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Review Article

Frontier insect pest management technologies for sustainable rice production

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Abstract

Although effective management of rice insect-pests can be achieved by insecticides but their excessive long term use poses human health and environmental risks in addition to effect on non-targets organisms. Now-a-days, some pest management practices such as agronomic practices like smart fertilizer and nutrient application, real time monitoring and surveillance, ecological engineering through habitat manipulation, biological control by more effective strain, nanotechnology, host plant resistance by RNAi and marker assisted selection, have been introduced and adopted to manage rice insect pests which are eco-friendly in nature and also promote natural pest management. Here, this article intended to discuss the various frontier pest management technologies which will help for sustainable rice production.

Key words: Eco-friendly, ecological engineering, insect resistant, IPM, RNAi, smart agronomic practices

1. Introduction

Rice (*Oryza sativa* L.) is one of the important cereals and staple foods in the world. More than 60% of the global population depends on it for fulfillment of their nutritional requirement (Joshi *et al.,* 2018). In India, it is grown almost one-fourth of the total cropped area and providing food to about more than half of the Indian population (Seni and Naik, 2020). It grows well under different topographic and hydrologic conditions ranging from rain fed upland to lowland as well as in deep water conditions (Seni *et al.,* 2019). The production of rice has been found to be hampered by infestation of various insect pests at different growth stages. Insect pests causing significant yield loss over the years are yellow stem borer [*Scirpophaga incertulas* (Walker)], plant hoppers, both brown plant hopper (BPH), *Nilaparvata lugens* (Stål) and white backed plant hopper (WBPH), *Sogatella furcifera* (Horvath), gall midge [*Orseolia oryzae* (Wood-Mason)], a group of leaf-eating caterpillars like rice leaffolder (*Cnaphalocrocis medinalis* Güenée) and grain sucking bug complex like earhead bug; *Leptocoriza oratorius* (Fabr.) that feed on developing grains (Seni and Naik, 2018; Ali *et al.*, 2019; Jasrotia *et al.*, 2019). Beside insects, other arthropods like rice panicle mite, *Steneotarsonemus spinki* Smiley, was also appeared as a destructive pest of rice (Seni and Mandal, 2021). These pests cause hundreds of millions of dollars of losses every year and threaten food security in regions where rice is grown. For this, rice pest management is crucial to achieve rice production in a sustainable manner (Savary *et al.*, 2006). The yield losses varies from one region to another, however range from 1.2 to 2.2 tons/ha due to the combined attack of diseases, insects, and weeds in Asia (Savary *et al.*, 2012). On the other hand, potential yield gains of at least 10-20% of the current yields may be achieved through effective pest management techniques (Willocquet *et al.*, 2004; Oerke, 2006; Savary *et al.*, 2012).

Since 1970s, Integrated Pest Management (IPM) is in practice and it relies on ecologically based management that aims to suppression of the pests through a combination of techniques such as modification of agronomic practices, mechanical and physical methods, use of resistant varieties, biological control and need based insecticide application. However, IPM was not proved successful as it was thought to be at the beginning due to low adoption and unawareness about its usefulness of management technologies and their application in real farm situation. In addition, inappropriate credit and subsidies, weak public sector and influential agrochemical companies further lead to the failure of IPM on the ground level (Bentley and Andrews, 1996; Savary *et al.*, 2012). As still now, in many rice growing areas insect pest control strategies are solely dependent on various synthetic chemicals which are designed to quickly eradicate insect pests from fields (Savary *et al.*, 2012). However, indiscriminate and excessive use of agrochemicals has led to many negative effects such as development of insecticide resistant in insects, pest resurgence, secondary pest outbreaks besides environmental pollution and human health hazards. With this perspective, focus should be shifted to develop modern pest management technologies that are not solely dependent on insecticides. This will not only increase rice production in sustainable manner but will also improve health and environmental quality.

In this direction, many new technologies and strategies have been developed to tackle the insect pest menace in rice without hampering the environmental quality. In this article will highlight and discuss those frontier technologies, are presently being used for effective pest management in rice aiming towards sustainable rice production.

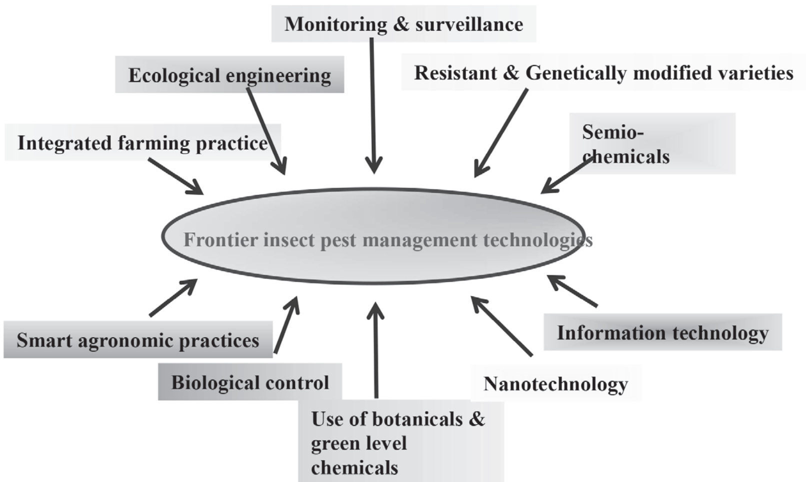

Fig. 1: Different components of frontier insect pest management technologies

2. Frontier insect pest management technologies for rice insect pests

2.1 Pest monitoring and surveillance

Pest monitoring and surveillance is the most important and integral part of Insect pest management programme. It helps to know the occurrence of insect pest, developmental stage and infestation level at certain intervals. In rice, mainly sampling of 25 plants in 5 clusters on a diagonal line of the plot at 7-10 days interval is suitable for determining insect pest's intensity, natural enemy populations and infestation rate (Pasalu *et al.*, 2004). These form the base for taking the management decisions by taking economic thresholds as guidelines. The economic thresholds of common insect pests of rice and yield loss incurred by them are given in table 1 and 2. Installation of light traps is useful for the monitoring and management of certain rice insect pests, mainly planthoppers, stem borers, gall midge and leafhopper. Many light traps are operating throughout north-eastern China and Japan to detect movement of migrating planthoppers (Horgan, 2017). During the spring season in northern hemisphere, brown and white-backed planthoppers migrate many thousand miles from South East Asia to the north east of Asia. In this context, light traps have been very useful for early warning of farmers by ascertain the magnitude, route and environmental factors that favour those movements (Matsumura, 2001; Cheng, 2009). Likewise, rustic light traps have been used in Vietnam as a escape strategy whereby farmers decide rice planting dates on the basis of planthopper catch in light traps (Bentley, 2009). In field installation light trap, the light should be switched on at sunset and switched off, after capturing large population. However, these lights may harm beneficial insects, and thus should not be used continuously throughout the rice growth period (Hong-xing *et al.*, 2017).

Table 1. Economic thresholds of common insect pests of rice

Pest	Economic thresholds	Reference
Stem borer	10% dead hearts or 1 egg mass or 1moth/m^2	Pasalu *et al.*, 2004
BPH and WBPH	10 insects/ hill at veg. whereas 20 insects/hill at later stage	Pasalu *et al.*, 2004
Green leaf hopper	2 insects/ hill in tungro endemic areas. 20-30 insects/hill in other areas	Pasalu *et al.*, 2004
Gall midge	1 gall/m^2 or 10% silver shoot	Pasalu *et al.*, 2004
Leaf folder	2-3 damaged leaves/ hill post active tillering stage	Pasalu *et al.*, 2004
Case worm	1-2 cases/hill	Misra and Jena, 2007
Cutworm	1 damaged tiller/hill or 2 larvae/m^2	Prakash *et al.*, 2014
Earhead bug	1 nymph or adult/hill	Prakash *et al.*, 2014
Rice hispa	2 adults or 2 dead leaf/hill	Prakash *et al.*, 2014
Rice black bug	5 bugs/hill	Prakash *et al.*, 2014
Whorl maggot	25% damage leaves	Misra and Jena, 2007

Table 2. Yield loss caused by major insect pests of rice

Insect	Yield loss	Reference
Yellow stem borer	1-19% in early planted and 38-80% in late transplanted crop	Catinding and Heong, 2003
Plant hopper	10- 90%	Seni and Naik, 2017
Gall midge	0.8% of the total production	Krishnaiah, 2004
Leaf folder	10% flag leaf infestation reduces grain yield by 0.13 g per tiller and the number of fully filled grains by 4.5%.	Murugesan and Chelliah, 1983
Earhead bug	10-40%	Israel and Rao, 1954
Rice hispa	20-28%, Yield reduction from 33.72 g/plant at 5% infestation to 3.50 g/plant at 70% infestation.	Nath and Dutta, 1997
Rice black bug	Ten black bug adults per hill can cause losses of up to 35% in some rice.	http://www.knowledgebank.irri.org/training/fact-sheets/pest-management/insects/item/black-bug
Rice panicle mite	30-90%	Seni and Mandal, 2021

Insect sex pheromones can be used for both monitoring and management purpose by mating disruption or mass killing of insect pest populations. Mass trapping of yellow stem borer can be done by installing of 20 sleeve traps per hectare each with 5 mg pheromone impregnated lures (Pasalu *et al.*, 2004; Misra and Jena, 2007). Whereas, mating disruption can be done by an application of slow release formulation of pheromones @ 40g a.i./ha and it is also found that by adopting this techniques starting from fortnight after planting through multipoint sources could result in season-long control of stem borer and produced grain yields at par with plots received two sprays of conventional insecticides (Pasalu *et al.*, 2004; Misra and Jena, 2007). Verma *et al.,* 2000 tested sex pheromone blend consisting of 2 components viz., (Z)-11-hexadecenal and (Z)-9-hexadecenal @ 3:1 ratio and observed that peak dead-heart and white-ear appeared 2-3 weeks after the highest male moth captures in pheromone traps. They further stated that when trap captures 30 and 19 male moths/week then it caused 10% dead hearts and 5% white ears respectively in field. Beside yellow stem borer, sex pheromone components of striped stem borer; *Chilo suppressalis*, pink stem borer; *Sesamia inferens*, leaf folder; *C. medinalis*, gall midge; *O. oryzae* and rice hispa; *Hispa armigera* have been identified (Misra and Jena, 2007). However, a lot of efforts and refinement studies are necessary in pheromone usages technology which will play an important role in insect pests monitoring and surveillance in near future.

2.2 Smart agronomic practices

Smart agronomic practices for crop protection are those which are helpful to growing crops, and at the same time are useful in pest suppression. Here no large extra cost is necessary for insect pest management. Many times these work very effectively in reducing the multiplication of insect pests. These include:

- Early and synchronous rice planting often less attack by various insect pests like yellow stem borer, gall midge, BPH, WBPH and GLH particularly in wet season and produce more yield. At Chiplima, Sambalpur it was observed that when rice crop was transplanted on 31st July, 2020, produced 3.8 t/ha rice grain whereas when transplanted in 10th September, 2020, rice yield was 1.76 t/ha (var: MTU 7029, 25 days old seedling, without any plant protection measure).
- Application of optimum dosage of nitrogen in 2-3 splits avoids build up of insects such as stem borer, gall midge, leaf folder, BPH and WBPH. Excessive use of nitrogenous fertilizer has positive effects on development, survival, reproduction of rice insect pests by improving their nutritional conditions which ultimately hasten their infestation rate (Balasubramanian *et al.*, 1983; Ma and Lee, 1996; de Kraker *et al.*, 2000; Visarto *et al.*, 2001). Balanced application of N, P, K and other important nutrition elements can improve the plant vigor, and increase the resistant ability against various insect pests (de Kraker *et al.*, 2000). It is found that application of silicon can induce rice resistance or tolerance to heat, drought, lodging, stem borer and plant hoppers (Agarie *et al.*, 1998; Yang *et al.*, 2014; Hong-xing *et al.*, 2017).
- Crop rotation with other non host crop is important to break continuity in insect pest life cycle and population build up (Pasalu *et al.*, 2004; Misra and Jena, 2007).
- Providing alleyways of 30 cm width after every 2-3 metres, is helpful against BPH and WBPH (Misra and Jena, 2007).
- Stubble destruction by ploughing, irrigation or machine after harvesting is helpful to check the carryover of the stem borer and gall midge insects (Pasalu *et al.*, 2004; Misra and Jena, 2007).
- Water management like intermittent draining of water from the fields is helpful when planthopper population become abundant (Pasalu *et al.*, 2004; Behera *et al.*, 2013).

2.3 Host plant resistance

Host plant resistance is the most effective, economical and reliable means for plant protection for centuries ((Pasalu *et al.*, 2004). Before the discoveries of molecular markers, conventional breeding programmes helped to get desired traits for insect pest management. For this, large scale screenings were done to find rare resistant gene from the wild rice species and landraces (Panda and Khush, 1995). In early period, maximum released resistance rice varieties was of the 'vertical', single gene type, and while this had been effective at the releasing time, but evolution of virulent biotypes has become a major setback to that strategy. To overcome this problem, the selection of resistance genes needs to be done with a better knowledge of the virulence composition of the insect pest populations in the target area and the genetics of plant resistance (Behera *et al.*, 2013). Asian rice gall midge (ARGM), *O. oryzae* is one of the serious insect pests of rice in South and Southeast Asia. Till now, in India seven biotypes has been characterized based on their reaction pattern against various groups of rice varieties. It is observed that none of the resistant gene conferred resistance against all the biotypes of gall midge. So, the varietal resistance can be enhanced by combining several resistance genes through gene pyramiding (Fujita *et al.*, 2013; Bentur et al., 2021). Another serious insect pest of rice in Asian rice growing areas is brown plant hopper (BPH), *N. lugens*. There are four biotypes of brown plant hopper have been reported from all over the world and in India biotype 4 is present (Khush and Brar, 1991; Mohanty *et al.,* 2017). Regarding BPH resistance, so far 38 major resistance genes were identified and three genes mainly *bph-5, Bph-6* and *bph-7* showed resistance against biotype 4 only (Behera *et al.*, 2013; Bentur *et al.,* 2021). But, rapid gene flow among migratory insects like plant and leafhoppers may reason for high degree of genetic diversity (Behera *et al.*, 2013) and causes difficulty to manage them. To overcome this problem, uses of molecular techniques are helpful. For this, scientists first identify the effective resistance genes/QTL (quantitative trait loci) from various sources, characterize them genetically and make reliable tightly linked molecular markers for their introgression through marker-assisted backcross breeding (MABB) into popular rice varieties (Chen *et al.*, 2012; Fujita *et al.*, 2013; Horgan, 2017; Mohanty *et al.,* 2017). Till date many QTLs associated BPH resistance has been identified from various land races and wild rice and mapped in different chromosomes like 1, 2, 3, 4, 6, 7, 8, 10 and 12 (Mohanty *et al.,* 2017). Soundararajan *et al.* (2004) reported the presence of BPH resistance QTLs in chromosomes 1, 2, 6, and 7 in the population derived from the cross between IR64 and Azucena and among them QTLs on chromosome 7 were associated with seedling resistance, QTLs on chromosome 2 were associated with antibiosis and QTLs on chromosomes 1, 6, and 7 were associated with tolerance. Likewise, Sun *et al.* (2005) identified three resistance loci on chromosome 4 for BPH resistance in Rathu Heenati. Likewise, Mohanty *et al.,* 2017 identified two QTLs on chromosome 4 for BPH resistance in Salkathi and successfully transferred to two elite rice cultivars namely Pusa 44 and Samba Mahsuri. Similarly, Yao *et al.,* 2016 identified five QTLs associated with African rice gall midge resistance on chromosome 4 in ITA306 x TOS14519 population. So, these QTLs can be integrated into elite rice varieties to make resistant varieties through marker assisted selection.

Currently, research into RNAi technology has gained some attention for controlling of various insect pests in rice (Yu *et al.,* 2014; Horgan, 2017). RNA interference (RNAi) act through gene silencing mechanism by affecting mRNA synthesis at the cellular level triggered by double-stranded RNA (dsRNA). It is observed that by successful delivery of dsRNA molecules into insects by ingestion causes the target gene silencing (Price and Gatehouse, 2008; Bentur *et al.,* 2021), resulting the detrimental effect on physiology and ultimately causes the mortality of the target insect. Pan *et al.* (2018) used RNAi by injecting specific dsRNAs to knock down 135 CP (chitin and cuticular protein) genes in BPH and found that 32 CPs are important for their development and egg production. In further development, Li *et al.* (2015) stated that dsRNAs are stable under diverse environmental conditions and can be absorbed by roots of crop plants. Likewise, Kola *et al.* (2016) observed that by feeding YSB larvae with dsRNA of cytochrome P450 derivative (*CYP6*) and amino peptidase N (*APN*) treated cut stems resulted in increased mortality of the insect.

Another molecular approach, CRISPR (Clustered regularly interspaced short palindromic repeats) based genome editing can be promising in near future to develop resistant varieties against various insect pests. Genome editing can be done by targeting either the host genes or genes in insect population by replacement of nucleotides/domains/motifs or editing of specific bases (Bentur *et al.,* 2021). However, more research is necessary to precise replacement of bases and making them as a viable strategy.

It is found that, transfer of genes in rice expressing snowdrop lectin gene, *Galanthus nivalis agglutinin* (*GNA*), protease inhibitors and *Bt* genes such as *cry1A(b)*, c*ry1A(c)* showed resistance against various insect pests particularly stem borers and both plant and leaf hoppers (Murdock and Shade, 2002; Chen *et al.*, 2012). Transfer of soybean trypsin inhibitor gene and *Allium sativum* leaf agglutinin (*ASLA*) in transgenic rice increase the resistance against the *N. lugens* and *Nephotettix cincticeps* (Lee *et al.*, 1999; Saha *et al.*, 2006). *ASLA* conferred its action in transgenic rice lines by affecting NADH quinone oxidoreductase (NQO) action which is an important component in the electron transport chain (Bala *et al.,* 2013). Pradhan *et al.,* 2016 inserted a vegetative insecticidal protein (*vip*) in MTU 7029 rice variety and found that the transgenic rice showed resistance against various lepidopteran pests like yellow stem borer, leaf folder and rice horny caterpillar. Boddupally *et al.,* 2018 inserted both *Cry 1Ac* and *ASLA* in rice plant and reported that the transgenic rice showed resistance against multiple insect pests including stem borer, leaf folder and BPH.

2.4 Biological control

Use of biological control agents to manage crop insect pests is an important tool for integrated pest management. The successful use of several parasitoids and predators has made biological control as a promising alternative to the chemical control. However, they showed their effectiveness only one or a few insect pests mainly yellow stem borer and leaf folder but not effective against other sporadic pests like gundhi bug, rice hispa, and cutworm

(Pasalu *et al.*, 2004). In comparison to other crops, use of biocontrol agents through inundative or inoculative releases in rice ecosystem has provided sporadic success (Pathak *et al.,* 1996).

In India in rice ecosystem, inundative releases of natural enemies have been restricted to mainly egg parasitoids, particularly *Trichogramma japonicum* and *T. chilonis*, because they are easily multiplied in laboratories. In rice, selection and release of appropriate *Trichogramma* spp. is important for their effectiveness as all *Trichogramma* spp. found in rice ecosystem are not effective in all environmental condition. Among various *Trichogramma* spp., mainly four species *T. japonicum*, *T. chilonis*, *T. ostriniae* and *T. dendrolimi*, are commonly observed in rice fields in China (Guo *et al.*, 2012; Hong-xing *et al.*, 2017). *T. dendrolimi* performs well on parasitizing stem borer eggs at 18 to 26°C while *T. japonicum* performs well at 30 to 34°C (Yuan *et al.*, 2012). In India, it is reported that the inundative release of exotic parasitoid, *T. japonicum* @ 20,000 per acre was effective in reducing stem borer infestation (Pasalu *et al.*, 2004). Likewise, 4 to 9 times releases of *T. japonicum* @ 1,00,000 adults/ha starting from 20 to 38 days after transplanting with an gap of 7-10 days resulted in 4 to 59% reduction in leaf damage due to leaf folder (Pasalu *et al.*, 2004). But in a field test conducted in China reported that parasitism of yellow stem borer eggs, by *T. japonicum* was 9% whereas parasitism by *T. chilonis* was 15% (Tang *et al.*, 2017). It was also evident that *Trichogramma* species parasitized more new eggs of stem borer (<24 h old) compared to older eggs (>24 h old) (Babendreier *et al.*, 2020). Similarly, they parasitized 1–3 day old leaf folder eggs efficiently, but the parasitism of 4-day-old eggs was significantly low (Hong-xing *et al.*, 2017).

Use of microbial pesticides like *Bt (Bacillus thuringiensis),* virus, fungi are another useful approach for rice insect pest management as they are harmless to the humans, natural enemies and environment. Nayak *et al.*, 1978 studied the effect of *Bacillus thuringiensis* var. *Kurstaki* (Thuricide), against different stages of rice yellow stem borers, *S. incertulas* and found that *Bt* had no toxicity effect on egg, pupae and adult stages of stem borer whereas spraying *Bt* @ 1% concentration, at the time of hatching of the larvae, reduced the incidence of dead hearts and white heads by 76.36% and 67.45% respectively under green house conditions. Likewise, the efficacy of *Mamestra brassicae* nuclear polyhedrosis virus on leaf folder at 14 days after spraying was more than 83% (Hong-xing *et al.*, 2017). *Cnaphalocrocis medinalis* granulovirus (CnmeGV), showed synergism action with *Bt* against rice leaf folder (Liu *et al.*, 2013). The initial mortality of leaf folder treated by the agents consisted of CnmeGV and Bt was 3 day shorter than that solely treated with CnmeGV, the mortality was increased by 20.23%, and the persistent time was more than 30 days (Hong-xing *et al.*, 2017). In India, fungal pathogens mainly *Beauveria bassiana* was found promising against rice hispa (Hazarika and Puzari, 1997), whereas *Pandora delphacis* was found promising against BPH (Narayanasamy, 1995).

2.5 Integrated farming system

Despite the traditional rice cultivation, integrated rice farming with animal husbandry such as rice-duck, and rice-fish is an effective mutual benefitted combination because of their healthy co-development (Hong-xing *et al.*, 2017). In a rice-duck system, ducks are introduced into the rice fields to change the microclimate in field, reduce ineffective tillers, promote to enter more sunlight, gas exchange, improve soil health and reduce the insect pests (Long *et al*, 2013; Hong-xing *et al.*, 2017). It is found that, the rice planthoppers in the fourth and fifth generations are reduced by more than 70% in middle rice season and more than 50% in late rice season, respectively (Yang *et al.*, 2004). Similarly, the rice damage caused by stem borer was decreased by 13–47% in middle-season rice and by 62% in late-season rice (Hong-xing *et al.*, 2017). The rice-duck system also helped to increase the number of bio control agents which ultimately reduce the rice insect pests. Yang *et al.*, 2004 observed that the spider population in the rice-duck fields was 1.66–2.61 folds higher than that of the conventional rice fields. Likewise, the parasitization rates of leaf folder larvae were 53–61% in early-season rice field with duck and 29–38% in late-season rice field with duck (Hong-xing *et al.*, 2017). Similarly, rice fish farming also help sustainable rice production by decreasing input costs in terms of fertilizer and insecticide application as fish decreasing insect population by feeding them whereas enhance soil organic matter by their excreta (Ahmed and Garnett, 2011; Rahman, 2016). Although rice duck and rice fish integrated rice farming system is followed in different low lying areas of West Bengal and Assam but that should be popularize in other places in India for sustainable rice production.

2.6 Semio-chemicals

It is established fact that when plants are attack by arthropod herbivores they emanate volatiles chemicals which attract natural enemies (Bruce and Pickett, 2007). Some of those herbivore-induced plant volatiles (HIPV) have been identified, synthesized, used in slow-release dispensers or as sprays. It is evident that under field condition, methyl salicylate, cis-3-hexen-1-ol, (Z)-3-hexenyl acetate and benzaldehyde has resulted in more number of catches of natural enemies (James, 2005; Gurr, 2009). Plants attacked by *N. lugens* produced ethylene 2 to 24 hours after infestation along with HIPV as well as activates salicylate signaling pathways which ultimately affect the more parasitization by attracting *Anagrus nilaparvatae*, a major parasitoid of *N. lugens* (Gurr, 2009). So, the application of such exogenous products on rice plants can lead to more attraction of natural enemies which ultimately help in management of insect pests.

2.7 Ecological engineering techniques

The population size and outbreak frequency of insect pests can be effectively managed by habitat diversification through ecological engineering method (Lu *et al.*, 2015; Gurr *et al.*, 2016; Hong-xing *et al.*, 2017). It was observed that when rice fields were surrounded with nectar-rich flowering plants, more yields were obtained as well as higher natural enemies population were recorded in fields (Lu *et al.*, 2015). Actually, like other plants, rice lacks floral nectar resources that can be used by natural enemies. So, right selection and planting of nectar-rich flowering plants or vegetable patches in rice landscapes can provide year-round resource for natural enemies which not only improve their longevity and reproduction, but also increasing their biological control efficiency (Hong-xing *et al.*, 2017). For effective results, flowering plants should be planted on the bunds of rice fields before rice transplanting and new plantings should be done one month after rice transplanting so as to ensure flowering plants should be available at all rice growing stages (Lu *et al.*, 2015). In China, growing the flowering plant such as *Sesamum indicum*, *Impatiens balsamen*, *Emilia sonchifolia, Trida procumbens, Tagetes erecta* on rice field bund improved the biological management of planthoppers (Lu *et al.*, 2015). Y-tube olfactometer assays indicated that the egg parasitoids *Anagrus optabilis* and *A. nilaparvatae* were significantly attracted by the volatiles from sesame. Similarly, both of these two parasitoids significantly parasitized more BPH eggs in the presence of sesame flowers (Zhu *et al.*, 2015; Hong-xing *et al.*, 2017). Similarly, it was observed that with presence of sesame flowers, adult longevity of predatory bug *Cyrtorhinus lividipennis* was extended, which ultimately helped increased egg consumption and predation rate (Zhu *et al.*, 2015). Likewise, the fecundity of *Trichogramma chilonis*, a common egg parasitoid of many *Lepidopteran* insects, was significantly increased by sesame flowers (Hong-xing *et al.*, 2017). In India, when flowering plants like marigold, balsam and crops like sesame, sunflower were cultivated in rice bund then more numbers of spiders, mirid bug and parasitoids of planthoppers were found in rice fields (Anonymous, 2021). In Bangladesh, growing flowering plants such as sesame, marigold, sunflower and cosmos to rice bunds helped in higher abundance of natural enemies in rice fields and were responsible for more parasitism of planthopper, yellow stem borer, and rice hispa eggs than the broad-spectrum insecticide treated rice plots (Ali *et al.*, 2019). It was observed that yields in ecological engineering strategies adopted rice plots surrounded by sesame and nectar-rich flowering plants with no insecticides applied were at par with rice plots without ecological engineering and sprayed three times (Heong, 2011).

2.8 Botanicals

Use of botanicals is a novel approach as these are consider as harmless to the humans and environment. Unlike synthetic pesticides, botanicals do not kill the insect pests in field condition but reduce their activity by repellency, feeding deterrency, reproductive inhibition and oviposition deterrence (Pasalu *et al.*, 2004). Various greenhouse and field studies have reported that neem formulations are moderately effective against stem borer, leaf folder, plant and leafhoppers (Pasalu *et al.*, 2004; Seni and Naik, 2019). Neem seed kernel extract @ 0.001-0.4% were found effective to repellent the planthoppers (Misra and Jena, 2007). It was also observed that eucalyptus oil @ 1000 ml/ha was found promising against yellow stem borer and plant hoppers whereas Cedar wood oil @ 1000 ml/ha was against gall midge (Seni, 2019).

2.9 Chemical insecticides

Chemical control is one of the quickest and reliable tools of decreasing insect pest populations in rice, particularly in emergency situations where there is no suitable alternative.

Various studies also reported that insect pest outbreaks occurred due to the misuse of insecticides (IRRI, 2011; Ali *et al*., 2019) which ultimately threatening the whole rice growing areas. Efficacy of chemical control technique depends on the right selection of active ingredient, suitable formulation and application methods on the knowledge of pest life cycle and crop phenology (Pasalu *et al*., 2004). Beside this, information regarding the most vulnerable stage of the pest, pest intensity and their effect on yield as well as on natural enemies are also important for economic and successful pest management. Further, knowledge of the negative effects of pesticides to the users, consumers and environment is necessary. Among the insecticide formulations, granular formulations of chlorantraniliprole 0.4 GR @ 10 kg/ha, and fipronil 0.3 GR @ 12 kg/ha are effective against stem borer and leaf folder. Among spray chemicals, in situations where leaf folder and stem borer cause problem then cartap hydrochloride 50 SP @ 750 g/ha, fipronil 5 SC @ 1500 ml/ha and rynaxypyr 20 SC@ 150 ml/ha are useful (Seni and Naik, 2020). For plant and leaf hoppers flonicamid 50 WG @ 150 g/ha, pymetrozine 50 WG @ 300 g/ha and triflumezopyrim 10 SC @ 240 ml/ha are very effective (Seni and Naik, 2017; Seni et al., 2019; Seni and Naik, 2020). Farmers should use insecticides for management of rice insect pests only as last resort to avoid economic damage.

2.10 Nanotechnology

Nanotechnology opens up a wide range of opportunities in agriculture like plant protection through the formulations of nano-particle-based pesticides, increase of agricultural productivity by using bio-conjugated nanoparticles (encapsulation), nano based biomarkers which can detect damaging stage of the pest, nanoparticle-mediated gene or DNA transfer in plants for the development of insect resistant varieties. Beside this, nanoparticles can be used for preparation of various types of biosensor, which would be useful in remote sensing devices required for precision farming (Rai and Ingle, 2012). Using nanoparticles and nanocapsules of pesticides can decrease the environmental pollution by reduce the pesticide dose whereas enhance the efficacy of the pesticides. Goswami *et al.* (2010) studied the effects of various types of nanoparticles viz. silver nanoparticles (SNP), aluminium oxide (ANP), zinc oxide and titanium dioxide for the management of rice weevil, *Sitophilus oryzae* and after 7 days they found that 86% and 95% mortality with hydrophobic and hydrophilic SNP and 70% mortality of the insects was noticed when the rice was treated with lipophilic SNP whereas, 100 % mortality was observed in case of ANP. Similarly, Vani and Brindhaa (2013) reported 100% mortality of rice moth, *Corcyra cephalonica* when silica nanoparticle was tested against them.

2.11 Information technology

Proper use of information technology helps rice insect pest management more effectively and economically. Rice knowledge banks, which were developed and made available through specialist websites, could convey the knowledge in various aspects of rice production systems to farmers as well as other government extension workers. Knowledge banks are mainly digital information repositories with simplified retrieval interfaces which help users understand rice crop management, pest problems and, natural enemies as well as other beneficial insects (Horgan, 2017). Several national and international institutes maintain such websites. Several rice knowledge 'apps' have been made available to farmers through smartphones (i.e., IRRI Rice Knowledge Bank), while in others, farmers can get various diagnostic support from remote specialists after answering some questions or uploading photographs of potential pests encountered in their fields (i.e., IRRI Crop manager and IRRI Rice doctor). In India, National Centre for Integrated Pest Management (NCIPM), New Delhi has developed "e-National Pest reporting and alert system" based on the information collected directly from the farmer's fields and then data has been processed carefully so that the system can deliver the outcome immediately to the farming community through short messaging service (SMS) in their own language. Likewise, Kisan Call Centers, formed by Indian Government deliver extension services to the farming community by providing solution to their queries. Although such systems are incepted to help sustainable rice production through effective pest management but, main drawback is unavailability of trained staff always and financial support, and if not regulated properly, they could encourage unnecessary insecticide applications (Horgan, 2017). Government and other private support and proper monitoring for such remote extension activities are necessary to deliver effective results.

3. Conclusion

Excessive use of synthetic chemicals causes environmental pollution, detrimental to natural control agents and insecticidal residue in food grains. For this, some alternative techniques should be promoted to reduce the over reliance on chemical pesticides. For this, a series of eco-friendly techniques such as conservation and utilization of indigenous natural enemies through ecological engineering, integrated farming like rice duck system, use of pheromones and semio-chemicals, smart agronomic practices, resistant varieties are helpful to grow rice in sustainable manner. Regarding new techniques in host plant resistance, QTLs mapping and marker assisted selection has great role in development of resistant varieties but still many efforts are necessary to harness that technology effectively. While other new techniques like RNAi and genome editing have promising role in insect pests management strategy but, more research still needed to make them as a viable strategy.

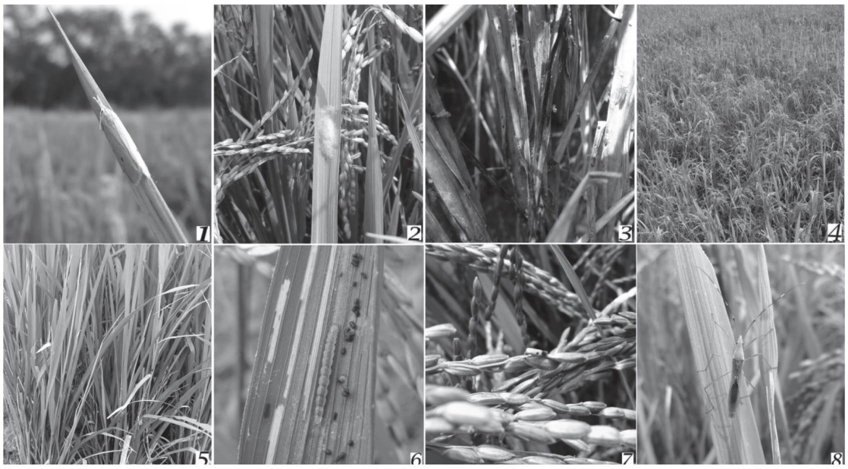

Fig. 2: *1;* Yellow stem borer adult, *2;* Egg mass of YSB, *3;* Plant hopper infested rice plant, *4;* Hopper burn symptom, *5;* Silver shoot produced by gall midge, *6;* Leaf folder larvae *7;* Green leaf hopper, *8;* Rice earhead bug

Conflict of Interest

NO

Ethical Compliance Statement

NA

Author contribution statement

Conceptualization of research and designing of experiments, Data collection and analysis, Preparation of manuscript (AS).

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