

# Emerging and re-emerging biotic stresses of agricultural crops in India and novel tools for their better management

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*Food security of our country is at risk due to heavy yield losses of agricultural crops caused by pests and diseases known together as biotic stresses. Conventional management practices in vogue are not competent under the current situations obscured by the incitants of biotic stresses which have either enhanced their offensive capabilities due to adaptive mutations or regained their pathogenic/herbivory potential owing to climate change. Numerous causal agents of biotic stresses are also introduced in the country or new regions of the country either through natural dispersal as invasive species, or on account of quarantine irregularities at national or international levels. Therefore, it is of utmost importance to appraise the impact of these new biotic stresses burgeoned in the recent past and to develop novel technologies for their management. To devise an effective preventive and eradicated strategy for containing these biotic stresses, new research innovations need to be practiced such as deciphering basic/molecular mechanism of host-pathogen/insect interactions; endophytic mechanisms of plant protection; nanotechnology in pest management; host resistance strengthening by gene cloning, recombinant DNA technologies, RNA biology, utilizing gene editing technologies such as CRISPR/Cas9, etc. This article presents a comprehensive account of new biotic stresses of agricultural crops built up in the country and also reviews the novel scientific inventions made worldwide which can be further employed to devise more efficient methods for alleviating impact of these biotic stresses of food crops in the country.*

**Keywords:** Agriculture, biotic stress, crops, food security, management.

ANNUAL yield of agricultural crops are lost to the tune of 30–35% in India due to attack of various pests and diseases or biotic stresses<sup>1</sup>. Of late, upsurges of several new stresses have also been noted. Several factors are responsible for build up of biotic stresses such as shift of secondary causal agents to primary status, injudicious use of pesticides, climate change, resistant pest populations, invasive pests, biotype development, human interventions, etc. As an overhaul of this pitfall, there is a necessity to re-look the basic information of biology and ecology of these biotic stresses, molecular basis of their identification and interaction between causal agents and their hosts, fine tuning of existing mitigation practices and/or formulation of novel ecologically viable management strategies. Build up of biotic stresses in nature is a continuous process, particularly in favourable environments. Environmental aberrations often may cause emergence of

new pathogenic races/biotypes. Pathogens and insect pests prevailing with minor status acquire major proportion due to enhanced adaptation capabilities owing to mutational changes for survival. The agricultural crops are also vulnerable to threats from exotic pests/pathogens/weeds which may get purposefully or accidentally introduced to the country or new areas in the country in addition to natural dispersal. Insect pests and other pathogens of important crops in India built up in the recent times under the influence of climate change, mutational changes for survival, acquired resistance to pesticides, transboundary invasions, etc. are shown in Tables 1 and 2. A brief account of these biotic stresses is reviewed below.

## Insects

### *Emerging insect pests*

A pest reported from an area on a particular crop showing considerable increase in its population and potential to

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**Table 1.** Pests and diseases of agricultural crops emerged in India as consequences of climate change

Crop	Insect pests	Diseases
<b>Cereals</b>		
Rice	Swarming caterpillar ( <i>Spodoptera mauritia</i> ) <sup>1</sup> , Gallmidge ( <i>Orseolia oryzae</i> Wood-Mason) <sup>81</sup> , Brown plant hopper ( <i>Nilaparvata lugens</i> ) <sup>82</sup>	Sheath blight ( <i>Rhizoctonia solani</i> ) and False smut of rice ( <i>Ustilaginoides virens</i> ), Bakane ( <i>Fusarium oxysporum</i> f. sp. <i>fujikuroi</i> ) <sup>82</sup>
Wheat	Pink stem borer ( <i>Sesamia inferens</i> Walker) <sup>5</sup> , Sugarcane pyrrilla ( <i>Pyrilla perpusilla</i> Walker) <sup>6</sup> , Aphid complex: ( <i>Sitobion avenae</i> F.), <i>Rhopalosiphum maidis</i> (Fitch), <i>Schizaphis graminum</i> (Raandani) <sup>83</sup>	Rice blast ( <i>Pyricularia oryzae</i> var. <i>tritricum</i> ) <sup>24,84</sup> Black rust (UG 99) – a potential looming threat to India, yellow rust pathotypes 46S119 & 238S119 (ref. 25)
Maize	Fall armyworm ( <i>Spodoptera frugiperda</i> J. E. Smith) <sup>85</sup>	–
<b>Pulses</b>		
Chickpea	Blister beetle ( <i>Mylabris pustulata</i> ) <sup>5</sup>	Dry root rot ( <i>Rhizoctonia bataticola</i> ) <sup>82</sup> and collar rot of chickpea ( <i>Sclerotium rolfsii</i> ) <sup>86</sup>
Cowpea	Spotted pod borer ( <i>Maruca vitrata</i> Geyer) <sup>82</sup>	–
Mung bean/Urdu bean	White fly ( <i>Bemisia tabaci</i> ): not a concern but the mosaic virus vectored by it causes severe disease and reduction in crop yield <sup>82</sup>	Stem blight ( <i>Stemphyllium botryosum</i> ) <sup>82</sup>
Pigeon pea	Spotted pod borer ( <i>Maruca vitrata</i> ) <sup>82</sup>	<i>Phytophthora</i> stem blight of pigeon pea <sup>82</sup>
<b>Fruits</b>		
Mango	Fruit fly ( <i>Bactrocera dorsalis</i> Hendel) <sup>87</sup> , Leafminer ( <i>Acrocercops syngamma</i> Meyrick) <sup>88</sup> , Fruit borer ( <i>Autocharis albizonalis</i> and <i>Tirathaba mundella</i> ) <sup>82</sup>	Wilt (Vector borne <i>Ceratocystis</i> ) <sup>82</sup>
Apple	–	Leaf spot ( <i>Marssonina coronaria</i> ) <sup>82</sup>
Guava	Spiralling whitefly ( <i>Aleurodicus disperses</i> Russell) <sup>89</sup>	–
Sapota	Seed borer ( <i>Trymalitis margarius</i> Meyrick) <sup>90</sup>	–
Citrus	Fruit sucking moth ( <i>Otheris fullonica</i> Clerck), ( <i>O. ancilla</i> ) <sup>91</sup>	–
Grapevine	Shield bug ( <i>Scutellera perplexa</i> F.) <sup>92</sup>	Rust ( <i>Phakospora euvitis</i> ) <sup>82</sup>
Pomegranate	Tea mosquito bug ( <i>Helopeltis antonii</i> Stonedahl) <sup>93</sup>	Bacterial leaf spot ( <i>Xanthomonas axonopodis</i> pv <i>punicae</i> ) <sup>82</sup>
Banana	Skipper ( <i>Erionata torus</i> Evans) <sup>94</sup>	Wilt TR 4 ( <i>Fusarium oxysporum</i> f. sp. <i>cubense</i> TR4) <sup>82</sup>
Litchi	Fruit borer ( <i>Conopomorpha sinensis</i> Bradley) <sup>95</sup>	–
Coconut	White fly ( <i>Aleurodicus rugioperculatus</i> ) <sup>82</sup>	–
Areca nut	White grub ( <i>Holotrichia consanguinea</i> ) <sup>82</sup>	–
<b>Vegetables</b>		
Brinjal	Mealybug ( <i>Phenacoccus solenopsis</i> Tinsley) <sup>96</sup>	–
Tomato	Mealybug ( <i>Phenacoccus solenopsis</i> Tinsley) <sup>96</sup>	Tomato spotted wilt virus <sup>82</sup>
Okra	Mealybug ( <i>Phenacoccus solenopsis</i> Tinsley) <sup>96</sup>	–
Chilli	Gall midge ( <i>Asphondylia capparis</i> Rubsaman) <sup>96</sup> , White fly ( <i>Bemisia tabaci</i> ) and Aphids ( <i>Aphis gossypii</i> ), Capsicum also <sup>82</sup>	–
Onion and garlic	Army worm ( <i>Spodoptera exigua</i> Hubner) <sup>96</sup>	–
Cowpea	Spotted pod borer ( <i>Maruca vitrata</i> Geyer) <sup>4</sup>	–
Bottle gourd	Mirid bug ( <i>Nesidiocoris cruentatus</i> Ballard) <sup>97</sup>	–
Cucurbits	Red spotted mite ( <i>Tetranychus urticae</i> ) <sup>98</sup>	–
<b>Commercial and ornamentals</b>		
Cotton	Green ired bug ( <i>Creontiades biseratense</i> Distant) <sup>1</sup> Mealybug ( <i>Phenacoccus solenopsis</i> Tinsley) <sup>99</sup> Whitefly ( <i>Bemisia tabaci</i> Gennadius) <sup>23</sup>	– – –
<b>Protected cultivation (due to conserved temperature, humidity and diffused light)</b>		
Tomato	White fly ( <i>Bemisia tabaci</i> ) <sup>82</sup>	Leaf curl virus, Root knot nematode ( <i>Meloidogyne incognita</i> Race 1) <sup>82</sup>
Cucumber	Cucumber mosaic virus, Spidermites ( <i>Tetranychus urticae</i> ), White fly ( <i>Bemisia tabaci</i> ) <sup>82</sup>	<i>Fusarium</i> wilt ( <i>Fusarium oxysporum</i> ) <sup>82</sup>
Capsicum	Thrips ( <i>Scirtothrips dorsalis</i> ), spidermites ( <i>Tetranychus urticae</i> ) <sup>82</sup>	–

## GENERAL ARTICLES

**Table 2.** Pests and diseases of agricultural crops built up in India as consequences of invasion

Crop	Pest	Diseases
<b>Cereals</b>		
Maize	Fall armyworm ( <i>Spodoptera frugiperda</i> J.E. Smith) <sup>100</sup>	–
Wheat	–	<i>Yr 9</i> pathotype of yellow rust of wheat <sup>101</sup>
<b>Fruits</b>		
Apple	Woolly apple aphid ( <i>Eriosoma lanigerum</i> ) <sup>102</sup>	–
Papaya	Mealybug ( <i>Paracoccus marginatus</i> Williams and Granara de Willink) <sup>103</sup> introduced from USA (CS)	–
Banana	–	Banana wilt ( <i>Fusarium oxysporum</i> f. sp. <i>cubense</i> tropical race 4 ( <i>Foc</i> TR4) <sup>27</sup>
Coconut	White fly ( <i>Aleurodicus rugioperculatus</i> ) <sup>82</sup> , <i>Paraleyrodes minei</i> <sup>104</sup>	–
<b>Vegetables</b>		
Potato	Tuber moth ( <i>Phthorimaea operculella</i> Zeller) <sup>105</sup>	–
Cabbage	Diamondback moth ( <i>Plutella xylostella</i> Linn.) <sup>106</sup>	–
Tomato	Leaf miner ( <i>Tuta absoluta</i> ) <sup>107</sup>	–
Chilli	Western flower thrips ( <i>Frankliniella occidentalis</i> Pergande) <sup>108</sup>	–
Onion	<i>Thrips palmi</i>	–
Many vegetable crops	Serpentine leaf miner ( <i>Liriomyza trifolii</i> Burges) <sup>109</sup>	–
Many vegetable crops	Silver leaf whitefly ( <i>Bemisia argentifolii</i> Bellows) <sup>105</sup>	–
<b>Horticultural crops</b>		
Papaya	–	<i>Papaya ringspot virus</i> strain PRSV-P <sup>87</sup>
Several crops	Spiraling whitefly ( <i>Aleurodicus disperses</i> Russell) <sup>110</sup>	–
<b>Commercial and ornamentals</b>		
Coconut	Eriophid mite ( <i>Aceria gurreronis</i> Keifer Singh) <sup>105</sup>	–
	Rugose spiraling whitefly ( <i>Aleurodicus rugioperculatus</i> Martin) <sup>111</sup>	–
	Neotropical whitefly ( <i>Aleurotrachelus atratus</i> Hempel) <sup>112</sup> , <i>Paraleyrodes minei</i> <sup>104</sup>	–
Cotton	Mealybug ( <i>Phenacoccus solenopsis</i> Tinsley) <sup>113</sup>	–
Coffee	Berry borer ( <i>Hypothenemus hampei</i> Ferrari) <sup>114</sup>	–

cause economic damage over a period of time is termed as emerging insect pest<sup>2</sup>. Sucking insect pests, mirid bug, mealybug, whitefly, aphids and plant hoppers on major crops; *Helicoverpa armigera* on vegetables and pulses; *Spodoptera litura* on vegetables, cotton and oil-seeds; *Pieris brassicae* on crucifers; *Liriomyza trifolii* on vegetables; *Atherigona* spp. on spring maize; aphid complex like *Sitobion avenae*, *Rhopalosiphum maidis* and *Schizaphis graminum* on wheat, barley and oat; green mirid bug, *Creontiades biseratense* on cotton in states such as Karnataka, Tamil Nadu, Maharashtra, Andhra Pradesh; eriophyid and tetranychid mites on bean, brinjal, cotton, cucurbits, okra, apple, ber, citrus, mango in North India, *Maruca vitrata* on pigeonpea and cowpea in Andhra Pradesh, sugarcane pyrilla on wheat and oat in Chhattisgarh, etc. have been reported to emerge in India<sup>3-6</sup>. The possible reasons for the emergence of insect pests are climate change, physiological and ecological impacts, change in feeding habit of herbivory, increased overwintering survival, increased number of generations of pest, breakdown of host resistance, change of genotypes/impact of transgenics, injudicious use of pesticides, modification of cultural practices/tillage, etc. A noteworthy

instance in this context has been that of 11 genetic groups of whitefly (*Bemisia tabaci*) reported to emerge in India out of a total of 42 in the world. These genetic groups have differed in their ability to transmit begomoviruses and on many occasions this became a reason for the emergence of begomoviral disease epidemics<sup>7</sup>.

### Invasive insect pests

Invasive insect species cause huge economic losses and their threat is on continuous rise in the areas of Indian agricultural biodiversity, livelihoods, human and animal health, forestry and biodiversity<sup>8</sup>. Since 1889, a total of 24 insect species have been reported to invade India<sup>9,10</sup>. India witnessed its first ever invasive insect pest San Jose scale (*Quadraspidiotus perniciosus* Comstock) in 1879 from China. As on 2019, the tally rose to a total of 23 insect pest species and since 1879 they are affecting the agro-ecological balance of the country and causing huge economic loss over the years. Tomato leaf miner (*Tuta absoluta* Meyrick) has become the most destructive major nocturnal pest of tomato production as well as other

solanaceous crops due to its invasions in different parts of the world<sup>11</sup>. Since it originated in South America, it is known as South American tomato moth, tomato borer or American tomato pinworm<sup>12</sup>. It is also reported to attack potato, eggplant, hot pepper, some weeds (*Datura stramonium* and *Nicotiana glauca*) and some other non-solanaceous crop plants like green beans or *Malva* spp<sup>13</sup>. Melon thrips (*Thrips palmi* Karny) is a polyphagous pest with wide host range including Solanaceae, Cucurbitaceae and Leguminosae plants in tropical and subtropical countries<sup>14</sup>. Another notorious invasive pest, the fall armyworm (*Spodoptera frugiperda*) was first noticed at Shivamogga, Karnataka during May 2018 (ref. 15). This has been spreading fast into new territories in the states of Karnataka, Telangana, Andhra Pradesh, Maharashtra, Gujarat and Tamil Nadu<sup>15</sup>.

### Climate change impacts on insect pests

Climate change is another important issue to determine the status of insect pests in India. Changed patterns in climatic factors like temperature, precipitation, humidity and other meteorological parameters affect the biology and ecology of insect pests and increase their population. The damage potential of pests ameliorated by their expanded distribution, enhanced survivability and adaptability, alteration in tri-trophic interaction, emergence of new biotypes, etc. in turn, increased the yield losses further by 10–25% (ref. 16). A study revealed that the number of eggs laid by yellow stem borer (YSB) increased at higher temperatures while egg hatching was reduced leading to a lesser survival of YSB with increased temperature<sup>17</sup>. Temperature below or above the range of 27°–30°C limited the survival and development of *Spodoptera litura* on peanut. The life patterns of *S. litura* were also significantly affected by higher rate of CO<sub>2</sub> (ref. 18). Elevated temperature and CO<sub>2</sub> significantly increased the reproductive time of aphids leading to production of offsprings for longer periods affecting growth and development at second trophic level in cowpea<sup>19</sup>.

### Pesticide induced resistant insect populations

Evolutionary biologists are generally confounded with the process of evolution of resistance in various pest organisms against pesticides<sup>20</sup>. Several biological, genetic and operational factors affect resistance development in pest populations<sup>21</sup>. An estimated 954 pest species have developed resistance against various types of pesticides<sup>22</sup>. Once resistance to pesticides is detected, the ineffective molecules can be avoided and such information also assists in making a proper recommendation of alternative molecules that are less resisted and can effectively control insect pests. Application of pesticides that would have otherwise harmed the environment without actually

having served the designated purpose of pest management can be avoided if information on resistance to that particular pesticide is determined<sup>23</sup>. Periodical monitoring and following insecticide resistance management suggested by Insecticide Resistance Action Committee (IRAC) would be useful to manage the insecticide resistant insect populations<sup>22</sup>.

## Plant pathogens

### Burgeoning fungal pathogens of plants

Prevalence and distribution patterns of several fungal pathogens have changed over the years. Blast of rice remains the most important fungal disease in India, however, sheath blight's (*Rhizoctonia solani*) severity and drastic spread and increase in almost all rice growing regions during the past few years caused major losses to the yield as well as increasing fungicidal sprays. Similarly, increased occurrence of false smut of rice has been observed in recent years<sup>24</sup>. Among other cereals, large areas under wheat are continuing to be vulnerable to yellow rust pathogen (*Puccinia striiformis*) which is evolving regularly rendering wheat varieties susceptible<sup>25</sup>. Stalk rot, downy mildew and leaf spots are the major constraints in maize crop in India, and sugarcane red rot with continuous emergence of variability in the pathogen is posing a threat to sugarcane yield<sup>26</sup>. The emergence of virulent Tropical race 4 (TR4) of *Fusarium* wilt has a devastating effect on banana cultivation in the world and has also been detected in India in the recent past with high incidence and crop damage<sup>27</sup>. Soil-borne fungal pathogens are becoming increasingly devastating to the crops which are difficult to control. These pathogens cause heavy losses in economically valuable crops like pulses, vegetables, rice, etc. In recent years, dry root rot of chickpea (*Rhizoctonia bataticola*) and *Phytophthora* stem blight of pigeon pea (*Phytophthora drechsleri* f. sp. *cajani*) have emerged as potential threats<sup>28</sup>. Soil-borne diseases caused by fungal pathogens *Phytophthora*, *Pythium*, *Rhizoctonia solani* and *Sclerotium rolfsii* are favoured by excess soil moisture, especially in pulses<sup>29</sup>.

The inevitable climatic changes also affected the reproduction, spread and severity of fungal pathogens resulting in the increased frequency of occurrence and severity of different diseases. Climate change reduced the efficiency of many *Sr* genes in wheat which were governing resistance against Ug99 race of *Puccinia graminis* f. sp. *tritici*. Also, elevated temperature and CO<sub>2</sub> aggravated virulence of *Phytophthora infestans* causing late blight of potato, *Pyricularia oryzae* causing rice blast and *Rhizoctonia solani* causing sheath blight of rice<sup>30</sup>.

Plant health is globally endangered through introduction of exotic pathogens as consequences of increasing globalization, travel and international trade. Certain

virulent races of fungal pathogens, viz. Ug99 group of races of wheat stem rust pathogen, wheat blast pathogen, and soybean downy mildew, though not present in India, are a serious threat to our crop production programmes if they occur in India. A severe outbreak of wheat blast in the neighbouring country Bangladesh in early 2016 had roused a serious phytosanitary concern in India<sup>31</sup>.

#### *Emergence of new bacterial diseases*

Considerable yield losses occur in agricultural crops in India due to infection of phytopathogenic bacteria. Some of them which have emerged with significant importance are bacterial blight of rice (*Xanthomonas oryzae* pv *oryzae*), bacterial blight of pomegranate (*X. axonopodis* pv *punicae*), bacterial wilt of vegetables (*Ralstonia solanacearum*), black spot of mango (*X. citri* pv *mangiferae indicae*), and bacterial blight of cotton (*X. citri* sub sp. *malvacearum*). Apart from these, panicle blight of rice (*Burkholderia glumae*) and stalk rot of maize (*Pectobacterium chrysanthemi* var. *zetae*) have also emerged in the recent years as potential threat to yield of respective food grains in India<sup>32</sup>.

#### *Emergence of new viral diseases*

Climate change and human population pressure also favour emergence of new viral diseases in plants<sup>30</sup>. Several viruses and their strains or isolates or their combinations caused diseases in crops especially vegetable crops due to introduction of hybrids. Recently, *Tiranga* disease<sup>32</sup> was reported from Maharashtra and the diseased samples were found to be associated with five different viruses. Rice tungro, ground nut bud necrosis, sunflower necrosis, yellow mosaic of legumes, pigeon pea sterility mosaic, soybean bud blight, cotton leaf curl, cassava mosaic, potato apical leaf curl, banana bunchy top, banana bract mosaic, papaya leaf curl, papaya ringspot, chlorotic leaf spot in peach, piper yellow mottle are some of the emerging viral diseases which have built up in the recent times<sup>33</sup>. The incidence of papaya ringspot virus has also been recorded all over the country<sup>34,35</sup>.

#### *Emergence of new nematode diseases of plants*

Our country is also facing a plethora of nematological problems in cereals, pulses, oilseeds, vegetables, fruits, fibre and plantation crops. The root-knot nematodes belonging to the genus of *Meloidogyne* have gained importance and are responsible for causing severe yield losses to vegetable crops under intensive cultivation. They also became a major threat to protected cultivation of vegetables and ornamental crops. Rice root-knot nematode,

*M. graminicola* has established in low land rice cultivation. *Pratylenchus* spp. and *Rotylenchulus* spp. are noticed in high frequencies in important pulse and oilseed crops of the country. Guava and pomegranate crops are also facing severe threat from an invasive nematode pest, viz. *M. enterolobii*<sup>36</sup>.

#### **Weed problems in crops and cropping systems**

South American *Asteraceae* weeds such as *Parthenium hysterophorus*, *Eupatorium adenophorum*, *Eupatorium odoratum*, *Mikania micrantha*, *Ageratum conyzoides*, *Galinsoga parviflora*, *Ageratum conyzoides* L. have invaded and naturalized in several parts of Southern Asia including India<sup>37</sup>. Species of parasitic dodders (*Cuscuta* spp.) has emerged as a menace in several parts of South India and are becoming serious constraints in successful cultivation of pulses and oilseeds, throughout the country<sup>38,39</sup>.

#### **Quarantine lacunae**

From time to time, the pests and pathogens introduced from exotic sources have devastated crop yields in several parts of the country. Prior to implementation of Plant Quarantine Order 2003, woolly aphid, cottony cushion scale, golden cyst nematode of potatoes, San Jose scale, the giant African snail were introduced into India from across the border. The domestic quarantine systems and regulations are not up to the mark in our country due to the unorganized and multi-dimensional nature of the farm sector<sup>40</sup>. Further, the pest risk analysis (PRA) procedure and quarantine regulations cannot be imposed in their true sprits in a largely populated country like India<sup>41</sup>. Recently, after ravaging cornfields of sub-Saharan Africa, the Fall Armyworm (FAW) entered India in 2018, and the infestation has already spread to most parts of the sub-continent. The severe infestation has been reported from more than 20 maize growing states of India<sup>10</sup>.

#### **Raging mammalian pests emerging as the biggest menace in farming sector**

##### *Blue bull (Nilgai)*

Among mammals, Blue bull (*Boselephus tragocamelus*, commonly called as Nilgai) prevails as a major pest of wild animal category in agriculture dominated landscapes in central and northern India<sup>42</sup>. Crop raiding and crop damage by Nilgai are quite often reported in agricultural fields around protected areas. To tackle the problem of Nilgai crop damage, various management interventions have been suggested and implemented. The fodder plants have been planted in the forest area for feeding Nilgai. Permanent watchers have been placed by Forest

Department to prevent raid on agriculture crops. Many indigenous measures are employed to curb the menace of Nilgai which include use of effigy models, use of shining tapes like video or audio tapes, live fencing along with use of beating bells, animal excreta, phenyl solutions, fire crackers, forate insecticide granules, walled fencing, barbed fencing, watchers by involving local communities, etc.<sup>43</sup>.

### *Wild boar and monkey menace*

The wild boar (*Sus scrofa*) and langur monkey (*Semnopithecus entellus*) are the widely distributed large mammals gaining pest status and have become regular menace for farmers in case of major crops<sup>44</sup>. The wild boar damages crops at all growth stages<sup>45,46</sup>. Population of wild boars increased as a result of heavy deforestation as forests are the natural habitats of these species<sup>47</sup>. The natural predators of wild boars, i.e. tigers, panthers, wild dogs, wolf and jackal also reduced owing to indiscriminate deforestation<sup>48</sup>. Several indigenous techniques may be employed to ward off wild boars. Some of such effective ways like spraying of local pigs dung solution (up to 50% damage control), human hair as deterrent (40–50% damage control), erection of used coloured sarees (30–55% control), burning of dried dung cakes (35–50%), planting of thorny bushes and xerophytes around the crop (50–70%), creation of sounds and light through bonfire (40–60%), and traditional use of local dogs for scaring away wild boars (up to 50% control), practiced by local people were scientifically evaluated and validated for efficiency and economic feasibility<sup>49</sup>.

### *Novel tools for devising innovative strategies of plant protection*

Agriculture in India is witnessing rapid transition from mere sustenance to entrepreneurial commercial farming. Farmers now opt for high yielding varieties and hybrids. Yields are maximized through input intensive farming which often paves way for indiscriminate misuse of fertilizers and pesticides, making crops vulnerable to various diseases and pests. Overuse of fertilizers and pesticides also cause water and air pollution, residual toxicity in fruits and vegetables, resistance to pesticides in insects and pathogens, mortality of natural biocontrol-friendly insects, rise of secondary pests, etc.<sup>50</sup>. At this juncture, novel mitigation measures need to be contrived on priority for curtailing the huge yield losses caused by various biotic stresses of agricultural crops. In this context, various key research areas for future work include deciphering basic/molecular mechanism of host–pathogen/insect interactions, nanotechnology in pest management, fumigants, volatile and acoustic techniques for stored grains, post-harvest and vertebrate pest management, utilizing

gene editing technologies such as CRISPR/Cas9, elaborated tritrophic pheromone/kairomone studies, deployment of remote sensing technology for pest management, disease/pest prediction and forecasting, determination of factors leading to evolution of pests and pathogens, development of technologies to minimize the adverse effects of climate change on biotic stresses of plants, allelopathy based weed management etc. Efforts have been made worldwide to search novel and more efficient tools for mitigating losses due to biotic stresses and a brief account of the same is presented below.

### *Transgenic crops with insecticidal toxins*

With the advancement of molecular biology in the recent times, a new innovation of genetic engineering lure the plant scientists worldwide and so is also true with agricultural scientists as well. Plant protection scientists are now capable of manipulating the genetic material of a cell in order to produce pest resistant varieties of several crops. Genetic engineering technology has been successfully employed in developing cotton genotypes resistant to lepidopteran larvae (caterpillars) and maize genotypes resistant to both lepidopteran and coleopteran larvae (root worms) leading to reduction in pesticide usage and that of production costs<sup>51,52</sup>. The transgenic plants of these crops had *Bt* genes derived from the soil bacterium *Bacillus thuringiensis* (*Bt*). Genotypes with *Bt* genes show insecticidal activity toward pests, and constitute a large reservoir of genes encoding insecticidal proteins. *Bt* genes are responsible for accumulation of crystalline inclusion bodies produced by the bacterium on sporulation (Cry proteins, Cyt proteins), or expressed during bacterial growth (Vip proteins). Additional *Bt* Cry genes can be transgenically incorporated into the crop for achieving protection against a wider range of pests. Transgenic cotton containing two *Bt* genes was first used in 1999, three years after the release of the original single *Bt* variety. Cotton plants containing two genes corresponding to Cry1Ac and Cry2Ab proteins respectively, showed more toxicity towards bollworms (*Helicoverpa zea*; target pest) and two species of armyworms (*Spodoptera frugiperda* and *Spodoptera exigua*; secondary pests), than the cotton with single gene related to Cry1Ac<sup>53,54</sup>. Site-directed mutagenesis modifies *Bt* toxins resulting in increased toxicity towards target pests. Such an alteration due to chemical domain exchange in *Bt* genes is termed as ‘domain swap’ approach. The key role of domain II in three-domain Cry proteins in mediating interactions with insect receptors has been exploited by mutation of amino acid residues in the loop regions of this domain. Mutation of *Cry1Ab* increased its toxicity towards larvae of gypsy moth (*Lymantria dispar*) by up to 40 folds<sup>55</sup>. Hemipteran plant pests are not affected by known *Bt* toxins. But these are susceptible to lectin toxicity conferred by lectin genes

which can be potentially exploited to develop insect resistant transgenic plants. About 50% reduction in survival of brown plant hopper (*Nilaparvata lugens*) and other hemipteran pests could be achieved through expression of the Man-specific snowdrop lectin (GNA) in transgenic rice plants using constitutive or phloem-specific promoters<sup>56,57</sup>.

### Nematodal bacteria

Symbiotic enterobacteria present in nematodes of *Heterorhabditis* species offer a small-scale biological control of insect pests. These nematodes with bacterial cells in their gut release bacteria into the insect circulatory system. The bacterial toxins inside the insect circulatory system cause cell death in the insect host. A large number of insecticidal components have been investigated in the bacterium *Photorhabdus luminescens*<sup>58</sup>. A compound, cholesterol oxidase released by such bacteria exhibit insecticidal activity similar to *Bt* toxins through membrane destabilization.

### Secondary metabolites

By-products of some metabolic pathways in transgenic plants have been found to exhibit toxic properties against pest species. For example, coding sequence fused to a chloroplast-targeting peptide or expression constructs containing part or all of the coding sequence of the protein, resulted in production of toxic active enzyme in transgenic tobacco<sup>59</sup>. Alkaloid caffeine produced in tobacco by the introduction of three genes encoding N-methyl transferases is another example of a by-product of secondary metabolite with toxicity to pests in transgenic tobacco<sup>60</sup>.

### Volatiles

Plants are known to emit volatiles with properties of inhibiting pests. Such volatiles are known to be synthesized by RNA interference (RNAi)-mediated suppression of a *cytP450* oxidase gene expressed in tobacco and *Arabidopsis* by constitutive overexpression of a plastid dual linalool/nerolidol synthase<sup>61,62</sup>. These volatiles may be used as attractants for predators and parasitoids. For example, transgenic plants of *Arabidopsis* having maize terpene synthase gene *TPS10* emitted the sesquiterpene volatiles which attracted parasitoid wasps that attack maize pests<sup>63</sup>. Another example of volatile employed in pest control can be coated with sesquiterpene (E)- $\beta$ -farnesene used by insects to communicate with each other and can be used as an alarm pheromone in aphids for attracting aphid predators and parasitoids<sup>64</sup>. *Arabidopsis* containing (E)- $\beta$ -farnesene synthase gene from mint

(*Mentha piperita*) exhibited significant levels of aphid deterrence and also acted as the chosen attractant to the aphid parasitoid *Diaeretiella rapae*.

### RNAi and its complementing techniques

RNA applications made revolution in the field of crop protection due to their environmentally friendly approach. RNA interference (RNAi) utilizes the plant's natural process for mediating management of pest control and is emerging as an alternative to chemical spray<sup>65,66</sup>. The RNA-based active ingredients will be used for biocontrol in the near future. This depends upon the quality of double stranded RNA (dsRNA), its stability and large scale production<sup>65</sup>. Also, modification of an organism's genome is possible by employing genome-editing tool<sup>67</sup>. One such tool based upon CRISPR/Cas9 systems has been utilized for modification of susceptibility genes in agricultural crops to enhance resistance to crop pests<sup>68</sup>.

Furthermore, RNAi has emerged as a well-established technique of disrupting gene function in insect genome based on delivery by injection into insect cells or tissues. Partial resistance to insect pests can also be achieved by reducing the level of gene expression, measured by mRNA level, when fed to insects<sup>69</sup>. This led to the development of transgenic plants producing dsRNAs in transgenic maize corn rootworm by suppressing mRNA in the insect, reducing feeding damage compared to controls<sup>70</sup>. Similarly, in transgenic tobacco and *Arabidopsis*<sup>71</sup>, dsRNA directed against a detoxification enzyme (Cyt P450 gene *CYP6AE14*) for gossypol in cotton bollworm caused the insect to become more sensitive to gossypol in the diet.

To foster a healthier environment in modern agriculture, it has been advocated that plant viral defense strategies with the new revolutionary tools such as RNAi silencing, ZFN, TALENS, SmART and CRISPR/Cas9 have to be used to manage viral diseases. Several new viruses belonging to Poty, Cucumo, Illar, Gemini, Tospo and other groups<sup>72</sup> have been identified in agricultural crops. Polymerase chain reaction (PCR) based techniques as well as Real-time PCR have been successfully used for detection of virus strains and their variants in various crops. Understanding molecular interaction between viruses and the resistant and susceptible plants leading to resistance or pathogenesis is the need of the hour, which has to be pursued by employing genetic engineering techniques and functional genomics. Apart from this, factors contributing to upsurge of polyphagous vectors like whitefly need to be understood which involve mixed cropping pattern, overlapping host range, suitable weather which supports the survival and prevalence of whitefly. Also, recombination is one of the genetic events which foster the evolution of diverse strains of whitefly in India<sup>73</sup>.

### Nanotechnological innovations

The side effects of chemical pesticides caused by their poisonous components like heavy metals and non-biodegradable constituents necessitate searching safer alternatives for environmental friendly plant protection. Nano-based antimicrobials offer the best potential in this context. The nanopesticide is a formulation that is characterized with (a) Entities in the nanometer size range (up to 100 nm), (b) Designated nano prefix (e.g. nanohybrid, nanocomposite) and/or (c) Novel properties associated with small size. A wide variety of nanoproducts employed to protect from diseases/pests have been described in detail by European Commission Joint Research Centre<sup>74</sup>. In the field of plant protection, nanopesticides involving organic ingredients, polymer-based inorganic silica, titanium dioxide, nanoemulsions and nanoclays in various forms (e.g. particles, micelles) have been evaluated and applied<sup>75</sup>. Application of nano-pesticides is still in the incipient stages. However, nanosized silica silver (Si-Ag) particles have been successfully used for controlling fungal pathogens, viz. *Pythium ultimum*, *Magnaporthe grisea*, *Botrytis cinerea*, *Colletotrichum gleosporioides*, *Rhizoctonia solani* and also bacterial pathogens such as *Xanthomonas campestris*. Similarly, iron nanoparticles coated with carbon have been used for treating localized infections in plants. A nano-based product 'Nano-Gro' has been launched as plant growth regulator and immunity enhancer. Another product 'Nano-5' is also available in the market as natural mucilage organic solution for controlling several plant pathogens and pests.

### Endophytes in plant protection

Endophytic microbes, mostly bacteria and fungi live inside the plants and provide protection against pathogen attack and enhance tolerance to abiotic stresses also. Usage of endophytes in plant protection significantly reduces the usage of agricultural chemicals<sup>76</sup>. Endophytes have been reported to induce systemic acquired resistance (SAR) against a variety of pathogens by triggering metabolic pathways in host leading to synthesis of phytohormones, viz. salicylic acid, jasmonic acid and ethylene, leading to the formation of infection barriers and antimicrobial substances in plants. These microbes are also used as biocontrol agents in plant protection, as they restrict the growth of pathogens by producing a range of bioactive metabolites, hydrolytic enzymes, antibiotics and lipopeptides<sup>77-79</sup>. Endophytes promise an eco-friendly and viable option as biocontrol agents and may thus contribute potentially to sustainable agriculture.

### Strengthening quarantine services

Government quarantine system offers services which are beyond the capabilities of individual beneficiaries due to

cost factor. But in real sense, plant quarantine is supposed to serve at national level by creating barriers to the introduction of exotic pests and pathogens and also prevent their further spread. Quarantine measures can be successfully implemented with the active support of administrators, general public, farmers, scientists, communication media, customs and other stakeholders involved in the farm sector<sup>80</sup>. Subsequently, an effective quarantine system depends on several important pre-requisite data such as updated lists of endemic pests, authentic data on country-wide survey and surveillance, as well as current literature, which are also vital in implementing the PRA procedures. Further, to achieve an effective output of quarantine processing and biosecurity measures, it is essential to synchronize the plant quarantine system with the global plant quarantine system standards<sup>41</sup>.

### Conclusions

Plant health needs to be viewed as an important perspective of measures to ensure food security which involves a multidisciplinary approach, reforms in human resources, natural resource management, agricultural research, rural infrastructure, etc. In this context, contriving novel mitigation measures of biotic stresses in farming sector by revamping the inadequacies of the ongoing national programmes for assuring national food and nutrition security menaced by viciously vibrant pests/pathogens due to climate change, mutations, invasions, etc. is the need of the hour. Various priority research areas for future work include novel measures for deciphering basic/molecular mechanism of host-pathogen/pest interactions, nanotechnology in pest and disease management, fumigants, volatile and acoustic techniques for stored grains, post-harvest and vertebrate pest management, utilizing gene editing technologies such as CRISPR/Cas9 for strengthening transgenic resistant crops. Research should also supplement aspects of tritrophic pheromone/kairomone studies, identification of broad spectrum resistance, utilizing wild species gene pool for durable resistance, deployment of remote sensing technology and other artificial intelligence based measures for pest management, development of disease/pest prediction models, determination of factors leading to evolution of pests and pathogens, minimizing the effects of climate change on aggravation of biotic stresses of plants, innovative weed management, vertebrate pest control, etc.

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## GENERAL ARTICLES

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