990). Larvae are also more difficult to control because they are still protected.

Instar 8-10.

These are the last stages, which develop into adult insects of the species. Late Instar. These are the final stages, which grow into adult insects of the species. Late instar larvae measure 20-25 mm long and they cause the highest structural destruction to the cane (Easwaramoorthy, 2004). Such larvae broaden the bore holes and could move and leave a number of frass-filled holes along the stalk (Kalra & David, 1971). Vast boreholes provide entry of secondary pathogens which cause more degradation of stems and further decline in quality of cane. At this point, the larvae are very resistant to the control of chemicals because of their sheltered feeding place (Rajendra Prasad, 1994). Internode Tunneling Extensive tunneling in the internodes is the characteristic feature of the attack of internode borers. Young internodes are penetrated by newly hatched larvae that consume parenchymatous tissue surrounding the vascular bundles interrupting water and nutrient flow and causing a decrease in the level of sucrose (David *et al.*, 1986). Typical indicators of infestation are the galleries filled with frass and dark powdery extrusions of frass on the cane surface (Kalra, 1970). Deformed Internodes and Stunted Internodes. Feeding of larvae leads to shorter and narrowed internodes leading to deformed and weak brittle canes (Avasthy, 1983). Stems that are severely infested can be broken in the process of harvesting or forced under the wind and rain, causing further losses to the yield (Easwaramoorthy, 2004). primary infection of dead heart. The larva can cause death of the central shoot in young plant and ratoon crops when larval feeding is done close to the base of the internodes and is widely known as dead heart (Kalra and David, 1971). The ratoon crops are especially susceptible with weakened shoots being unable to develop leading to low tillering and irregular crop establishment (David and Easwaramoorthy, 1990). Secondary Infections The entry and exit holes caused by larvae serve as an access point by opportunistic fungi and bacteria,

increasing stalk rot and degradation of the quality of the juice (Easwaramoorthy, 2004). These secondary infections usually increase the visual and economic effects of internode borer infestation (Rajendra Prasad, 1994). Yield and Quality Losses Direct and indirect losses in yield are caused by *C. sacchariphagus indicus* infestation. Severe cases are reported to decrease the cane yield by up to 830 per cent and commercial recovery of sucrose by a significant margin (Avasthy, 1983; Easwaramoorthy, 2004). Cumulative pest pressure particularly affects the yield losses in the ratoon crops (David *et al.*, 1986). Patterns of Damage in Space and Time. The damage tends to be patchy during the early stages, and most mostly at field borders, weeds and areas with alternative host grasses (Kalra, 1970). Infestation is spread to the main crop as the season advances with the greatest losses realized in the mid- to late-season stages (June-November in southern India) (Easwaramoorthy and Santhalakshmi, 1996). The number of rainfalls, humidity, and temperature have a significant impact on pest activity and the degree of damage (Singh *et al.*, 2017). The effective Integrated Pest Management (IPM) is based on the accurate identification of such symptoms as frass extrusion, dead hearts, and deformed internodes, which is accompanied by timely field scouting. Treating early larval instar with suitable measures can greatly reduce the loss in yield and quality and increase the sugarcane production (David and Easwaramoorthy, 1990; Easwaramoorthy, 2012).

Individual Psychological Management.

Economic Threshold Level (ETL) is one of the elementary notions in pest management and it is described as the pest population density of the pest that results in the expected economic loss due to the pest that is equal to the cost of the control measures (Stern *et al.*, 1959). In the case of the sugarcane internode borer, *Chilo sacchariphagus indicus* (Kapur), it is especially important to determine an accurate ETL since such a pest has a secret feeding behavior which makes it difficult to detect until it has caused substantial harm to the cane stalk (David and Easwaramoorthy 1990). The implementation of ETLs allows the sugarcane farmers to engage efficient, financially viable, and ecologically sound control interventions without having to engage in unjustified pesticides application (Easwaramoorthy, 2004). Setting Economic Threshold. ETL of *C. sacchariphagus indicus* depends on the agroclimatic factor, the variety of sugarcane, stage of crop development and the existing pest pressure (Kalra, 1970; Easwaramoorthy and Nandagopal, 1998). Field research carried out in various sugarcane-producing areas in India has revealed that an infestation of around 1015 per cent bored internodes or 1520 bored canes per 6 meter row leads to the loss of economic significance in terms of yields hence the need to initiate control measures (Avasthy, 1983; Rajendra Prasad, 1994). The limited

level of infestation in high-sucrose and premium cultivars can be considered as grounds to intervene because the least amount of damage can negatively impact the sugar recovery and processing efficiency (Easwaramoorthy, 2004). On the other hand, relatively high levels of infestation can be maintained without direct economic damage by tolerant or moderately resistant ones (David *et al.*, 1986). The stage of crop is also very significant in dictating the ETLs of the internode borer. With plant crops, early infestation at the early stages of growth can cause the development of dead heart and subsequent losses in tillering with long term yield penalties and hence lower ETLs is advisable at this stage (Kalra and David, 1971; David and Easwaramoorthy, 1990). The relatively older plants of the ratoon crops, however, the systematic destruction caused by the generations of the pest can drastically lead to decrease of cane production and quality of the juice and therefore, moderate but reasonable ETLs are recommended (Easwaramoorthy, 2004).

Assessment Methods

Between scans of the field, ETLs cannot be estimated properly without organizing an almost routine field scan. Some of the assessment methods that are commonly advised are:

1. Count: To determine the intensity of infestation, determine the number of bored internodes or bored canes in 10 20 random canes in each plot (Kalra, 1970).
2. Frass observation: Tracking the occurrence of frass extrusion of boreholes on cane stalks as a good and predictable sign of larval activity (David *et al.*, 1986).
3. Mapping of infestation: Documentation of spatial distribution of damages in the field to establish high pest-risk areas (Easwaramoorthy and Santhalakshmi, 1996).

These observations can be integrated to enable growers and extension personalities to be able to compare the level of infestations in the fields with the already known ETLs and undertake decisions about the need and timely action to be taken to control these infestations. Integrated Pest Management (IPM) strategies involve adoption of ETL-based interventions as a major approach towards the sustainable management of the sugarcane internode borer (David and Easwaramoorthy, 1990; Easwaramoorthy, 2012).

Management Strategies in India.

The sugarcane internode borer, *Chilo sacchariphagus* is a pest that needs to be managed in India using a multidisciplinary method that incorporates cultural, biological, chemical, and resistance of the host plant. The obscurity of larval feeding within the cane stalk and multivoltic nature of the pest makes it impossible to control using single methods; therefore, Integrated Pest

Management (IPM) is deemed as the most viable method (David and Easwaramoorthy, 1990; Easwaramoorthy, 2004).

Cultural Practices

The principle of cultural control underlies the IPM of sugarcane internode borers by decreasing pest load at the initial phase and eliminating the carryover (Kalra, 1970; Avasthy, 1983).

Field hygiene: At harvest time, populations of larvae and pupae that develop over winter are eradicated by ridding the fields of crop remains, stubbles, and infected canes (Kalra and David, 1971).

Planting time adjustment: It has been observed that planting time can be developed to prevent peak seasons of borer infestation to minimize early infestation especially in endemic regions (Easwaramoorthy and Santhalakshmi, 1996).

Ratoon management: Appropriate ratoon management procedures, like stubble shaving, off-barring and destruction of ratoons with heavy infestation can control pest carry-overs between seasons (David *et al.*, 1986). Use of alternate host grasses and wild *Saccharum* species are removed around field bunds and irrigation channels to minimize the survival of pests in the off-season (Williams, 1969; Easwaramoorthy, 2004). **Mechanical control:** local control of pests in small and seed cane plots can be achieved by the local destruction of infested canes and by hand removal of frass-infested stalks (Avasthy, 1983).

Biological Control Biological control has been found to be instrumental in sustainable control of *C. sacchariphagus indicus* through the use of its natural enemies (Greathead, 1971; Easwaramoorthy, 2012).

Parasitoids: The egg parasitoids like *Trichogramma chilonis* Ishii and the larval parasites like *Cotesia flavipes* Cameron have been utilized. Repeated releases of *T. chiloni* at weekly intervals during the areas of maximum oviposition and conservation of *C. flavipes* have turned out to cause a substantial decrease in internode borer infestation (David and Easwaramoorthy, 1990; Easwaramoorthy and Nandagopal, 1998).

Predators: Generalist predators such as ants, spiders, coccinellids, and predatory beetles help in natural control of the population of borers especially in fields where pesticides have not been

disturbed to a large extent (Kalra, 1970).

Entomopathogens: Entomopathogenic fungi *Beauveria bassiana* and *Metarhizium anisopliae*, and nuclear polyhedrosis viruses have been proposed as potential sugarcane borers, but the activity of these organisms depends on humidity and temperature.

Chemical Control

The use of chemical control should be adopted to a situation where pest population is at Economic Threshold Level (ETL) and it should be combined with other control strategies to prevent resistance and environmental risks (Stern *et al.*, 1959; Kranthi *et al.*, 2009).

- ✓ **Early instar stages:** The most effective insecticides applied to control stalk instar stages are systemic and contact insecticides like chlorantraniliprole, thiamethoxam and indoxacarb, which should be applied targeting early instar stages before the instar penetrates deeply within the stalk (David and Nandagopal, 1990; Easwaramoorthy, 2012).
- ✓ **Sett treatment and soil application:** Sett dips and soil application of suggested systemic insecticides prevent early infestation of young shoots at the time of early crop establishment (Avasthy, 1983).
- ✓ **Prudent application and rotation:** Insecticides with varying modes of action, application of recommended doses and application at the right time are important in slowing the resistance evolution and minimize non-target impacts (Kranthi *et al.*, 2009). On the whole, cultural, biological, and need-based chemical control measures with the assistance of a regular monitoring system and ETL-based decision-making represent an efficient IPM approach to the control of *Chilo sacchariphagus indicus* in India. Such integrated solutions do not only minimize economic losses but also facilitate the sustainability of the environment and productivity of sugarcane agroecosystem in the long term (David and Easwaramoorthy, 1990; Easwaramoorthy, 2012).

Integrated Pest Management

Integrated Pest Management (IPM) is an eco-prudent decision-based methodology that incorporates cultural, biological, chemical, and host plants resistance management practices, based on frequent pest monitoring and Economic Threshold Levels (ETLs) to control the levels of pests at economically non-damaging levels (Stern *et al.*, 1959; David and Easwaramoorthy, 1990). In the case of the sugarcane internode borer, *Chilo sacchariphagus indicus* (Kapur), IPM is especially necessary because of the secretive feeding behavior of the pest and

overlapping generations which reduce the efficacy of unilateral control strategies (Easwaramoorthy, 2004).

An effective IPM program to control internode borer in India focuses on the preventive and need-based control, which include:

- **Periodic outdoor scouting:** Infestations which are still young including extrusion of frass, bore internodes, and dead hearts can be detected and prevented early on (Kalra, 1970; David *et al.*, 1986).
- **Biological control:** Augmentative release of egg parasitoids (*Trichogramma chilonis*) at the time of high oviposition (Greathead, 1971; Easwaramoorthy and Nandagopal, 1998). • Reasoned use of insecticides: Selective insecticides should only be applied when the pest population is more than ETLs and this will provide good control with minimal side effects on the natural enemies and environment (Stern *et al.*, 1959; Kranthi *et al.*, 2009).
- **Resistance of the host plants and agronomy:** The acceptance of more tolerant or resistant sugarcane varieties, paired with good agronomic practices, e.g., balanced fertilization, appropriate irrigation, and good management of ratoon, makes the crop more tolerant to the damage caused by the pests and decreases the severity of the infestation (Avasthy, 1983; Easwaramoorthy, 2012).

Comprehensive approach towards carrying out IPM practices has proven to result in heavy reduction in yield losses, decrease in pesticide residues, and ecological sustainability in sugarcane agroecosystems (David and Easwaramoorthy, 1990). The contemporary studies in India are oriented towards enhancing IPM by designing predictive pest forecasting systems, pheromone-based monitoring and mass trapping systems, and applying microbial biopesticides to enhance accuracy and efficiency in different agroclimatic settings (Easwaramoorthy, 2012; Singh *et al.*, 2017).

Resistant Varieties

Chilo sacchariphagus indicus sugarcane internode borer has an important and eco-friendly constituent of Integrated Pest Management (IPM) as host plant resistance. A number of systematic field screening and breeding have discovered sugarcane varieties and genetic resources with different degrees of resistance or tolerance to internode borer infestation (Avasthy, 1983; Easwaramoorthy, 2004). The variety **Co 293** was found by a four-year comprehensive field screening study of 535 Indian sugarcane hybrids as one that would consistently suffer

no damage caused by the internode borer (Easwaramoorthy and Nandagopal, 1998). **The Co 293** resistance against **Co 293** was further corroborated in controlled artificial infestation conditions whereby it was characterized by low larval survival, retardation of larval development and low occurrence and severity of internode borer attack (David and Easwaramoorthy, 1990). These observations indicate the potential that exists between both antixenosis (non-preference) and antibiosis (adverse effects on pest biology) mechanisms of resistance and **Co 293** can be used as a parent in breeding programs to enhance the level of borer resistance in commercial sugarcane cultivars. The introduction of resistance to wild relatives has also been a major factor in improving the resistance to borers. *Erianthus* spp. genetic material has also been used successfully in sugarcane improvement programmes, in which better tolerances to stem borers have been introduced. Other genotypes such as **Co 06022** and **Co 06030** produced with an *Erianthus* background have demonstrated reduced internode borer occurrence and reduced larval tunnel length than other genotypes produced solely using *Saccharum* (Nair *et al.*, 2012; Singh *et al.*, 2017). This suggests that the resistance genes that come with wild species lead to less larval establishment and feeding hence minimizing the source of damage. Follow-up screening on the progenies of *Saccharum robustum* revealed several promising clones such as **GUK 14-722**, **GUK 14-129**, **GUK 14-130** and **GUK 14-745** that are resistant to internode borer, early shoot borer and termites (Easwaramoorthy, 2012). These progenies showed comparatively low incidence of internode borer (below 10 percent) relative to other genotypes, meaning that they can be used as sources of multi-pest resistance. Such clones can be considered as precious breeding material to enhance the resistance base when it comes to the sugarcane breeding programs. New genotypes have also been reported to include **GU 19-4**, **GU 19-24**, **GU 19-38**, **GU 19-55**, and **GU 19-77** which showed reduced morphological alterations in internodes and lower internode borer infestation when exposed to natural field conditions (Singh *et al.*, 2020). These clones are also believed to be good candidates in the future testing of multilocation and varietal development and can be successfully incorporated in the IPM programs because of the tolerance traits they possess. Altogether, the utilization of resistant and tolerant types especially the ones that are based on wild germplasm provides a long-term and economical method of controlling *C. sacchariphagus indicus*. The inclusion of these varieties in IPM programmes decreases reliance on chemical insecticides, decreases production expenses and leads to eventual ecological stability in the sugarcane agro ecological systems (David and Easwaramoorthy, 1990; Easwaramoorthy, 2012).

Conclusion,

To control *C. sacchariphagus indicus* in India a multifaceted and dynamic strategy involving the combination of cultural, biological, chemical, and genetic resources in an ecological context is necessary. With a better knowledge in the biology of pests, coupled up with sustainable practices, economic losses can be minimized, environmental impacts can be minimized and the profitability and productivity of sugarcane farming can improve.

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