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INTEGRATED PEST MANAGEMENT OF FIELD CROPS

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ABSTRACT

Insect pests, diseases, nematodes and weeds constitute major biotic stresses in crop production systems inflicting 15 to 25% or more yield losses. Adverse effects of pesticides can be countered through adoption of integrated pest management (IPM), which emphasizes harmonious use of safer and environment friendly methods of pest suppression. IPM works on the premise that all pest population levels are not injurious to crops. It is a knowledge intensive decision based activity and requires tools and techniques for its execution. IPM algorithm involves crop loss assessment, pest risk analysis, development of pest surveillance and forewarning methodology and decision support tools for harmonious integration of management tactics within the framework of Integrated Crop Management system. IPM modules for various field crops are based upon integration of resistant cultivars, cultural, mechanical and physical methods, natural enemies, biopesticides and pesticides to suppress pest population without jeopardizing the environment. Various organizations addressing the issue of plant health management need to converge in a mission mode to disseminate IPM throughout the country. This review covers the latest developments in these areas of IPM with main reference to India.

Key words: Insect pests, field crops, pest surveillance, forewarning, crop losses, pest zones, remote sensing, ICT, ICM, IPM

Our national priority today includes production of safe quality food, conservation of environment, doubling of farmers' income and promotion of exports. Agriculture plays a very important role in Indian economy. The government policies and technological innovations by the National Agriculture Research, Education and Extension System (NARES) during the last six decades have transformed the Indian agriculture and achieved splendid success in increasing food and fibre production. India has attained an unparalleled distinction of achieving rainbow (Green, White, Golden, Brown, and Blue) revolution by attaining outstanding productivity gains in food grain, pulses, oilseeds, horticulture, milk, meat, poultry and fisheries sectors. While the progress made has been exemplary, a lot more needs to be done to meet the food and fibre needs, as well as nutritional security of the teeming human population. It is an irony that malnutrition is still widespread in some parts of the country. The country not only needs food security but also nutritional security.

Insect pests, diseases, nematodes and weeds constitute major biotic stresses in crop production systems inflicting 15 to 25% or more yield losses (Oerke et al., 1994), the monetary value of which, in India, has been estimated to exceed Rs 1.9 - 2.25 lakh crores. There is ample scope to enhance our food production to an extent of 60 million tons (Mt) of food grains and 65.3 Mt of horticultural produce, by curtailing avoidable pest induced yield losses. The saved food will be sufficient to feed 30 crores of population. Despite the annual investment of US$ 40 billion for the application of pesticides, and various biological and other non-chemical control worldwide, global crop losses remain a matter of concern (Pimentel and Peshin, 2014). The only option to boost our production remains in growing improved crop cultivars with better crop and pest management options, in view of shrinking land resource for agriculture.

Synthetic pesticides have mainly been used to combat pest menace in agriculture and public health. Pesticides have, of course, played a commendable role in achieving attainable yield in crops and in protecting us against disease transmitting vectors. However, sole reliance on pesticides has created several problems such as development of resistant pests, pest outbreaks, mortality of useful organisms, adverse effect on human and animal health due to presence of toxic residues in food and environmental degradation. However, the adverse effects of pesticides can be countered through adoption of integrated pest management (IPM), which emphasizes harmonious use of safer and environment friendly methods of pest suppression. The IPM has been our 'Cardinal Policy' for crop protection since 1985 and a lot of efforts have been made to promote its use among farmers so as to minimize pesticide use with the least possible disruption to agro-ecosystems and encouragement to natural pest control mechanisms.

Pest management is a complex system involving many interrelated components such as crop, pests, natural enemies, beneficial organisms and non-target organisms subjected to man's production-oriented interventions under the variable weather (Teng and Savary, 1992). Pest management is known as an ecological approach and works on the premise that all pest population levels are not injurious to crops and crops can always compensate for certain injury due to pests. Moreover, some pest population is always required for the survival of natural enemies of the pests. This has given rise to the concept of economic injury level (EIL), which helps to avoid unwarranted application of control measures, thereby ensuring favourable benefit-cost to farmers. Pest management also underlines that pest control tactics should be socially acceptable and economically viable. Pest management should function as an integral part of 'Integrated Crop Management (ICM) programme as many crop management practices influence pest and natural enemy populations.

Despite continuous efforts, IPM adoption among farming community has not been very satisfactory due to several reasons; a few of these being lack of awareness among various stakeholders, unavailability of non-chemical inputs and lack of holistic modules. Besides, there has been aggravation of pest problems during post green revolution years owing to intensive agriculture in the form of heavily fertilized monocultures with high yielding cultivars and multiple cropping (Kiritani, 1979) and now additionally due to climate change. The number of pest species associated with various crops as well as frequency of pest outbreaks has been on the rise. There is emergence of new pests and several exotic invasive pests have gained entry in to the country.

IPM has the potential to provide effective solutions to obnoxious pest problems. It needs concerted efforts of various agencies to create awareness among growers regarding need for adopting IPM, harmful effects of pesticides and their judicious use. Farmer Field School (FFS) concept, needs to be strengthened and popularized for agro-ecosystem analysis (AESA). Information and communication technology (ICT) and geo-spatial techniques such as remote sensing can be used for e-surveillance and fast monitoring in large areas. Drones based on remote sensing techniques could play an important role in crop stress monitoring and application of agricultural inputs during ensuing years. Pest management information systems (PMIS) should be developed for different crops comprising of IPM algorithm based on pest economic thresholds and management options that could provide pest forewarning and management options based on prevailing pest and weather data. Biosecurity also needs to be revamped through strong quarantine and international collaboration under the provisions of the 'International Plant Protection Convention (IPPC), Regional Plant Protection organizations (RPPO) and National Plant Protection Organization (NPPO). Strong surveillance and communication network will facilitate quick detection of invasive species and their containment. Nowadays, climate change is also being projected to have strong negative influence on biodiversity including aggravation of pest problems and on effectiveness of various IPM tactics such as host plant resistance, bio control agents and pesticides that would necessitate appropriate mitigation and adaptation strategies.

IPM ALGORITHM

IPM is a decision intensive activity and requires tools and techniques for its execution. The algorithm *i.e.* stepwise procedure for implementing IPM thus involves, crop loss assessment, pest risk analysis, development of pest surveillance and forewarning methodology and decision support tools, harmonious integration of management tactics and convergence of various crop protection agencies.

Assessment of crop losses due to pests Assessment and extrapolation of yield losses are mandatory at both the strategic and tactical decision levels. Empirical approach has generally been used for establishing regression damage functions between pest damage and crop yield. These models do not explain the physiological mechanism of yield loss due to pests and thus behave in a location specific manner. This is a weakness common to all empirical regression models (James and Teng, 1979). On the other hand, the assessment of crop losses due to pests, with mechanistic approach, through simulation models is based on the concept of pest damage mechanisms that specify plant physiological processes affected by the pest injury. Major types of pest damage mechanisms are classified as germination reduction, stand reduction, light stealing, assimilation rate reduction, assimilate sapping, tissue consumption and turgor reduction (Rabbinge et al., 1994). Accordingly the pests can be classified as germination reducers like mole crickets and seed maggots; stand reducers such as stem borers, cutworms, termites, damping off and wilts; light stealers such as rusts, blights, mildews and sooty mould; assimilation rate reducers like plant diseases; assimilate sappers such as aphids, plant hoppers, whiteflies, mites, thrips, and bugs; tissue consumers like defoliating beetles, grasshoppers, leaf folders, leaf miners, node borers, grain feeders and foliar diseases such as leaf blight, blast and sheath blight and turgor reducers such as nematodes and root pathogens. InfoCrop, a generic simulation model for annual crops in tropical environments, developed at ICAR-IARI, New Delhi is coupled with pest damage mechanisms and being used for crop protection application (Aggarwal et al., 2004). Simulation models are also capable of addressing injury to the crop due to multiple pests which is very difficult to achieve in field experiments. These models enhance efficiency of field experiments greatly and have great potential for applications in the field of pest management.

Crop-pest simulation models can be used to establish location-specific decision support tools, thereby helping to overcome deficiency of the empirical approach. These models can be easily calibrated and validated for local situations and used to determine location-specific economic injury levels (EILs). Simulation models have been used for simulating EILs for bean leaf beetle infesting soybean (Nordh et al., 1988), Russian wheat aphid damage in winter wheat (Chander et al., 2006), and rice leaf folder (Satish et al., 2007). Likewise, these models can be used to generate iso-loss curves that may be used for pest monitoring, especially crop diseases and need-based management intervention. Iso-loss curve depict different pest incidence levels at different crop growth stages that result in same yield loss. InfoCrop model has been used to formulate EILs and iso-loss curves for rice stem borer (Reji et al., 2008) and brown planthopper (Yadav and Chander, 2010).

Pest surveillance

Pest surveillance can be termed as backbone of IPM as it facilitates timely decision making in regard to interventions based on the existing pest and natural enemy densities. Mostly it has been done in physical inspection mode. However, with the availability of ICT tools, a paradigm shift in the approach has been witnessed. Information and communication technology (ICT) and geo-spatial techniques such as "remote sensing" can be used for e-surveillance and quick monitoring in large areas.

In the recent past, ICT-based system of real time pest surveillance by NCIPM has played an important role in our country in collection and transfer of data from remote villages to main station through web-based portal. The information is compiled and displayed on the website in tabulated and graphical form which can be directly accessed by State Agriculture Department for issue of advisory through SMS to farmers and extension workers for implementation. ICT-based surveillance and advisory has facilitated wide area pest management that is currently being implemented in about 170 lakh hectare in Maharashtra and Haryana in collaboration with State Agriculture Departments through the ongoing programmes, 'Crop pest surveillance and advisory project' (CROPSAP, Maharashtra), 'Horticulture pest surveillance and advisory project' (HortSAP, Maharashtra) and 'e-pest surveillance in vegetables' (Haryana) for surveillance and delivery of the pest management advisories to farmers, resulting in prevention of pest outbreaks (Dhillon and Thind, 2016; Vennila et al., 2016). Many 'Mobile Apps' as information and expert systems along crops and theme areas of crop protection are currently available.

Remote sensing of crop canopies involves measurement of electromagnetic radiation reflected or emitted from plant parts, which are known as spectral signatures. The amount and quality of light reflected from crop canopies are strongly dependent on both the crop species and condition of the crop. Plant pigments, leaf structure and total water content are three important factors affecting spectral reflectance of vegetation. External factors, which influence spectral reflectance of vegetation are: moisture stress, soil nutrients/salinity, pests, seasonal variation and climatic factors. The spectral reflectance of healthy vegetation/crop is characterized by i) high absorption *i.e.* low reflectance in blue and red regions of electromagnetic spectrum; ii) high reflectance in near infrared (NIR) region due to internal cell structure and iii) water absorption bands *i.e.* low reflectance in the mid infrared (MIR) region. Any deviation in reflectance from the above pattern indicates some sort of stress on the crop. High value of reflectance in visible blue and red regions, low reflectance in near IR and high reflectance in mid IR would indicate some stress on the crop. Hyper spectral remote sensing has been used to develop spectral signatures for rice BPH and the pest damage was found to affect the reflectance from plant canopy in visible and mid infrared regions of electromagnetic spectrum, thereby discriminating damaged crop from undamaged crop (Prasannakumar et al., 2013). Biological control is considered as one of the fundamental tactics of IPM but natural enemies are rarely considered in decision making that leads to indiscriminate use of pesticides. The involvement of natural enemy population in decision making through sequential sampling facilitated avoidance of unwarranted pesticide application, thus saving farmers unwarranted expenditure, conserving natural enemy population and preventing environmental contamination (Rajna and Chander, 2013).

Pest zoning is a concept that is particularly applicable for large area pest management (Teng and Savary, 1992) and is accomplished using pest-weather model and geographic information system (GIS). Pest population dynamics model is developed based on long term pest and weather data of a representative site in a region. The model is run with requisite weather data to determine probability of pest outbreak for that site. The site predictions are then extrapolated through GIS to carve out the zones of equal pest outbreak potential in entire region. Knowledge of pest epidemic potential in different zones of a region would allow strategic decisions with respect to selection of crop cultivars and appropriate management options. Historical climate data from sites have been used for analyzing the suitability of a site for specific wheat diseases (Coakley, 1990), while assessment of environmental risk for tomato viruses was undertaken in Arizona using geostatistics and GIS (Teng and Savary, 1992). Likewise, pest zoning has been used for delineation of pest hotspots for rice BPH in Andhra Pradesh (Yadav et al., 2010) and rice leaf folder, *Cnaphalocrocis medinalis* infestation in Haryana (Chander et al., 2004).

There is an opportunity to increase applications of ICT, geo-spatial and simulation techniques, and artificial intelligence (AI) for pest surveillance, diagnostics and forewarning for wide area pest management.

Pest forewarning

In general, both biotic and abiotic factors influence pest dynamics, but insects being poikilothermic organisms are affected more by abiotic factors and pest outbreaks are thus often associated with the congenial weather conditions. Weather-based fore warning systems have proved useful in case of desert locust, and potato and grape pests. Rule-based decision tools for location specific forewarning of rice insect pests; *Spodoptera litura* on groundnut; early blight of tomato (*Pestpredict*-RBS); empirical models (*Pestpredict*-EMS) for rice, pigeonpea, groundnut and tomato insects and diseases have been developed as mobile Apps. However, their utility would depend on thorough validation for issuing reliable agro advisories. In view of the changing scenario both of weather and pests, there is need for development of new tools as well as refinement of the existing weather based early warning systems (Kumar et al., 2015). Climatic variability in respect of monsoon rainfall was observed to significantly influence rice BPH population and more than 30 rainy days during June to September months resulted in the pest outbreaks with >75% probability (Chander and Husain, 2018).

Impact of climate change on pests has been analyzed through empirical models but these studies being location specific are limited in their application (Coakley et al., 1999). Process based crop-pest simulation models are thus more suited for this purpose. Mechanistic insect population simulation model have been developed based on various bio-ecological factors of a species viz., fecundity, sex ratio, migration, abiotic and biotic mortality factors, development thresholds and thermal constants (Reji and Chander, 2008; Sujithra and Chander, 2013; Selvaraj and Chander, 2015). Simulation models facilitate understanding of factors affecting outbreak and damage caused by pest as a component of crop ecosystem and detect the crucial knowledge gaps in view of a holistic assessment of pest status (Graf et al., 1992). Coop et al. (1989) developed GHLSIM modeling system to provide decision makers a means of estimating feeding injury and economic losses by *Oedaleus schegalens* in millet and sorghum grown in semi-arid regions. Further, these models were linked to the InfoCrop crop simulation model and the crop-pest model could be used to analyse climate change impact both on pest dynamics and crop-pest interactions (Sujithra and Chander, 2013; Selvaraj and Chander, 2015).

INTEGRATION OF IPM TACTICS

IPM modules for various crops are based upon integration of resistant cultivars, cultural, mechanical and physical methods, natural enemies, biopesticides and pesticides to suppress pest population without jeopardizing the environment. Any pest management programme should be, preferably based upon, utilization of resistant cultivars, cultural control and natural enemies and other control methods blended together for tackling pest menace.

Host plant resistance

One of the fundamental pillars of pest management is the host plant resistance (HPR). Germplasm diversity has been exploited for development of varieties and hybrids in different crops. Preference should be given to the cultivation of resistant cultivars because their use greatly reduces need for other methods of pest control. The resistant cultivars enhance the efficiency of some natural enemies against the pests as there is more predation of spiders against plant hoppers on moderately resistant rice cultivars than susceptible varieties and these are also compatible with cultural methods of pest suppression. Likewise, the need for pesticide application is greatly reduced on moderately resistant cultivars. A number of cultivars resistant/tolerant against various pests of rice have been developed (https://icar-nrri.in/wp-content/uploads/2020/01/Rice-Varieties-of-NRRI.pdf). Recently, ICAR-IARI, New Delhi has released basmati cultivars, Pusa Basmati 1847, Pusa Basmati 1885 and Pusa Basmati 1886 that are resistant against bacterial leaf blight (BLB) and blast (https://www.pib.gov.in/PressReleseDetailm.aspx?PRID=1863885). Commercialization of *Bt* transgenic cotton hybrids since 2002 followed by Bollgard-II double gene technology in 2006, has been a standalone HPR attempt against bollworms of cotton and it brought down insecticide usage by 69%. India has gained considerably through the commercialization of Bt cotton hybrids covering around 11m ha and benefitting millions of farmers through doubling of productivity, thereby making India a leading cotton export nation fetching around USD 3 billion annually. However, unregulated release of highly susceptible Bt hybrids led to white fly outbreak in North India in 2015, following which Bt hybrids having some tolerance to white fly are being recommended for cultivation (http://aiccip.cicr.org.in/main_aiccip_achievements.html). In recent years, Bt resistant pink bollworm populations have emerged in various parts of the country that calls for its effective management. Continuous cultivation of resistant cultivars has caused biotype development in some insects. Biotypes of brown plant hopper and gall midge have developed due to cultivation of monogenic resistant varieties of rice. Breakdown of temperature-sensitive resistance under increased temperature under climate change may also lead to more rapid evolution of pest biotypes. Sorghum varieties that were resistant to sorghum midge, Stenodiplosis sorghicola in India became susceptible to the pest under high humidity and moderate temperatures in Africa (Sharma et al., 2010). Biotype emergence can be averted through rotational cultivation of monogenic resistant cultivars and breeding of polygenic resistant cultivars. Likewise, in context of climate change, thermo-tolerant sources of resistance against pests need to be explored.

Cultural, mechanical and physical tactics

Routine agronomic practices are utilized as preventive method for minimizing pest infestation, by slight modification in timing or method of their application. Destruction of crop residues helps to prevent carryover of pest to next season crop in case of pumpkin beetle in cucurbits, pink bollworm in cotton, painted bug and white rust in mustard-rapeseed and stem borers in rice, maize and sorghum. Deep ploughing of fields exposes the soil inhabiting stages of pests such as army worm, cut worms, borers and white grubs, termites and mole cricket to vagaries of nature and thus reduces their infestation in crops. Likewise, summer deep ploughing reduces incidence of early blight in mustard, nematodes in wheat and exposes the inoculum of soil borne pathogens like *Fusarium oxysporum*, *Macrophomina phaeseolina* in chickpea. The raking of rice field bunds destroys egg pods of grasshopper. On the other hand, zero tillage had higher infestation of pink stem borer, Sesamia inferens in wheat irrespective of early or late sowing (Beant, 2012).

The change in sowing/planting time is aimed for disturbing synchrony between host and pest populations. Early planting (June-July) results in low populations of BPH in rice (Chander et al., 2020) and early sowing of cucurbits escapes the attack of pumpkin beetle. Likewise, mustard sown by mid-October escapes aphid attack, but is prone to attack by painted bug (Chander and Gujar, 2014). However, early sowing of mustard with treated seed helps to ward off problems of painted bug as well as aphids. Early planting of pigeon pea by mid-June in North West Plain Zone avoids *H. armigera.* Early sown wheat crop had higher incidence of aphids during ear head stage compared to normal or late sown crop (Chander et al., 2016). As far as possible, crops should be planted around the same time in a locality as staggered planting increases pest incidence. Global climate change would cause alteration in sowing dates of crops, which may alter host-pest synchrony. There is thus need to explore changes in pest-host interaction due to agronomic management adaptations to be adopted under climate change.

Intercropping helps in reducing incidence of certain pests by making microclimate less favourable for them and hindering their free movement among the plants of same species. Tomato intercropped in cabbage against diamondback moth, African marigold intercopped in tomato against fruit borer *Helicoverpa armigera,* and Napier grass as trap crops against stem borer *Chilo partellus* in maize and sorghum have proved very effective for pest suppression. Intercropping with sorghum in pigeon pea, urdbean and moong bean reduces wilt, conserves beneficial insects and serves as perch for insectivorous birds.

Crops sharing the same pest fauna should not be grown in a rotation. In rice-wheat cropping system, the incidence of pink borer and root knot nematode has increased. Rotating rapeseed-mustard with wheat/ onion helps in management of *Sclerotinia* blight in mustard and nematodes on the cereals. Trap crops provide protection by preventing the pests from reaching the main crop. The trap crop must be more attractive to the pests and less economical than the main crop. Mustard as trap crop with cabbage reduces the incidence of diamond back moth, leaf-webber, web worm and aphids. Marigold planted with tomato as a trap crop is highly effective against fruit borer and root knot nematodes. Likewise, marigold can be used as a trap crop in pigeon pea, chickpea on border or interspersed with crop for pod borer management.

Excess use of nitrogen intensifies incidence of several pests such as planthoppers and leaf folder in rice (Chander, 1999) and the rust disease in wheat and thus balanced application of fertilizers should be ensured. However, farmers often apply only nitrogen and not phosphorus and potash. Potash induces resistance in plants against pests. Likewise, excess use of water should also be avoided. In rice, continuous flooding of field has been found to be as good as alternate wetting and drying. Drying of field at some intervals is helpful in reducing incidence of planthoppers in rice. Timely irrigation in summer/ spring crop of urd bean and moong bean avoids thrips damage. Optimum use of nitrogen and water would also reduce emission of nitrous oxide and methane, both very important greenhouse gases, from rice fields. Crops should be harvested at the optimum time and in a manner that pests inside the stubbles get destroyed. The harvesting of rice at ground level destroys larvae of stem borer, thereby reducing pest survival for the next season

The removal of infested plant parts and conspicuous pest stages manually or mechanically can reduce pest incidence to a certain extent. Clipping of rice seedling tips before transplanting reduces incidence of yellow stem borer and hispa. Dead hearts, whiteheads, silver shoots, aphid-infested shoots, and bored fruits of brinjal and lady finger should be picked and destroyed. Collection and destruction of egg masses of *Spodoptera frugiperda*, egg masses and skeletonized leaves along with early instar larvae of hairy caterpillars and S*podoptera litura* proved very effective. White rust infected mustard-rapeseed plants and wheat plants diseased with smut should be burnt.

The use of nets as physical barriers to cover nurseries of tomato and chillies to protect against transmission of virus by whiteflies has proved effective. Yellow sticky traps are deployed for monitoring and mass trapping against whiteflies, whereas blue sticky traps are often installed in poly houses for management of thrips. Likewise, light traps have been particularly important in monitoring the seasonal appearance of many species of moths, hoppers and beetles. Advanced insect light trap technology viz. 'Light trap safer to beneficial insects' for mass trapping of selective phototrophic macro-lepidopteran insect pests has been developed that facilitates escape of beneficial insects and non-targeted insect fauna through a porous filter chamber (Singh, 2015). The technology in being used by different organizations in various states of the country.

Biological pest suppression

There is a rich diversity of natural enemies viz. predators, parasitoids and pathogens in fields which helps to reduce pest incidence, if not harmed by broad spectrum pesticides. The egg parasitoid, *Trichogramma* spp. are very effective against stem borers, fruit borers and bollworms. Predators such as coccinellids, syrphids, spiders, dragon flies, ground beetles and rove beetles etc., also devour pest populations in the field. The vertebrate predators like fish, ducks and frogs also consume pests in rice ecosystems. Likewise, several native hymenopteran parasitoids and pentatomid bug predators *viz*., *Eocanthecona furcellata* and *Andrallus spinidens* in maize ecosystem exhibited scope of natural bio control of fall armyworm (FAW). *Epiricania melanoleuca*, a parasitoid of *Pyrilla perpusilla* and the ichneumonid, *Isotima javensis* a parasitoid of sugarcane top borer, *Scirpophaga excerptalis* have been found effective.

Growers must differentiate between pests and useful insects and should conserve the useful ones. Efforts should be made to enhance natural enemies by providing artificial foods and shelters. Ecological engineering can be practiced through planting of flowering plants on field bunds, creating hedges of flowering plants and ensuring water availability to vertebrate predators such as birds on the farm, thus creating favourable environment for useful organisms. Likewise, suitable intercropping can be used to discourage pests and encourage natural enemies.

Beneficial nematodes, a large array of fungi, viruses, and bacteria have been developed for greenhouse, turf, field crop, orchard and garden use. Neem (*Azadirachta indica*)-based pesticides, *Bacillus thuringiensis* (Bt), Nuclear Polyhedrosis Virus (NPV) and *Trichoderma* species are some of the major bio-pesticides produced and used in India. Bio pesticides do not pose the regulatory problems as seen with chemical pesticides. They are often target-specific, safer to beneficial insects, do not cause air or water contamination, and crops can be visited soon after treatment. Naturally occurring microbes can be used in organic production as human health risks are low due to them. There is a need to explore local strains of such microbes and develop efficient mass rearing techniques.

Success stories of bio-pesticides in India include suppression of diamondback moths by *Bacillus thuringiensis;* mango hoppers, mealy bugs and coffee pod borer by *Beauveria; Helicoverpa* on cotton, pigeonpea, and tomato by *Bacillus thuringiensis; Helicoverpa* on chickpea by HaNPV; whitefly on cotton by neem products; Sugarcane borers by *Trichogramma*; root rots and wilts in various crops by *Trichoderma*-based products. In India, the use of bio pesticides witnessed significant growth from 123 tonnes in 1994-95 to 8110 tonnes in 2011-12 and 9108 tonnes in 2021-22. However, still there is considerable gap between demand and supply of pesticides, which needs to be urgently bridged to reduce dependence on chemical pesticides in the country.

Several efforts have been made to contain invasive species through biological control. Under classical biological control, examples of pest suppression with imported natural enemies include the parasitoid, *Acerophagous papayae* against papaya mealy bug, *Paracoccus marginatus* (2010); parasitoid, *Quadrastichus mendeli* against eucalyptus gall wasp, *Leptocybe invasa* (2018); parasitoid, *Encarsia guadeloupae* against coconut rugose spiraling whitefly, *Aleurodicus rugioperculatus* (2019). The latest introduction has been the parasitoid *Anagyrus lopezi* from Benin for the control of cassava mealy bug in Tamil Nadu and Kerala during 2021 (Sampathkumar et al*.,* 2021).

Augmentative releases of laboratory reared bio control agents are also made for pest suppression. Mass production protocols have been developed for predators, parasitoids and pathogens. Multiple insecticide and high temperature tolerant strains of the egg parasitoid, *Trichogramma chilonis*, pesticide tolerant strain of predator *Chrysoperla zastrowi sillemi*, formulations of entomopathogenic nematode *Heterorhabditis indica* for the biological control of white grubs and other soil insects and indigenous *Bacillus thuringiensis* liquid formulations against many lepidopteran crop pests have been the technologies promoted for agribusiness in biocontrol.

The application of broad-spectrum pesticides poses greatest hazard to the natural enemies of pests. The preference should be given to bio pesticides and selective pesticides, which do not harm non-target organisms. Since discovery of antifeedant activity of neem seed kernel extract against desert locust (Pradhan et al., 1962), significant progress has been made in research and development of azadirachtin based bio pesticides. In the absence of selective pesticides, even non-selective pesticides can be applied to achieve same purpose through suitable formulations. The granular formulations of pesticides pose less threat to natural enemies of pests.

Non-availability of IPM inputs such as bio control agents, bio pesticides and pheromone traps are considered as one of the main hurdles in adoption of IPM by farmers. The availability of bio pesticides and bio control agents can be ensured by creating entrepreneurship in their mass production among rural youth and farm women. This calls for exploration of more potent local strains of natural enemies and development of efficient mass production technology. Different organizations such as ICAR Institutes, SAUs, KVKs, NGOs and private agencies should converge to make concerted efforts for creating awareness about IPM and to enhance availability of IPM inputs to farmers in mission mode.

Behavioural methods

The behaviour of the insects can be exploited for their monitoring and management (Heinz et al., 1992). These methods involve the use of behavioural chemicals, mainly sex pheromones in management of pests. Female sex pheromones of important pests such as *Helicoverpa armigera,* (Helilure); *Spodoptera litura*, (Spooler); *Earias vittella*, (Eri-vitlure); *Pectinophora gossypiella*, (Gossyplure); *Scirpophaga incertulas*, (Scirpolure), and *Leucinodes arbonalis*, (Leucinlure) etc. are being widely used for pest suppression. Attract and annihilate technique using lures effectively controls fruit flies too in vegetable and fruit crops. Pheromones are also used for mating disruption with delivery mechanism such as traps or ropes or specialized pheromone and lure application technology (SPLAT) formulation against *P. gossypiella* in Bt cotton ecosystem (Sreenivas et al., 2021). At present availability of pheromones is not sufficient in the country and serious efforts are required to bridge the gap between demand supply of these important pest management tools. Use of nano-technological approaches in delivery of the semio-chemicals is expected to improve use of sex pheromones for monitoring, mass trapping and mating disruption.

Chemical methods

Pesticides have a definite role to play in pest management. However, their application should be need-based and in a judicious manner. The pesticide consumption can be greatly reduced and these can be made safer to environment by adopting improved techniques and proper timing of application e.g. plant hoppers are controlled more effectively if spray is directed at the base of rice plant. The economic threshold based (ETL) based pesticide use causes substantial reduction in pesticide requirement. In pest infestation begins in nursery then it should be nipped there itself because it is easier to manage pests at a small scale and this will also not pollute the environment. Seed treatments can play important role in ensuring minimum use of pesticides and also preventing environmental contamination and harmful effects on non-target organisms, besides being very economical. Seed treatment can be done with pesticides/bio pesticides. Natural enemy cum beneficial fauna such as coccinellids, spiders and Chrysoperla, pollinators and honey bees remain unharmed due to seed treatment (Birah et al., 2014). Many of newer pesticides are in general required at lower dosage than conventional pesticides and therefore care should be taken in this regard. Care should be taken not to repeat application of the pesticides with same mode of action to avoid insecticide resistance in pests, rather pesticides with different mode of action should be used in rotational manner. Preference should be given to bio-rational compounds such as bio-pesticides. Waiting periods of pesticides should also be observed earnestly. There is a need to further strengthen the IPM adoption in Indian agriculture to overcome the prevailing three evil “Rs” (Resistance, Resurgence, and Residues). Climate change could affect efficacy of crop protection chemicals through changes in temperature and rainfall pattern, as well as morphological and physiological changes in crop plants (Coakley et al., 1999). The pesticide application rates thus may need to be revisited according to new situations.

Pesticides should only be used at their recommended doses according to label claim. A total of 299 pesticides have been registered in India as on July, 2021. As pesticides have not been registered against pests on all crops, farmers often use off-label products that have implications for food safety and export. Government has taken important step by way of grouping of crops and commodities (554 numbers) in accordance with the codex classification and guidelines for label expansion in respect of maximum residue limits (MRL). Draft notification of 2020 on ban of 27 pesticides including 12 insecticides is still under review. The adoption of IPM tactics in conjunction with pest surveillance and forewarning will help to reduce dependence on pesticides and manage pests in an eco-friendly and sustainable manner.

CONCLUSIONS

Agricultural organizations in NARES, such as ICAR Institutes, SAUs, KVKs and State Departments that address the issue of plant health management need to converge in a mission mode to disseminate IPM throughout the country. Integrated pest management needs to evolve continuously by assimilating innovations in bio/nano technology, ICT and geo-spatial technology for improving its effectiveness and dissemination. The judicious use of pesticides must be ensured and conservation and enhancement of natures' gift of bio agents for pest suppression should be the fundamental approach. Likewise, large scale production of bio agents/biopesticides through entrepreneurship development in rural youth and women is needed to supplement their less availability in the country, besides creating employment avenues. IPM spread in the country will produce multiple benefits of reduction in production cost, mitigation of pesticide residue problem in food, and promotion of exports, thereby enhancing farmers' income, besides preventing environmental contamination and conserving biodiversity.

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