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CHAPTER 5

Brown Planthopper (*Nilaparvata lugens* Stål): Biology, Ecology, Climate Change and Integrated Pest Management in Rice

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Abstract: The brown planthopper (BPH), *Nilaparvata lugens* Stål, is one of the most destructive pests of irrigated rice in Asia, causing yield losses of 10–30% under moderate infestations and up to

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complete crop failure during severe outbreaks. This chapter reviews its taxonomy, biology, host range, and damage mechanisms, including direct phloem feeding leading to "hopper burn" and indirect losses from transmitting Rice Ragged Stunt and Rice Grassy Stunt viruses. High reproductive potential, migratory wing dimorphism, and growing insecticide resistance make BPH management increasingly difficult. The chapter also examines how climate change via rising temperatures, elevated CO_2, and shifting rainfall is intensifying outbreaks and expanding its range, and discusses natural enemies, economic threshold levels, and an integrated pest management strategy combining resistant varieties, cultural, biological, and judicious chemical control for sustainable rice production.

Keywords: Brown planthopper, *Nilaparvata lugens*, rice, climate change, integrated pest management, biological control

1. Introduction

Rice (*Oryza sativa* L.) is the most important staple food crop in Asia and provides the primary source of calories for more than half of the world's population. India is the second-largest producer of rice after China, contributing substantially to global food security. However, rice productivity is severely constrained by numerous biotic stresses, among which insect pests are one of the major limiting factors. More than 100 insect species are known to attack rice during different stages of crop growth, although only about 20 species attain economic significance under field conditions (Pathak & Khan, 1994). Among these, the brown planthopper (BPH), has emerged as one of the most destructive pests of irrigated rice ecosystems in Asia because of its high reproductive potential, migratory behavior, ability to transmit viral diseases, and rapid adaptation to resistant rice cultivars and insecticides (Heong & Hardy, 2009; Bottrell & Schoenly, 2012).

The brown planthopper belongs to the family Delphacidae under the order Hemiptera and is a phloem-feeding insect. Unlike chewing insects, BPH inserts its piercing-sucking mouthparts into the vascular tissues of rice plants and continuously extracts phloem sap(fig.1). Continuous feeding weakens the plant, resulting in reduced tillering, chlorosis, stunted growth, and eventually complete drying of plants, a symptom commonly referred to as "hopper burn." Besides causing direct feeding damage(fig.2), BPH also serves as an efficient vector of Rice Ragged Stunt Virus (RRSV) and Rice Grassy Stunt Virus (RGSV), thereby causing severe indirect yield losses (Hibino, 1996; Heong & Hardy, 2009). During epidemic outbreaks, grain yield losses may range from 30 to 100%, particularly in susceptible varieties cultivated under intensive production systems (Bottrell & Schoenly, 2012).

Historically, the importance of BPH increased significantly during the Green Revolution when high-yielding rice varieties, intensive fertilizer application, year-round irrigation, and indiscriminate use of broad-spectrum insecticides became common agricultural practices (Bottrell & Schoenly, 2012). Although these technologies substantially increased rice production, they also created favourable ecological conditions for planthopper multiplication. Excessive nitrogen fertilization enhances plant succulence and improves nutritional quality for sap-feeding insects, while repeated insecticide applications often eliminate natural enemies such as spiders, mirid bugs, and parasitoids, resulting in resurgence of BPH populations (Heong & Hardy, 2009; Horgan, 2018). Consequently, outbreaks have become more frequent across major rice-growing countries, including India, China, Vietnam, Thailand, Indonesia, Japan, and the Philippines (Catindig et al., 2009).

In recent decades, climate change has further intensified the threat posed by brown planthopper. Rising atmospheric temperatures accelerate insect metabolism, shorten developmental periods, and increase the number of generations completed within a cropping season (Bale et al., 2002). Elevated atmospheric carbon dioxide concentrations modify the carbon-to-nitrogen ratio in rice tissues, forcing planthoppers(fig.1) to increase their feeding activity to satisfy their nitrogen requirements (Bale et al., 2002). Changes in rainfall patterns, humidity, and extreme weather events also influence migration, survival, and seasonal abundance of BPH populations (Krishnaiah & Varma, 2011; Hu et al., 2014). These climatic changes are expected to expand the geographical distribution of the pest into previously unsuitable regions while increasing the frequency and severity of outbreaks in existing rice ecosystems (Horgan, 2018).

The economic significance of BPH extends beyond yield reduction because its management has become increasingly difficult due to the development of insecticide resistance and the emergence of new virulent biotypes capable of overcoming host plant resistance genes (Heong & Hardy, 2009). Sustainable management therefore requires an integrated approach combining resistant cultivars, conservation of natural enemies, ecological engineering, cultural practices, biological control agents, regular pest surveillance, and judicious use of selective insecticides (Pasalu & Katti, 2006; Horgan, 2018; Directorate of Plant Protection, Quarantine & Storage, 2022). Modern approaches such as molecular breeding, genome editing, remote sensing, artificial intelligence-based pest forecasting, and climate-smart integrated pest management are increasingly being explored to develop durable management strategies against this pest (Horgan, 2018).

This chapter comprehensively reviews the taxonomy, distribution, biology, ecology, damage symptoms, population dynamics, influence of climate change, and integrated management of

brown planthopper in rice. Emphasis is given to recent advances in climate-resilient pest management strategies that can contribute to sustainable rice production under changing environmental conditions.

2. Taxonomy and Distribution

The brown planthopper, *Nilaparvata lugens* (Stål), belongs to the order Hemiptera and the family Delphacidae, a group of insects commonly known as planthoppers. Members of this family are characterized by their piercing-sucking mouthparts, wedge-shaped bodies, and remarkable ability to migrate over long distances (Pathak & Khan, 1994). Since its first description by the Swedish entomologist Carl Stål in 1854, *N. lugens* has been recognized as one of the most economically important insect pests of rice throughout Asia (Heong & Hardy, 2009). The taxonomic classification of the species is as follows: Kingdom Animalia, Phylum Arthropoda, Class Insecta, Order Hemiptera, Family Delphacidae, Genus *Nilaparvata*, and Species *Nilaparvata lugens* Stål.

The brown planthopper is predominantly distributed across tropical and subtropical rice-growing regions of Asia. It is widely prevalent in India, Bangladesh, Sri Lanka, Nepal, Pakistan, Myanmar, Thailand, Vietnam, Cambodia, Laos, Malaysia, Indonesia, the Philippines, China, Japan, and the Republic of Korea (Catindig et al., 2009). In temperate countries such as Japan, Korea, and northern China, the insect is unable to survive the cold winter months and therefore re-establishes populations each year through long-distance migration from tropical regions aided by seasonal monsoon winds (Otuka, 2013). In contrast, tropical countries provide favourable climatic conditions that allow the pest to survive and reproduce continuously throughout the year.

In India, brown planthopper has become a serious pest in almost all major rice-growing states, including Andhra Pradesh, Telangana, Tamil Nadu, Karnataka, Kerala, Odisha, West Bengal, Chhattisgarh, Punjab, Haryana, and Uttar Pradesh (IIRR, 2023). Frequent outbreaks have been reported particularly in irrigated ecosystems where high-yielding rice varieties are cultivated under intensive fertilizer and irrigation management (Prakash et al., 2014). States such as Telangana and Andhra Pradesh have experienced recurring infestations during both the *kharif* and *rabi* seasons, especially in districts characterized by continuous rice cultivation (PJTSAU, 2023). Climatic conditions such as high relative humidity (80–90%), moderate to high temperatures (25–30°C), dense crop canopies, and abundant nitrogen fertilization provide ideal conditions for rapid population multiplication (Krishnaiah & Varma, 2011).

The distribution and abundance of brown planthopper are strongly influenced by ecological and climatic factors. Unlike many other rice pests, BPH possesses remarkable migratory capability.

The long-winged (macropterous) adults(fig.1) can travel hundreds of kilometers with prevailing winds, allowing rapid colonization of newly planted rice fields (Otuka, 2013). This migratory behaviour enables the insect to exploit favourable environmental conditions while escaping adverse climatic situations. Seasonal migration has become increasingly important under changing climatic conditions, as alterations in wind patterns, rainfall distribution, and temperature regimes influence the timing, direction, and distance of migration (Hu et al., 2014; Otuka, 2013). Consequently, climate change is expected to modify the geographical distribution of brown planthopper and increase its incidence in regions that were previously considered less vulnerable (Horgan, 2018).

3. Host Range and Economic Importance

3.1 Host Plant Preference

The brown planthopper (BPH), is a highly specialized phloem-feeding insect that depends almost entirely on rice(fig.1) (*Oryza sativa* L.) for its survival and reproduction. Unlike many other sap-feeding insects that attack several crops, BPH has a very narrow host range and completes its entire life cycle mainly on cultivated rice (Pathak & Khan, 1994; Heong & Hardy, 2009).

Besides cultivated rice, a few wild *Oryza* species, such as *Oryza rufipogon* and *Oryza nivara*, can serve as alternate hosts. Some grasses, particularly *Leersia hexandra*, may also support temporary survival of the insect during periods when rice is not available, although these plants generally do not support large populations (IRRI, 2020; Heong & Hardy, 2009). These alternate hosts help maintain low-level populations between rice-growing seasons and may contribute to the initiation of infestations in newly planted fields.

Brown planthopper populations are usually highest in irrigated lowland rice ecosystems, where rice is cultivated continuously and abundant food is available throughout the year. High-yielding semi-dwarf varieties grown under intensive nitrogen fertilization are particularly favorable for BPH development because nitrogen-rich plants contain higher concentrations of soluble amino acids in the phloem sap, improving insect survival, reproduction, and population growth (Bottrell & Schoenly, 2012; Horgan, 2018). In contrast, upland and rainfed rice ecosystems generally experience lower infestations because crop continuity and environmental conditions are less suitable for rapid population buildup.

In tropical and subtropical regions of Asia, where two or three rice crops are grown annually, continuous host availability enables BPH populations to survive throughout the year without entering diapause. This uninterrupted breeding cycle contributes to frequent outbreaks in major rice-growing regions (Heong & Hardy, 2009; Prakash et al., 2014).

3.2 Economic Importance

The brown planthopper is one of the most destructive insect pests of rice in Asia because it causes substantial economic losses through both direct feeding damage and transmission of viral diseases (Heong & Hardy, 2009; Bottrell & Schoenly, 2012).

Both nymphs and adults feed by inserting their piercing-sucking mouthparts into the phloem and continuously extracting plant sap. Prolonged feeding weakens the plants, resulting in yellowing, reduced tillering, stunted growth, poor panicle emergence, incomplete grain filling, and premature drying. Under severe infestations, plants dry rapidly and collapse, producing the characteristic symptom known as "hopper burn" (Pathak & Khan, 1994; IRRI, 2020). Depending on crop stage and pest density, yield losses generally range from 10–30% under moderate infestations but may exceed 70%, and in severe outbreaks complete crop failure has been reported (Bottrell & Schoenly, 2012; Prakash et al., 2014).

In addition to direct feeding damage, BPH acts as an efficient vector of Rice Ragged Stunt Virus (RRSV) and Rice Grassy Stunt Virus (RGSV). Infection by these viruses causes severe stunting, excessive tillering, ragged leaves, poor panicle development, and drastic reductions in grain yield, making indirect losses even more serious than feeding damage alone (Heong & Hardy, 2009; IRRI, 2020).

The importance of BPH increased markedly after the Green Revolution with the adoption of high-yielding rice varieties, intensive nitrogen fertilization, year-round irrigation, and frequent use of broad-spectrum insecticides. While these technologies enhanced rice production, they also created favorable conditions for rapid multiplication of BPH and reduced the abundance of natural enemies such as spiders, mirid bugs, and parasitoids, leading to pest resurgence (Bottrell & Schoenly, 2012; Horgan, 2018).

Management of BPH has become increasingly difficult because the insect has developed resistance to several commonly used insecticides and has evolved virulent biotypes capable of overcoming host plant resistance genes (Horgan, 2018; Pasalu & Katti, 2006). Climate change, including rising temperatures, elevated atmospheric CO_2, changing rainfall patterns, and increased frequency of extreme weather events, is expected to further enhance BPH survival, reproduction, migration, and outbreak potential (Bale et al., 2002; Krishnaiah & Varma, 2011). Therefore, sustainable management requires an integrated approach involving resistant varieties, biological control, ecological engineering, cultural practices, pest surveillance, and need-based application of selective insecticides (Directorate of Plant Protection, Quarantine & Storage, 2022; Horgan, 2018).

4. Host Range

The brown planthopper is considered a highly host-specific insect and is closely associated with rice. Cultivated rice (*Oryza sativa*) is its principal host, on which the insect completes its entire life cycle and attains maximum population growth (Pathak & Khan, 1994; Heong & Hardy, 2009).

Several wild rice species, including *Oryza rufipogon*, *O. nivara*, and *O. officinalis*, can also support BPH populations under natural conditions. In addition, grasses such as *Leersia hexandra* may serve as temporary refuge hosts during periods when rice crops are absent, although these hosts are generally less suitable for reproduction than cultivated rice (IRRI, 2020).

Brown planthopper prefers irrigated lowland rice fields, where continuous cropping, abundant moisture, and intensive nitrogen fertilization provide ideal conditions for rapid multiplication. Young, actively growing rice plants are particularly susceptible because they contain nutrient-rich phloem sap that supports faster development and higher fecundity of the insect (Bottrell & Schoenly, 2012; Horgan, 2018). In contrast, rainfed and upland rice ecosystems usually experience lower infestations due to less favourable environmental conditions and discontinuous host availability.

The narrow host range of BPH has important implications for pest management. Cultural practices such as synchronized planting, crop rotation with non-host crops, destruction of volunteer rice plants, and removal of alternate hosts can interrupt the insect's life cycle and reduce population carryover between seasons. These practices, when combined with resistant varieties and biological control, form an important component of integrated pest management for sustainable rice production (Pasalu & Katti, 2006; Horgan, 2018; Directorate of Plant Protection, Quarantine & Storage, 2022).

5. Identification and Morphological Characteristics

Accurate identification of the brown planthopper (BPH), is essential for effective pest surveillance and timely management in rice ecosystems. The insect belongs to the family Delphacidae and can be identified at different stages of its life cycle based on its characteristic morphology(fig.1) (Pathak & Khan, 1994; Heong & Hardy, 2009).

The eggs are elongate, slightly curved (Fig.1), and creamy white to translucent, measuring about 0.8–1.0 mm in length. Females insert the eggs individually or in small groups into the tissues of rice leaf sheaths or occasionally the midrib using a serrated ovipositor. Because the eggs remain embedded within the plant tissue, they are difficult to detect in the field. Only the fine respiratory

filaments project slightly outside the plant surface. Under favourable conditions (28–30°C), eggs hatch within 6–9 days (IRRI, 2020; Prakash et al., 2014).

The nymph passes through five instars before reaching adulthood (Fig.1). Newly hatched nymphs are creamy white and about 0.6 mm long. As they grow, their colour gradually changes to pale yellow and finally light brown. Wing pads become visible from the third instar and are fully developed by the fifth instar.

Nymphs are active feeders and usually remain clustered near the base of rice tillers, where they continuously suck phloem sap. Depending on temperature and humidity, the nymphal period lasts about 12–15 days (Pathak & Khan, 1994; IRRI, 2020).

Adults are small, soft-bodied insects measuring approximately 3.5-4.5 mm in length. Females are generally larger than males and have a broader abdomen (Fig.1). Adults are light to dark brown with characteristic brown markings on the thorax and wings. A distinctive feature of BPH is the occurrence of two wing forms: brachypterous (short-winged) and macropterous (long-winged). Brachypterous adults have shortened wings and invest more energy in reproduction, whereas macropterous adults possess fully developed wings that enable long-distance migration with seasonal winds (Heong & Hardy, 2009; Bottrell & Schoenly, 2012). Another important identifying character is the large movable spur present on the hind tibia, which is typical of insects belonging to the family Delphacidae. Both nymphs and adults usually remain hidden near the base of rice plants, making field detection difficult unless plants are carefully examined (Prakash et al., 2014).

6. Biology and Life Cycle

The brown planthopper undergoes incomplete metamorphosis (hemimetabolous development), passing through three stages-egg, nymph, and adult-without a pupal stage. Under favourable conditions, the complete life cycle is completed within 25-35 days, although temperature, humidity, and host plant quality can influence its duration (Pathak & Khan, 1994; Heong & Hardy, 2009). Warm temperatures (28-30°C), high relative humidity (80-90%), and healthy rice plants provide ideal conditions for rapid development and population increase.

Adult females usually mate within one or two days after emergence and begin laying eggs shortly afterwards. Using their saw-like ovipositor, females insert eggs into the tissues of rice leaf sheaths, where they remain protected from desiccation and many natural enemies. A single female can lay about 200-350 eggs during her lifetime, depending on the nutritional status of the host plant and prevailing environmental conditions (IRRI, 2020; Prakash et al., 2014). The incubation period generally lasts 6-9 days.

The nymphal stage consists of five instars. Newly emerged nymphs immediately begin feeding on phloem sap at the base of rice tillers. As they pass through successive moults, body size increases, wing pads develop gradually, and body colour changes from creamy white to yellowish-brown. Under optimum conditions, the nymphal period lasts around 12–15 days, while cooler temperatures may delay development and warmer conditions may shorten it, allowing more generations to develop within a season (Bale et al., 2002; Krishnaiah & Varma, 2011).

Following the final moult, adults emerge either as brachypterous or macropterous forms depending on environmental conditions such as population density, food availability, and host plant condition. Crowded populations or deteriorating host plants generally favour the production of macropterous adults, which are capable of long-distance migration. In contrast, favourable conditions promote brachypterous adults that allocate more energy to reproduction than dispersal (Heong & Hardy, 2009; Bottrell & Schoenly, 2012).

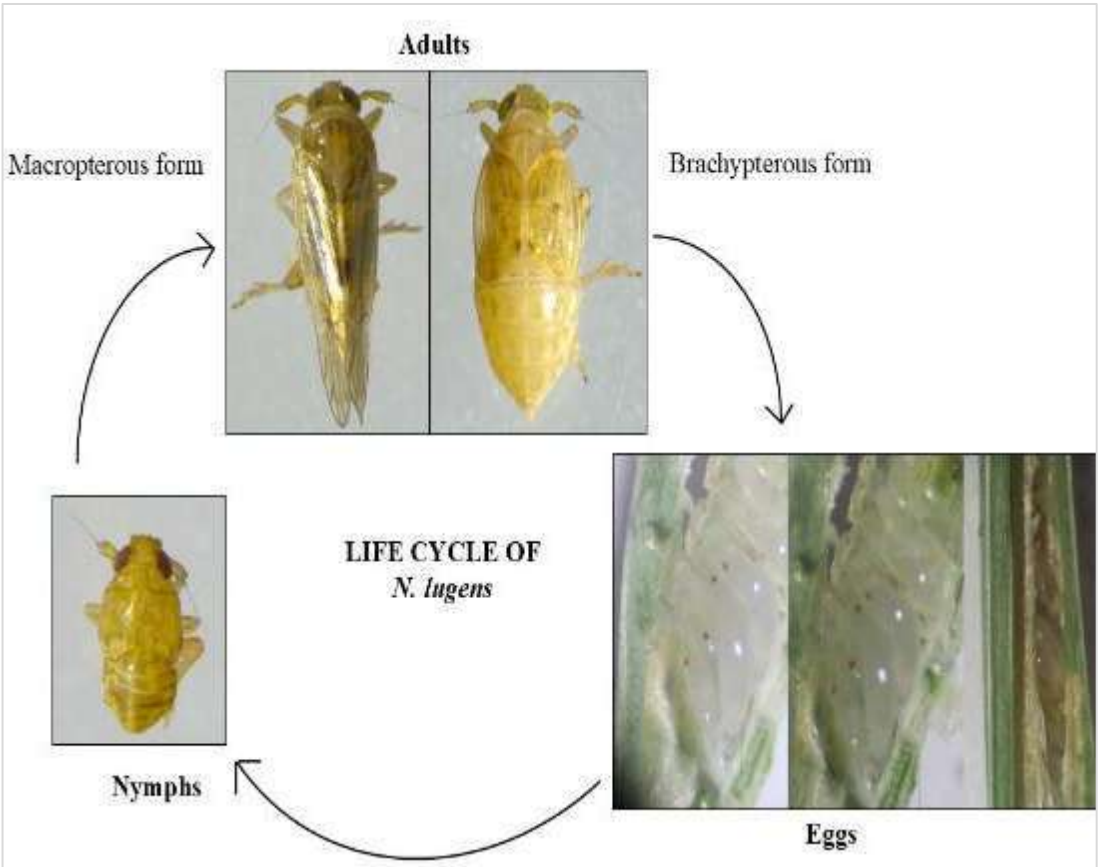

Fig. 1: Life cycle of Brown Planthopper *N. lugens*

Adult longevity generally ranges from 15 to 25 days, during which repeated mating and egg laying occur. In tropical rice-growing regions where rice is cultivated continuously, BPH can complete 10–12 generations in a year. Its high reproductive potential, rapid development, overlapping generations, and migratory behaviour contribute to frequent outbreaks in rice-growing areas (Horgan, 2018; Heong & Hardy, 2009). Climate change, particularly increasing temperatures and elevated atmospheric CO_2 concentrations, is expected to accelerate its life cycle and increase reproductive capacity, thereby enhancing the risk of severe infestations (Bale et al., 2002; Krishnaiah & Varma, 2011).

7. Feeding Behaviour

The brown planthopper is a specialized phloem-feeding insect that obtains all of its nutrients from the vascular tissues of rice plants. Both nymphs and adults possess piercing-sucking mouthparts that penetrate the leaf sheath and stem until they reach the phloem vessels (Pathak & Khan, 1994; Heong & Hardy, 2009).

During feeding, the insect injects saliva into the plant tissues while withdrawing phloem sap. The saliva contains enzymes and other compounds that facilitate feeding but also interfere with normal physiological processes in the plant. Continuous sap removal deprives the rice plant of essential carbohydrates, amino acids, minerals, and water needed for growth and grain filling (IRRI, 2020; Horgan, 2018).

Brown planthoppers excrete large quantities of honeydew, a sugar-rich waste product that accumulates on leaves and stems. Honeydew encourages the growth of sooty mould fungi, which cover the leaf surface and reduce photosynthetic efficiency. Under heavy infestations, thousands of nymphs and adults may congregate around the base of rice tillers, extracting large amounts of sap and rapidly weakening the plants (Pathak & Khan, 1994; Bottrell & Schoenly, 2012).

Prolonged feeding disrupts several physiological processes, including photosynthesis, nutrient translocation, water balance, and hormone regulation. As a result, affected plants show yellowing, reduced tillering, poor panicle development, incomplete grain filling, and finally the characteristic "hopper burn," where entire hills dry up and die. These effects not only reduce grain yield but also increase the vulnerability of rice plants to environmental stress and disease (Horgan, 2018; Prakash et al., 2014).

8. Nature of Damage

8.1 Direct Damage

The brown planthopper damages rice primarily by feeding on phloem sap. Both nymphs and adults usually remain at the base of rice tillers, where they continuously extract nutrients essential for plant growth (Pathak & Khan, 1994; IRRI, 2020). Early symptoms of infestation include yellowing of leaves, reduced tillering, and poor plant vigour. As the population increases, plants become stunted, panicle emergence is delayed, and grain filling is reduced. Continuous sap removal weakens the plants, lowers photosynthetic activity, and decreases carbohydrate accumulation, ultimately reducing both grain yield and quality (Prakash et al., 2014). Young rice plants are particularly vulnerable, and severe infestations may kill seedlings before tillering is complete. Prolonged feeding also weakens the root system, making plants more susceptible to drought and other environmental stresses (Heong & Hardy, 2009).

8.2 Hopper Burn



Fig. 2. Hopper Burn Rice Field

"Hopper burn" is the most characteristic symptom of severe brown planthopper infestation. It develops when large numbers of nymphs and adults feed continuously on rice plants, causing rapid depletion of plant nutrients. Initially, leaves turn yellow, followed by browning of leaf tips and margins. Eventually, the entire plant dries up and dies, giving the field a scorched appearance (Pathak & Khan, 1994; IRRI, 2020). Hopper burn usually appears in patches that gradually expand as planthoppers move to neighbouring healthy plants. Under favourable weather conditions, entire fields may be severely damaged within a few days if control measures are not taken in time (Bottrell & Schoenly, 2012).

8.3 Indirect Damage

Apart from direct feeding injury, BPH is an important vector of Rice Ragged Stunt Virus (RRSV) and Rice Grassy Stunt Virus (RGSV). Plants infected with these viruses show severe stunting, excessive tillering, ragged leaves, poor panicle development, and reduced grain filling (Heong & Hardy, 2009). Even relatively low BPH populations can cause significant yield losses through virus transmission, making indirect damage economically more important than feeding injury alone in some situations (IRRI, 2020).

9. Economic Importance

The brown planthopper is one of the most destructive insect pests of rice in Asia because it causes heavy yield losses through both direct feeding and virus transmission (Heong & Hardy, 2009; Bottrell & Schoenly, 2012). Yield loss depends on crop stage, pest density, varietal susceptibility, and environmental conditions. Moderate infestations generally reduce grain yield by 10–30%, while severe outbreaks may cause losses exceeding 70%. In extreme situations, complete crop failure has also been reported (Prakash et al., 2014).

Major outbreaks have occurred in India, China, Vietnam, Indonesia, Thailand, and the Philippines, resulting in substantial economic losses to farmers (Bottrell & Schoenly, 2012). Besides yield reduction, farmers spend considerable amounts on insecticides, field monitoring, and crop restoration. The repeated development of insecticide resistance and the emergence of virulent biotypes capable of overcoming resistant rice varieties have made BPH management increasingly difficult (Horgan, 2018). Therefore, it continues to be a major constraint to sustainable rice production across Asia.

10. Seasonal Incidence

The seasonal occurrence of brown planthopper varies with climate, cropping pattern, and crop management practices. In tropical regions, where rice is grown throughout the year, BPH populations can survive continuously because suitable host plants are always available (Heong & Hardy, 2009).

In India, populations usually begin to increase about 30–40 days after transplanting and reach their peak during the maximum tillering to reproductive stages of the crop (IIRR, 2022). During the kharif season, severe infestations are commonly observed from September to October, whereas during the rabi season, peak populations generally occur between February and March, depending on the region and planting time (PJTSAU, 2023). Long-winged adults migrate with monsoon winds and establish new populations in freshly planted rice fields, contributing to seasonal outbreaks (Otuka, 2013).

11. Factors Favouring Outbreaks

Brown planthopper outbreaks result from the combined effects of favourable weather, crop management practices, and ecological disturbances. Excessive nitrogen fertilization is one of the most important factors because it increases the amino acid content of rice plants, making them more suitable for planthopper feeding and reproduction (Bottrell & Schoenly, 2012; Horgan, 2018).

Dense planting creates a humid microclimate within the crop canopy that favours rapid multiplication of the pest. High relative humidity (80–90%), temperatures between 25 and 30°C, cloudy weather, and warm nights further enhance survival and reproduction (Krishnaiah & Varma, 2011). Continuous rice cultivation without a crop-free period allows uninterrupted breeding throughout the year.

Indiscriminate use of broad-spectrum insecticides often destroys beneficial predators such as spiders, mirid bugs, and parasitoids, resulting in pest resurgence (Heong & Hardy, 2009). The cultivation of susceptible rice varieties and the evolution of insecticide-resistant BPH populations further increase the risk of outbreaks (Horgan, 2018). Climate change has added another dimension by altering temperature, rainfall, and wind patterns, thereby favouring pest survival, migration, and population growth (Bale et al., 2002).

12. Influence of Climate Change

Climate change is increasingly recognized as an important factor influencing the biology, distribution, and outbreak potential of the brown planthopper. Rising temperatures, elevated

atmospheric CO_2 concentrations, changes in rainfall patterns, and more frequent extreme weather events affect both the insect and its rice host, making pest management more challenging (Bale et al., 2002; Krishnaiah & Varma, 2011).

12.1 Effect of Elevated Temperature

Temperature strongly influences the growth and reproduction of BPH. Warm conditions (28–30°C) accelerate egg development, shorten the nymphal period, and reduce the overall life cycle, allowing more generations to develop within a single cropping season (Bale et al., 2002). Higher temperatures also promote earlier reproduction and increased egg laying. However, temperatures above the optimum range may reduce survival and fecundity due to heat stress (Heong & Hardy, 2009).

12.2 Effect of Elevated Atmospheric CO_2

Elevated atmospheric CO_2 alters the nutritional quality of rice plants by increasing carbohydrate content while reducing nitrogen concentration. As a result, BPH feeds for longer periods to meet its nitrogen requirement, leading to greater sap removal, increased honeydew production, and more severe hopper burn symptoms (Bale et al., 2002). Prolonged feeding may also increase the efficiency of virus transmission (Krishnaiah & Varma, 2011).

12.3 Effect of Rainfall Variability

Rainfall patterns have a major influence on BPH populations. Extended dry periods weaken rice plants and make them more susceptible to infestation, whereas moderate rainfall followed by high humidity provides favourable conditions for rapid population growth (Krishnaiah & Varma, 2011). Although heavy rainfall may temporarily reduce planthopper numbers by washing insects from plants, populations often recover quickly once favourable conditions return. Changes in rainfall may also affect the abundance of natural enemies, reducing their ability to regulate BPH populations (Horgan, 2018).

12.4 Effect of Extreme Weather Events

Extreme weather events such as cyclones, floods, droughts, and heat waves can influence the survival and migration of BPH. Strong monsoon winds and cyclones assist long-distance migration of macropterous adults, enabling rapid colonization of newly planted rice fields (Otuka, 2013). Floods may temporarily suppress local populations, whereas prolonged drought and moderate warming often favour population build-up after crop recovery. Future climate change is expected to

alter migration patterns and increase the frequency of BPH outbreaks across major rice-growing regions of Asia (Bale et al., 2002; Krishnaiah & Varma, 2011).

13. Natural Enemies

Natural enemies play a crucial role in regulating brown planthopper (BPH) populations and form the foundation of sustainable integrated pest management (IPM). Rice ecosystems harbor a diverse community of predators, parasitoids, and entomopathogenic microorganisms that naturally suppress BPH populations. Conservation of these beneficial organisms is essential because indiscriminate application of broad-spectrum insecticides often destroys natural enemy populations, leading to pest resurgence and secondary outbreaks (Heong & Hardy, 2009; Horgan, 2018; Pasalu & Katti, 2006).

13.1 Predators

Several predatory arthropods are highly effective in reducing BPH populations under field conditions. The mirid bug *Cyrtorhinus lividipennis* is considered one of the most important predators because it feeds preferentially on BPH eggs and young nymphs (Heong & Hardy, 2009). Spiders such as *Lycosa pseudoannulata* (wolf spider) and species of *Tetragnatha* (long-jawed spiders) prey upon both nymphs and adults throughout the cropping season. Ladybird beetles (*Coccinellidae*), dragonflies, and damselflies also contribute to biological suppression by feeding on planthoppers and other soft-bodied insects (Pasalu & Katti, 2006; Horgan, 2018). Maintaining habitat diversity and minimizing unnecessary insecticide applications help conserve these natural predators and improve their effectiveness in regulating pest populations (Heong & Hardy, 2009).

13.2 Parasitoids

Egg parasitoids are important biological control agents of brown planthopper. Species belonging to the genera *Anagrus* and *Oligosita* parasitize eggs concealed within rice tissues, preventing successful emergence of nymphs (Heong & Hardy, 2009). These minute parasitoid wasps can significantly reduce BPH populations under favorable environmental conditions. Their activity is strongly influenced by climatic factors and insecticide use; therefore, conservation of parasitoid populations is an important component of ecological pest management (Pasalu & Katti, 2006; Horgan, 2018).

13.3 Entomopathogenic Fungi

Several naturally occurring entomopathogenic fungi infect and kill brown planthopper populations under humid field conditions. *Metarhizium anisopliae* and *Beauveria bassiana* are among the most widely studied fungal pathogens for biological control of BPH (Pasalu & Katti, 2006; Horgan, 2018).

Fungal spores adhere to the insect cuticle, germinate, penetrate the body wall, and proliferate within the insect, eventually causing death. These fungi are environmentally safe, compatible with natural enemies, and are increasingly used as components of integrated pest management programmes (Heong & Hardy, 2009).

14. Economic Threshold Level (ETL)

The Economic Threshold Level (ETL) is the pest population density at which management measures should be initiated before economic damage occurs. For brown planthopper, regular field surveillance is essential because populations can increase rapidly under favourable environmental conditions (Directorate of Plant Protection, Quarantine & Storage, 2022; IRRI, 2020). During the vegetative stage of rice, control measures are generally recommended when the population reaches about 10 insects per hill, while during the reproductive stage the threshold increases to approximately 20 insects per hill (PJTSAU, 2023; IIRR, 2022). Weekly field scouting should focus on the base of rice hills where nymphs and adults are usually concentrated. Early detection and timely implementation of integrated management practices help prevent severe outbreaks while minimizing unnecessary insecticide use (Prakash et al., 2014).

15. Integrated Pest Management (IPM)

Integrated Pest Management (IPM) is the most sustainable and environmentally sound approach for managing brown planthopper populations. It combines cultural, biological, mechanical, botanical, and chemical methods to maintain pest populations below economically damaging levels while minimizing environmental risks and conserving beneficial organisms (Horgan, 2018; Heong & Hardy, 2009).

15.1. Cultural Control

Cultural practices form the first line of defence against brown planthopper infestation. Growing resistant/ tolerant rice varieties possessing BPH resistance genes such as RP BIO 4918-230S, BM 71, RP 2068-18-3-5, IC 70613, IC 75975, ADT 37, ADT 38, ADT 42, ASD 17, Co. 46, MDU 4, TPS 2, Pant Shankar Dhan 3, Pant Dhan 11 is one of the most effective and economical management strategies (Heong & Hardy, 2009). Balanced fertilizer application, particularly avoiding excessive nitrogen fertilization, reduces plant susceptibility and discourages rapid pest multiplication (Bottrell & Schoenly, 2012). Water management practices such as Alternate Wetting and Drying (AWD) improve crop health and reduce conditions favourable for BPH. Synchronous planting within a locality, maintaining a crop-free period, and removing volunteer rice plants and grassy weeds help

break the pest life cycle and reduce carry-over populations (Directorate of Plant Protection, Quarantine & Storage, 2022; PJTSAU, 2023).

15.2 Mechanical Control

Mechanical methods provide supplementary control, particularly during the early stages of infestation. Light traps are useful for monitoring and reducing populations of migrating macropterous adults (Prakash et al., 2014). Rope dragging across rice fields disturbs resting insects and exposes them to predators, while portable vacuum devices can remove adults from heavily infested fields. Severely infested rice hills should be removed and destroyed to prevent further spread of the pest (IIRR, 2022).

15.3 Biological Control

Biological control emphasizes the conservation and augmentation of natural enemies present in rice ecosystems. Predators such as spiders, mirid bugs, dragonflies, and ladybird beetles naturally suppress BPH populations throughout the cropping season. Egg parasitoids and entomopathogenic fungi further contribute to population regulation (Pasalu & Katti, 2006; Horgan, 2018). Avoiding unnecessary applications of broad-spectrum insecticides helps preserve these beneficial organisms and enhances natural pest suppression (Heong & Hardy, 2009).

15.4 Botanical Pesticides

Botanical insecticides provide environmentally friendly alternatives for early-stage management of brown planthopper. Neem Seed Kernel Extract (NSKE) at 5% concentration and commercial formulations containing azadirachtin effectively suppress nymphal populations by reducing feeding, growth, and reproduction (Prakash et al., 2014). Botanical pesticides are generally safer to natural enemies than conventional insecticides and therefore fit well within integrated pest management programmes (Pasalu & Katti, 2006).

15.5 Chemical Control

Chemical insecticides should be used only when pest populations exceed the recommended economic threshold level *i.e.,* 10-15 hoppers per hill. Selective insecticides such as pymetrozine, dinotefuran, flonicamid, buprofezin, and nitenpyram have demonstrated good efficacy against brown planthopper while causing comparatively less harm to beneficial arthropods when applied judiciously (Directorate of Plant Protection, Quarantine & Storage, 2022; Horgan, 2018). Recommended insecticides include Acephate 75 SP 200 grams per acre, applied once 45 to 60 days after planting. Dinotefuron 20 SG at 80 grams per acre, and Pymetrozine 50 WG at 120 grams per

acre. To delay the development of insecticide resistance, insecticides with different modes of action should be rotated according to IRAC recommendations. Spray applications should target the basal portions of rice plants where BPH populations are concentrated, and prophylactic insecticide applications should be avoided (IRRI, 2020; IIRR, 2023).

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