Pest Management in 21st Century: Roadmap for Future

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ABSTRACT The twentieth century has witnessed rapid strides in the development and refinement of various biopesticide based pest management tactics, viz. bacteria, fungi, viruses, nematodes, natural plant products, etc. However, there is still ample need for the models which are easily accessible, convenient to develop and could be economically commercialized. Though to achieve this involves complex processes, yet it is obvious that concrete structured strategies need to be planned that require a complete roadmap for the development and commercialization of biopesticides. The advent of gene technology has added a new dimension to pest management on one hand but on the other it has generated several socioeconomic, ecological and ethical issues. Integrated pest management (IPM) programmes have been developed for various agricultural crops, but their widespread adoption at the farmers' level remains far from satisfactory. Therefore, what is required is to select an appropriate agent which has the potential to control the pest; to investigate the feasibility of the product on the larger scale; to maintain the quality control; to strategize the implementation protocols in any IPM model and finally the commercialization. The effort through this review is to discuss all these aspects in order to draw a future roadmap to achieve sustainable crop protection in the twenty-first century.

KEY WORDS : Integrated pest management, biopesticides, biocontrol, transgenic crops, semiochemicals, roadmap

INTRODUCTION

According to the United Nations *World Population Prospects-the 2008 Revision* (UN, 2009), the population data and projections suggest three alternative scenarios. World population is projected to grow from the 6.6 billion of the base year to 8.0, 9.15 and 10.5 billion in 2050 under the low, medium and high projections, respectively (Fig. 1). Accordingly, medium projection indicates that a rather drastic slowdown in world demographic growth is in prospect. The growth rate of world population peaked in the 1960s at 2.0% per annum and had fallen to 1.2% per annum in the decade ending in 2010. Thus, further deceleration should bring it down to 0.4% per annum by 2040-50. However, according to the medium variant projection, world population is expected to peak around the year 2075 at 9.4 billion and then start declining slowly to 9.2 billion by 2100. Interestingly, in the latest 2010 revision of the UN population projections, world population will continue to grow past 2075 to reach 10.12 billion by 2100 (UN, 2011). Obviously, there is no respite from expected population explosion and subsequently the need for higher productive agricultural inputs is required. In terms of food production, the data available suggest that world food production grew faster than population (Dhaliwal and Koul, 2010; Dhaliwal *et*

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al., 2013) and per capita consumption also increased, i.e. there was improvement in human food consumption of 2770 kcal/person/day in 2005/2007 (Alexandratos and Bruinsma, 2012). Therefore, this would imply that apparently everyone is well fed globally. But this is not true. It is well known that about 2.3 billion people live in countries where consumption is under 2500 kcal, and some 0.5 billion people consume less than 2000 kcal. The reasons are fairly well known: mainly poverty, which has many facets; in many low-income countries the situation is linked to failures to develop agriculture and in others there is limited access to food produced (Alexandratos and Bruinsma, 2012). Overall, crop production is based on improved varieties and strategic application of fertilizers and management of diseases and insect pests along with conservation measures. Therefore, pest management is an important component of agriculture where a healthy crop can provide high yield that can feed the ever growing populations. The question, however, is that do we follow specific integrated pest management (IPM) models or are they really ecologically based or based on area wide concept?

PERSPECTIVES IN PEST MANAGEMENT

Pest management may be considered an intelligent selection and use of pest control actions that will ensure optimal economic, ecological and sociological benefits. Pest management action without knowing if it is economically sound is disastrous. Treating a pest needlessly is not conducive to making a profit. Other values such as aesthetics of the management situation (pertinent to landscapes, indoor settings), and environmental and social costs (e.g., clean-up of water sources, pesticide disposal, medical costs for workers, etc.) can play major roles in pest management decision-making. This requires proper tools that would aid the pest manager in making economically sound decisions. Initially emphasis was on production agriculture and cost: benefit analyses. Then as landscape and urban pest management evolved, so did attempts to consider not only economic profits, but the aesthetic value of pest control as well. Recent efforts have focused on incorporating costs to the environment and society from pest control practices. Thus came the concept of economic-injury

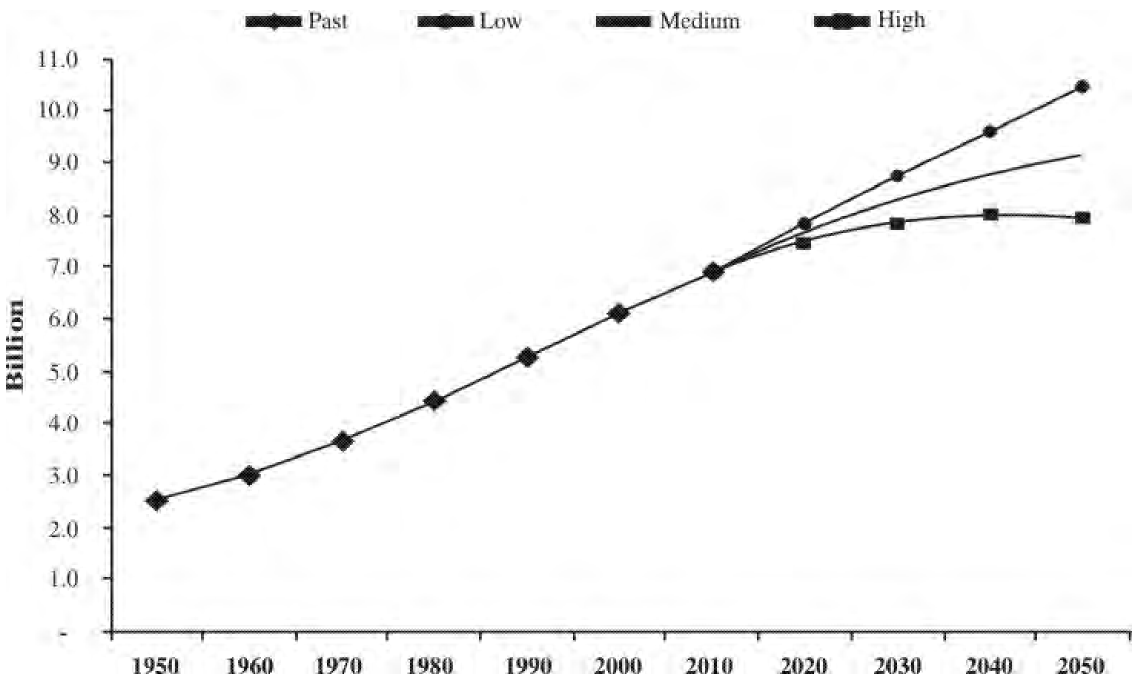

Fig. 1. World population from 1950 to 2010 and three variant projections (*Source*: UN, 2011)

level (EIL), i.e. having the lowest population density of a pest that will cause economic damage or the amount of pest injury which will justify the cost of control, which is based on simple equation:

EIL = (C/V) (1/L), where

C = pest management costs; V = market value of product; and L = loss caused to product (loss per unit measure per pest)

In fact, the EIL concept was developed hand-in-hand with the IPM concept which according to FAO definition means the "careful consideration of all available pest control techniques and subsequent integration of appropriate measures that discourage the development of pest populations and keep pesticides and other interventions to levels that are economically justified and reduce or minimize risks to human health and the environment" (FAO, 2003). IPM emphasizes the growth of a healthy crop with the least possible disruption to agroecosystems and encourages natural pest control mechanisms. IPM is the coordinated use of pest and environmental information with available pest control methods to prevent unacceptable levels of pest damage by the most economical means and with the least possible hazard to people, property and the environment (EPA, 2007). The idea is to rely on multiple strategies that would fit in organic farming on one hand and on the other can reduce the human and environmental exposure to chemical pesticides and also potentially lower overall costs of pesticide applications. The whole strategy is based on four major perspectives, i.e. identification of control agent, health risks, environmental risks and bioefficacy. In fact, multi-thronged approach is required. It is necessary to use resources to keep up-to-date on IPM developments. Researchers are always discovering new techniques, and ways to improve old techniques, therefore, an appropriate combination of management tactics is necessary. For any pest situation, there will be several options to consider. Options include mechanical or physical controls, cultural controls, biological controls and chemical controls. Mechanical or physical controls include picking pests off plants, or using netting or other material to exclude pests such as birds from grapes or rodents from structures. Cultural controls include: keeping an area free of conducive conditions by removing or storing waste properly, removing diseased areas of plants properly, late water floods, sanding, and the use of disease-resistant varieties (Sandler, 2010). Chemical controls in IPM would include pesticides derived from plants, such as botanicals, or other naturally occurring materials. Biological controls are numerous. It can be the pest control using microbials (Ravensberg, 2011). They can also include conservation of natural predators or augmentation of natural predators and sterile techniques (SIT) (Klassen and Curtis, 2005). Augmentation, inoculative release and inundative release are different methods of biological control and all affect the target pest in different ways. Augmentative control includes the periodic introduction of naturally occurring predators in sufficient numbers to keep pest damage below economoic damaging levels (Mills and Daane, 2005; Dhaliwal and Koul, 2007).

PARASITOIDS AND PREDATORS

Beneficial insects are often referred to as natural enemies, and by their mode of action against pests they can be grouped as predators or parasitoids. Predators feed on multiple preys over their lifetime, often killing their prey. Parasitoids utilize a single host during their lifetime and usually kill the host when they leave to pupate or when they emerge from the host as adult insects. There are two styles of parasitoids:

(i) Idiobionts, which attack eggs, pupae, or adults and are unable to grow after they are parasitized. They are either external parasitoids and kill hosts or internal parasitoids of pupae and adults that face immune counterattack e.g. Eulophid *Sympiesis marylandensis* Girault on apple blotch leafminer, *Phyllonorycter crataegella* (Clemens)

(ii) Koinobionts are the parasitoids which permit their hosts to continue to grow after oviposition thereby increasing the resource for progeny. They are larval and nymphal parasitoids and should defeat host immune system, e.g. *Pieris rapae* (Linnaeus) parasitized by *Cotesia rubecula* (Marshall)

Despite this increasing awareness and interest in natural enemies, many of them remain obscure or poorly known to the agricultural community, and their impact is sometimes similarly under appreciated. The natural enemies of insect pests are responsible for an estimated 50–90% of the biological pest control occurring in crop fields (Pimentel, 2005). Biological control is a result not only of enemy diversity and abundance, but also of the trophic interactions occurring between enemies (Koul and Dhaliwal, 2003; Tylianakis *et al*., 2007; Straub *et al*., 2008). If these interactions vary according to the landscape context, then understanding ecosystem service variability requires understanding the variations of trophic interactions at multiple spatial scales (Tscharntke *et al*., 2012). It has been estimated that only 15% of natural enemies of insect pests have so far been identified. Parasitoids belonging to the insect order Hymenoptera have been involved in about 66% of all successful biocontrol programmes. Most of the common predators occur in insect orders Coleoptera, Hemiptera and Neuroptera. In addition, there are several species of mites and spiders feeding on a wide range of insects and mites. More than 125 species of natural enemies are commercially available at global level for augmentative biological control programmes, including 37 commonly used species such as the moth egg parasitoid, *Trichogramma* spp.; whitefly parasitoid, *Encarsia formosa* Gahan, and the spider mite predator, *Phytoseiulus persimilis* Athias-Henriot. The potential of classical biocontrol has been demonstrated in Africa where the cassava mealybug, *Phenacoccus manihoti* Matile-Ferrero, has been virtually eliminated in 30 countries, by the exotic parasitoid, *Epidinocarsis lopezi* (De Santis) (Srivastava and Dhaliwal, 2010).

Cropping systems can be altered successfully to augment and enhance the effectiveness of natural enemies. Optimal microclimatic conditions, nectar sources, and alternate hosts may exist in some cropping systems, but not in others. Physiochemical characteristics of the host plants also play an important role in host specificity of both the insect hosts and their parasitoids. The average rates of parasitism of the eggs of *Helicoverpa armigera* (Hubner) (mainly by *Trichogramma* spp.) have been found to be 33, 15 and 0.3% on sorghum, groundnut and pigeonpea, respectively. Parasitism of *H. armigera* eggs by *Trichogramma chilonis* Ishii on tomato, potato and lucerne was observed to the tune of 98%. However, no egg parasitism was recorded on chickpea, probably because of the acid exudates secreted by the leaves. Therefore, due consideration should be given to the host plant and the species of the parasitoid involved while planning for biological control of insect pests (Sharma, 2009).

Parasitoids and predators can provide long term regulation of pest species provided proper management practices are followed to make the environment conducive to furthering their abundance and efficiency in target agroecosystems. Biological control can potentially become a self-perpetuating strategy, providing economic control with the least environmental hazards. However, much work needs to be done to optimize the utilization of parasitoids and predators in integrated pest management.

- There is an urgent need to establish a network of large scale multiplication units so that the natural enemies are available to the farmers at reasonable prices. A new industry of mass propagation of natural enemies is born as costs of mass rearing are reduced, making this process commercially competitive. As the technology of mass propagation of natural enemies develops, more arthropod pest species will become amenable to biological control.
- Heat-and cold-tolerant strains have to be selected/developed in the case of a number of natural enemies. The environmental implications of releases of these organisms, especially in cases of introductions and genetically engineered organisms should be investigated.
- One frequent explanation for the failure of biological invasions is the Allee effect due to positive density dependence, initially small invading populations may fail to establish and spread. Populations released for biological control are similar to fortuitous invading populations and may, therefore, suffer from Allee effects. Thus, it is important to look into this aspect in 21st century and it is possible because

biological control allows the experimental manipulation of initial population size and offers a unique opportunity to test for the occurrence of Allee effects. Some studies are known in this regard where population manipulations of parasitoids changed the dynamics and suggested an absence of Allee effects but clear negative density dependence. Such studies are apparently the first experimental evidences of the Allee effect in an invading parasitoid which also implies that a number of behavioral and life-history features of many parasitoids could protect them from Allee effects. This aspect is very well reviewed in some recent publications (Fauvergue, 2013; Matter and Roland, 2013).

- Major improvements in biological control of insect pests can be made through habitat management. Increasing genetic diversity could provide useful means of augmenting natural enemy populations. However, the response varies across crops and cropping systems. Therefore, appropriate cropping systems should be identified for specific predators and parasitoids to increase their efficacy.
- Over the course of evolutionary time, insect parasitoids have developed diverse strategies for using chemical compounds to communicate with various protagonists within their environment. Unraveling the evolutionary meaning of such chemical communication networks provides new insights into the ecology of these insects and contributes to improving the use of parasitoids for the control of insect pests in biological control programmes. The significant knowledge and discoveries made over recent decades, and their potential uses in pest control (Wajnberg and Colazza, 2013) needs to be considered strategically in natural enemy based programmes.
- A concept of development of Entomophage Parks could become the raodmap for 21st century, i.e. to develop undisturbed habitats of natural vegetation near agricultural areas to protect and enhance specific natural enemies and provide them with resources such as nectar, pollen, physical refuge, alternative prey, alternative hosts and mating sites. This will improve natural enemy fitness and effectiveness (Gupta *et al.*, 2012). Both entomophage diversity and abundance in these parks will enhance the fecundity and survival of parasitoids and will also maintain the biodiversity of natural enemies and thereby enhance natural pest control.
- Landscape complexity is known to benefit natural enemies, but recently, it has been shown that natural enemy interactions constrain pest control in complex agricultural landscapes (Martin *et al.*, 2013) as the control at the landscape scale is driven by differences in natural enemy interactions across landscapes, rather than by the effectiveness of individual natural enemy guilds. Therefore, it is inevitable to be careful in handling the biodiversity of natural enemies within a multiple ecosystem that will predict the functional consequences of landscape-scale changes in trophic interactions.

MICROBIAL BIOPESTICIDES

So far, over 3000 microorganisms have been reported to cause diseases in insects. However, scientists familiar with specific pathogen groups agree that a very large number of insect pathogens remain undiscovered or unidentified. More than 100 bacteria have been identified as arthropod pathogens, among which *Bacillus thuringiensis* Berliner (Bt) has received the maximum attention as microbical control agent. Viruses have been isolated from more than 1000 species of insects from 13 different insect orders. World over, about 525 insect species in 52 families and 8 orders are known to be infected by nuclear polyhedrosis virus (NPV) and of this large number of species, 455 belong to Lepidoptera. Till now, over 800 species of entomopathogenic fungi have been identified. More than 1000 species of protozoa pathogenic to insects have been described and many more remain to be discovered. The two major groups of entomopathogenic nematodes are *Steinernema* (55 species) and *Heterorhabditis* (12 species) (Koul, 2011; Dhaliwal *et al.*, 2012).

The world's largest programme for the use of an entomopathogen to control a pest on a single crop involved the management of soybean caterpillar, *Anticarsia gemmatalis* (Hubner) by its nucleopolyhedrovirus (AgNPV) in Brazil. In pilot scale field trials with AgNPV, reductions of over 80% of *A. gemmatalis* larval populations were obtained. The virus is presently used on 2.0 million ha soybean in Brazil and it is expected that its use may increase to 4–5 million ha/year within 5 years. Although the microbical pesticides account for about 1.0–1.5% of global pesticide sales, microbial control of pests is gaining importance. The use of microbial pesticides is growing at a rapid rate of 10–25% per year. *B. thuringiensis* has been the principle target of product development. There are 67 registered Bt products with more than 450 formulations. Formulations based on Bt account for nearly 90% of the total biopesticide sales worldwide, with annual sales of nearly US$ 90 million (Koul and Dhaliwal, 2002; Dhaliwal and Koul, 2010).

In spite of their great potential, there are several constraints in the use of microbial pesticides, which require a focus in the future. Depending upon the country, registration of a microbial pesticide is a lengthy and expensive procedure. Microbial pesticides are widely used in South and Central America. While it is difficult to register products based on non-indigenous microorganisms, the regulatory regimes in these regions are largely founded on the presumption that "these are naturally occurring, indigenous organisms are much safer than the pesticides they replace" (Jaronski *et al*., 2003). This is also the case in Cuba and some Asian countries, where government regulatory objectives emphasize protecting consumers and farmers without stifling the thriving local industries that produce the products.

A new approach being considered in Europe is Qualified Presumption of Safety (QPS) (Todd *et al*., 2010). The concept has been accepted by the European regulatory agency, the European Food Safety Authority (EFSA) as a guiding principle for evaluation of microorganisms for a variety of purposes, including plant protection products. This scheme has 2-fold benefit, i.e. concentrate on microorganisms with least threat to human health or the environment and second, reducing the time period of development that can stimulate the marketing of microbial products. The granting of QPS status is dependent on a microorganism's characteristics in four areas: i) its taxonomic grouping; ii) their safety; iii) pathogen information and iv) the intended end use (Todd *et al*., 2010). The specificity of microbes within limited numbers could capture umpteen applications.

Owing to the early successes and continuing growth of biopesticide market, expectations for the performance of microbial biopesticides are quite high. However, there are many challenges that will need to be overcome so that the self-perpetuating nature of most of the microbial pathogens may prove to be an asset in sustainable agriculture.

- In order to increase the utility of microbial pesticides in IPM programmes, systematic surveys are required in different agroecological regions to identify naturally occurring pathogens. Detailed studies are necessary on the properties, mode of action and pathogenicity of such organisms.
- Ecological studies on the dynamics of diseases in insect populations are necessary because the environmental factors play a significant role in disease outbreaks and ultimate control of the pests.
- There is a need to develop and standardize mass production technologies of microbial biopesticides in order to solve potential problems associated with contamination, formulation potency, alternation of pesticidal activity and shelf-life.
- Suitable formulations should be developed to increase their residual activity and improve shelf-life. Commercially dry formulations are preferred over liquid formulations. Lyophilization and encapsulation should be explored to produce stable formulations with persistent toxicity. The use of formulations that include stilbene-derived optical brighteners, increase efficiency of NPV formulations.

- The relatively slow speed with which microbial pathogens kill their host has hampered their effectiveness as well as acceptance by potential users. Genetic improvement with conventional and biotechnological tools would lead to the production of strains with improved pathogenesis and virulence.
- Regarding the regulatory aspects there are global contradictions. However, Laengle and Strasser (2010) developed an indicator of environmental risk which can be used to rate both microbial and conventional pest control products, and could facilitate and streamline the introduction of microbials to the market, which can be generalized. Their method generates a single numerical score to represent the environmental risk of each product. The score is based on five separate criteria: persistence, dispersal potential, the range of non-target organisms affected, direct effects, and indirect effects. These criteria could become the stepping stone in 21st century to generalize the regulatory procedures globally.

BOTANICAL BIOPESTICIDES

The use of plants and their crude extracts for the protection of crops and stored products from insect pests has been a part of traditional agriculture for generations. Neem leaves and kernel powder have been traditionally used by farmers against pests of household, agricultural and medical importance. More than 6000 plant species from at least 235 plant families have been screened for pest control properties. A large number of plant products derived from neem, custard apple, tobacco, pyrethrum, etc. have been used as safer pesticides for pest management. Some most promising phytochemicals having anti-insect properties include isobutlyamides, limonoids, quassinoids, naphthoquinones, rocaglamides, sugar esters, etc. (Dhaliwal and Koul, 2007). Phytochemicals from Meliaceae family have shown remarkable feeding deterrency, repellency, toxicity, sterilant and growth disruptive activities. Azadirachtin, the major bioactive principle of *Azadirachta indica* A. Juss. and azadirachtin based formulations show wide array of pest control properties and are now globally available. Efforts are needed to identify more molecules of plant origin so that they can be used successfully in pest management in the future (Koul and Dhaliwal, 2001; Koul, 2012).

During past decade studies on pesticides based on plant essential oils or their constituents have made some headway to show their potential to control a large number of pests. Although many essential oils may be abundant and available year round due to their use in the perfume, food and beverage industries, large-scale commercial application of essential-oil-based pesticides could require greater production of certain oils. In fact, pesticides derived from plant essential oils do have several important benefits. Due to their volatile nature, there is a much lower level of risk to the environment than with current synthetic pesticides. Predator, parasitoid and pollinator insect populations will be less impacted because of the minimal residual activity, making essential-oil-based pesticides compatible with integrated pest management programs. It is also obvious that resistance will develop more slowly to essential oil based pesticides owing to the complex mixtures of constituents that characterize many of these oils. It is expected that these pesticides will find their greatest commercial application in urban pest control, public health, veterinary health, vector control vis-à-vis human health and in protection of stored commodities. In agriculture, these pesticides will be most useful for protected crops (e.g. greenhouse crops), high-value row crops and within organic food production systems where few alternative pesticides are available. There are thus the opportunities like (i) changing consumer preferences towards the use of 'natural' over synthetic products; (ii) existence of and growth in niche markets, where quality is more important than price; (iii) strong growth in demand for essential oils and plant extracts; (iv) potential to extend the range of available products including new product development through biotechnology; (v) production of essential oils and plant extracts from low cost developing countries (Koul *et al*., 2008).

Several problems have been encountered while commercializing the botanical pesticides, which are related to quantity of raw material, thermal and photostability, as well as quality control and product standardization. Like synthetic pesticides, the repeated and excessive use of botanical pesticides may also lead to pest resistance. The possibility of insects developing resistance looms large if single botanical pesticide like azadirachtin is allowed to be used too frequently. The phytotoxicity observed with the botanicals is also a matter of concern. Neem oil based formulations are often phytotoxic to tomato, brinjal and ornamental plants at oil levels above 1%. Although plant products are considered to be relatively safe to humans, however, this cannot be assumed for all plant species. Some of the most toxic substances known to man, e.g. aconitine and ricin are produced by plants. Some of the plant species such as *Taxus* spp., *Aconitum* spp. and *Ricinus communis* have notoriously high toxicity to man. Some of the commonly used plant materials in Africa such as *Tephrosia vogelii* Hook f. have well-known environmental impacts, particularly against fish (Stevenson *et al*., 2012).

To ensure there is a future for pesticidal plants, there are many issues that need to be addressed by the scientific community, policy makers and institutions involved in knowledge dissemination.

- Better information is required that could explain how pesticidal plants work, which arthropod species are affected, how the bioactive chemicals may vary according to season, locality or variety and how best plants should be harvested and processed to conserve and deliver bioactivity.
- Engagement with policy makers to tackle issues such as conservation of wild habitats and survey of unexplored plant biodiversity for pesticidal plants is required.
- There is a need for special set of guidelines for registration of plant products, which should be less stringent than other chemical pesticides. In terms of specific constraints, the efficacy of these materials falls short when compared to synthetic pesticides although there are specific pest contexts where control equivalent to that with conventional products has been observed. Essential oils, for instance, require somewhat greater application rates (as high as 1% active ingredient) and may require frequent reapplication when used out-of-doors. Additional challenges to the commercial application of plant essential oil based pesticides include availability of sufficient quantities of plant material, standardization and refinement of pesticide products, protection of technology (patents) and regulatory approval (Isman, 2005).
- Quality control in botanical pesticides is a major problem. The active ingredient levels are often affected by the agro-ecological factors in different regions of plant growth. There is an urgent need to define quality standards for botanical pesticides in order to obtain consistent results.
- The threshold of active ingredients such as azadirachtin in neem, pyrethrins in chrysanthemum, their biomass, etc. may be raised through natural selection, exotic introductions, tissue culture and other biotechnological manipulations.
- The photo- and heat-liability of botanical pesticides is another area which requires serious attention. Because of these undesirable traits, repeated outdoor applications of products are necessitated. Appropriate methodologies need to be developed to improve both residual and shelf life. Suitable stabilizers, UV-screens and antioxidants need to be identified for incorporation in the formulations.

SEMIOCHEMICALS

Semiochemicals or behaviour modifying chemicals have gained prominence recently. There was a rapid growth in the identification of insect pheromones during 1970s, and by the end of 1980s, pheromones and pheromone mimics were known for about 1000 species of insects. Today, more than 1500 moth sex pheromones and hundreds of other pheromones have been identified, including sex and aggregation pheromones from beetles and other groups. The first field trials that involved assaying pheromones for pest control were carried out in mid 1980s. Since then, hundreds of other pheromones have been identified and there are more than 50 (in over 300 different formulations) that can be used in pest management programmes. Over 30 target species have been controlled successfully by mating disruption. It has been estimated that at least 20 million pheromone lures are produced for monitoring or mass trapping every year. The world mean sale of semiochemical products is about US$ 70-80 million or 1% of the agrochemical market. The fact that producers rely on the deployment of air permeation and attract- and kill- techniques for pest control over 1 million ha would justify continued efforts to develop and implement management programmes based on the use of these semiochemicals (Witzgall *et al.*, 2010; Dhaliwal *et al.*, 2012). In fact, push-pull technology is an excellent example where intercrops and trap crops release semiochemical repellents and attractants that manipulate the distribution and abundance of pests and beneficial insects for management. It has been estimated that over 45,000 households are benefiting from this technology in East Africa, i.e. very effective and sustainable ecologically based pest management tool for low-input agriculture (Khan *et al.*, 2012).

The use of semiochemicals (sex pheromones) to disrupt mating was first attempted for *Trichoplusia ni* (Hubner), and this has now become an important method for controlling a number of lepidopteran species. Mating disruption has been successfully tried for managing several insect pests, such as pink bollworm, *Pectinophora gossypiella* (Saunders); gypsy moth, *Lymantria dispar* (Linnaeus); codling moth, *Cydia pomonella* (Linnaeus); tomato pinworm, *Keiferia lycopersicella* (Walsingham), etc. To develop an effective mating disruption programme, several conditions need to be fulfilled. The target insect should be relatively immobile so that the females that have mated outside the treated area do not enter and lay eggs in the treated fields. Insects such as cotton bollworm, *Helicoverpa armigera* (Hubner), which is a highly mobile pest, are very difficult to control with mating disruption unless thousands of hectares are treated simultaneously. The pest should ideally be restricted to a single crop; otherwise all the target crops within an area need to be treated. The pheromone should be synthesized at an economically acceptable cost, for example, the spotted bollworm, *Earias vittella* (Fabricius), can be readily controlled with mating disruption, but the method is not economically viable due to the high cost of pheromone. The pheromone must be stable and formulated such that it releases the pheromone in a controlled manner in the crop habitat (Sharma, 2009; Dhaliwal and Koul, 2010).

Another novel approach is the use of herbivore induced plant volatiles (HIPVs) and nectar rewards for enhancing biological control by attracting predators and parasitoids. Providing ‘rewards’ to biological control agents in the form of nectar and pollen can markedly increase success in otherwise inhospitable monocultures (Wäckers *et al.*, 2007). Laboratory work over two decades has shown that plants under attack by arthropod herbivores produce volatile chemicals that attract predators and parasitoid wasps. Many of the herbivore-induced plant volatiles (HIPVs) responsible for this effect have been identified, synthesised and used in slow-release dispensers. Under field conditions, they result in elevated catches of natural enemies. Remarkably, application of compounds such as jasmonic acid to plants can also induce the production of a natural blend of HIPVs. Such findings suggest that applying synthetic HIPVs to crops may attract – both directly and indirectly – the natural enemies that could protect crops from pest damage (Gurr *et al.*, 2012).

Development of semiochemical-based techniques for pest management needs stimulus from the scientific community, industry and the policy makers.

- Basic studies on understanding of the mechanisms underlying communication systems in insects, coupled with a good working knowledge of biology, behaviour and mating systems to target insects, should be undertaken. The effect of various meteorological and physiochemical factors on chemical language of insects and plants should be understood to achieve success with semiochemicals.
- Many of the semiochemicals are

photodegradable and, therefore, rapidly loose their efficacy following their applications on the crop. Therefore, suitable protected and controlled release formulations should be developed, which retain their effectiveness for a considerable length of time.

- Insects are believed to be less prone to development of resistance to semiochemicals because of their novel mode of action. However, several cases of semiochemical resistance have been documented and, therefore, timely and effective measures should be undertaken so that we may not loose the useful attributes of these safe compounds.
- The best successes with semiochemicals have been achieved where large, contiguous areas have been treated with these compounds. Therefore, an area-wide approach will have to be followed to control the target pests in a defined area. For this, cooperation of the farmers is essential and there is a need for more efficient technology transfer for those who will benefit by application of control methods based on semiochemicals.
- Commercialization of semiochemical-based products is strongly affected by the size of the potential market, cost of registration and the product's price competitiveness. The lack of commercial interest by major agrochemical firms has clearly hampered the development of semiochemical-based products. Therefore, the industry should be given proper incentives and the commercial successes achieved with semiochemicals should energize the level of commitment by industry in developing new products.
- Use of HIPVs is a potential concept and technologies based on this natural mechanism could constitute the foundation for a new approach to increasing the ecosystem service of biological pest control, especially when combined with the presence of nectar plants to 'reward' natural enemies once attracted.

CHEMICAL CONTROL

Pesticides have played a pivotal role in bringing about green revolution in many countries. The potential of high yielding varieties was realized under the pesticide umbrella. Pesticides are the most powerful tool in pest management. Pesticides are highly effective, economical, rapid in action, adaptable to most situations and flexible enough to meet the changing agronomic situations. Pesticides are the most reliable means of reducing crop damage when the pest populations exceed economic threshold levels (ETLs). When used properly based on ETLs, pesticides provide a dependable tool to protect the crops from the ravages of insect pests. Despite their effectiveness, much pesticide use has been unsound, leading to problems of development of resistance, pest resurgence, pesticide residues in the food commodities, non-target effects in the environment, and direct hazards to human beings. More than 577 species of insects and mites have developed resistance to different groups of pesticides. Resurgence of insect pests not only leads to increased use of pesticides, but also increases the cost of cultivation, greater exposure of the operators to toxic chemicals, and failure of the crop in the event of poor control of target pests. Many scientific studies have proved biomagnification of pesticide residues in human tissues, and products of animal origin. Over 100,000 cases of accidental exposure to pesticides are reported every year, of which a large number prove fatal. Hence, there is a need to look for new molecules, which are effective against insect pests but cause minimum environmental hazards (Dhaliwal and Singh, 2000; Dhaliwal *et al.*, 2013).

A number of novel pesticides with unique mode of action were registered during the late 1990s and early 2000s for pest control in agriculture, veterinary and public health. Neonicotinoids (imidacloprid) represent one of the most potent groups of insecticides and are so named because their development was based on the chemical structure of the alkaloid nicotine. Avermectins (abamectin and emamectin benzoate) and spinosyns (spinosad) are a new class of insecticidal macrocyclic lactones, derived from fermentation of the soil actinomycetes. Other novel groups of pesticides which have recently been developed include phenyl pyrazoles (fipronil), oxadiazines (indoxacarb), pyridine azomethines (pymetrozine), anthranilic diamides (rynaxypyr), benzylureas (novaluron), triazines (cyromazine), diacylhydrazines (methoxyfenozide), pyrroles (chlorofenapyr), pyridines (pyriproxyfen), pathalic acid diamides (flubendiamide), polynactins (mixture of tetranactin, trinactin and dinactin), tetronic acid derivatives (spiromesifen), and cyclic ketoenoles (spirotetramate). Most of these groups of pesticides play an important role in managing many arthropod pests with good bio-efficacy, high selectivity and low mammalian toxicity, which make them attractive replacements for synthetic organic pesticides. However, some of these pesticides exhibit toxicity to honey bees and fish. Abamectin is very active against honey bees and as such should not be sprayed during flowering. Polynactins exhibit a high degree of toxicity to fish. Moreover, care should be taken to use these novel insecticides in such a way that these do not encounter the problem of insecticide resistance as in case of conventional synthetic organic pesticides. These novel groups of pesticides are likely to play an important role in integrated pest management programmes in future (Dhawan *et al.*, 2011; Singh, 2013).

Many industrialized countries have enforced stringent pesticide regulations and developed alternative pest management approaches as a result of which pesticide use in these countries has shown a declining trend. Consequently, the magnitude of contamination of food materials has also slowed down. However, many developing countries continue to use persistent pesticides in agriculture and public health programmes, and the contamination of different components of the environment continues to be excessive and pervasive. In addition, pesticide subsidies coupled with improper pesticide application and use has further accentuated the problems. Therefore, there is an urgent need to rationalize the use of pesticides in the context of IPM.

- Development of resistance to pesticides has often resulted in widespread failure of chemical control. Pesticide resistance management strategies have aimed either at preventing the development of resistance or to contain it. All rely on a strict temporal restriction in the use of certain pesticides and their alteration with other pesticide groups to minimize selection for resistance. Because of economic advantages and safety to non-target organisms, all efforts should be directed towards developing management strategies aimed at prolonging the life of useful molecules.
- Resurgence of insect pests in several species on various crops has posed a serious problem. This phenomenon not only leads to increased use of pesticides, but also increases the cost of cultivation, greater exposure of the operators to toxic chemicals, and failure of the crop in the event of poor control of the target pests. Therefore, mechanisms underlying resurgence must be thoroughly investigated and timely measures must be taken to avoid/or delay insect resurgence.
- There is an urgent need for improvements in pesticide application methods, timing and placement. The refinement of spray technology will result in improved efficacy with reduced pesticide residues in raw agricultural commodities. Some of the application equipment does not give the desired performance for specific crop-pest, climatic, and topographic conditions. There is a need to devise suitable application equipment to meet the farmers' needs in rain-fed agriculture. Moreover, dry areas need different types of pesticide formulations, which require a minimum amount of water. Hence, research efforts should be concentrated on developing the right type of plant protection equipment vis-a-vis pesticide formulations.
- Efforts should continue to search and identify newer compounds that can be successfully used in pest management programmes. The pesticide industry must emphasize the development of new products with greater selectivity for natural enemies and minimal environmental hazards.
- In view of the environmental hazards of the

pesticides, there is an urgent need to rationalize the use of pesticides in pest management. This would require vigilant efforts on the part of policy planners, government implementing agencies, scientists, farmers and the consumers, to reduce the pesticide load in the environment. Pesticides would remain an indispensable part of modern agriculture and must be used in combination with other approaches in integrated pest management.

INSECT RESISTANT VARIETIES

Inspite of the significance of insect resistant varieties as an important component of IPM, breeding for plant resistance to insects has not been as rapidly accepted as breeding of disease-resistant cultivars. This is partially due to the relative ease with which insect control is achieved with the use of insecticides and slow progress in developing insect resistant cultivars because of the difficulties involved in ensuring adequate insect infestation for resistance screening. High levels of plant resistance are available against a few insect species only. In fact, very high levels of resistance are not a pre-requisite for use in IPM. Varieties with low to moderate levels of resistance or those that can avoid pest damage can be deployed for pest management in combination with other components of IPM. Deployment of pest-resistant cultivars should be aimed at conservation of natural enemies and minimizing the number of pesticide applications. Resistant cultivars can be used as a principal method of pest control, an adjunct to other management tactics, and a check against the release of susceptible cultivars. Resistant crop varieties developed in recent years represent some of the greatest achievements of modern agriculture in increasing and stabilizing world food and fibre supplies (Dhaliwal and Singh, 2005; Smith and Clement, 2012).

Despite the progress achieved in developing insect resistant varieties in major crops, there are several constraints which limit their widespread use in IPM. It takes a long time, usually 5–15 years to identify sources of resistance and transfer the resistance traits into cultivars with high yield potential and desirable quality traits. Hence, this method is not suitable for solving sudden or localized pest problems. Absence of adequate levels of resistance in the available germplasm may deter the use of plant resistance for managing certain pests. However, such limitations can now be overcome through the use of mutations, interspecific hybridization, and genetic transformation. Occurrence of new biotypes of the target pest may limit the use of certain insect resistant varieties in time and space. This problem may be taken care of by incorporating polygenic resistance or by continuously searching for new genes, and transferring them into high yielding varieties. Certain plant characteristics may confer resistance to one pest, but render such plants more susceptible to other pests. High levels of resistance may be associated with low yield potential or undesirable quality traits, and resistance may not be expressed in every environment wherever a variety is grown. Therefore, insect resistant varieties need to be carefully fitted into the pest management programmes in different agroecosystems (Sharma, 2009).

Considerable progress has been made in identification and utilization of plant resistance to insects. The current global economic value of plant resistance is several hundred million dollars per year. The ecological value of plant resistance has greatly decreased world pesticide usage, contributing to healthier environment for humans, livestock and wildlife. Agricultural producers have benefited from crops with arthropod resistance through decreased production costs. Consumer benefits derived from insect-resistant crops include safer and more economically produced food. Plant resistance to insects should form the backbone of pest management programmes in integrated pest management.

- Multilocational testing of the identified sources and breeding material need to be strengthened to identify stable and diverse sources of resistance or establish the presence of new insect biotypes. Resistance to insects should be given as much emphasis as yield to identify new varieties and hybrids.
- New and improved insect infestation techniques and devices that safely and efficiently place test

insects onto the crop plants will also be essential to future progress. The development and refinement of standardized rating scales to determine insect damage to more crops will greatly facilitate the development of insect-resistant cultivars to several additional crop plant species.

- More information is needed on mechanisms of resistance, genetic regulation of resistance traits, and biochemical pathways and their physiological effects. Our knowledge of how plants recognize insect-feeding attacks and the elicitors they produce in response to insect feeding is increasing rapidly The evolving model of the differences in plant defense-response elicitors must be researched, challenged and modified to better understand induced resistance function and how plant metabolism can possibly be modified to use induced crop-plant resistance in insect pest management programmes.
- The complexicity of tritrophic interactions plays a vital role in host plant resistance. Elucidation of these interactions can help further understanding, and provide greater potential for manipulation of these systems to specific crop species and varieties. The possibility of using compounds from plants to reduce herbivore damage and increase the effectiveness of biological control agents is quite attractive. Ideally, plant resistance should strive to reduce substances attractive to herbivores, while increasing the substances attractive to natural enemies.
- Occurrence of new biotypes of the target pest may limit the use of certain insect resistant varieties in time and space. In such situations, we should go for polygenic resistance or continuously search for new genes and transfer them into high yielding varieties.

TRANSGENIC CROPS

The introduction of transgenic technology has added a new dimension to pest management. The global area under transgenic crops has increased from 1.7 million ha in 1996 to 170.3 million ha in 2012. Of the 28 countries growing transgenic crops, 20 were developing and the remaining 8 were developed countries. A total of 17.3 million farmers grew transgenic crops in 2012; over 90% were small resource–poor farmers from developing countries. India celebrated a decade of successful cultivation of Bt cotton in 2011, when Bt cotton occupied 88% of the total 12.1 million ha of cotton crop. The increase from 50,000 ha of Bt cotton in 2002 to 10.8 million ha in 2012 represents an unprecedented 216-fold increase in 11 years. India enhanced farm income from Bt cotton by US$ 12.6 billion in the ten year period 2002 to 2011 and US$ 3.2 billion in 2011 alone. Thus, Bt cotton has transformed cotton production in India by increasing yield substantially, decreasing insecticide applications and through welfare benefits, contributed to the alleviation of poverty of 7.2 million small resource-poor farmers and their families in 2012 alone (James, 2012).

Transgenic crops have contributed to economic gains at the farm level of about US$ 98.2 billion during the sixteen year period (1996-2011), of which 51% were due to reduced production costs (less ploughing, less labour and fewer pesticide sprays), and 49% due to substantial yield gains of 328 million tons. Transgenic crops have helped conserving biodiversity by saving 108.7 million ha of land, which would probably have been required to produce 328 million tons of additional food, feed and fiber produced by these crops during the period 1996 to 2011. The accumulative reduction in pesticides for the period 1996 to 2011 was estimated at 473 million kg of active ingredient, a saving of 8.9% in pesticides. In 2011 alone, there was a reduction of 37 million kg, equivalent to a saving of 8.5% in pesticides. Transgenic crops have contributed to reduction of CO_2 emissions by 23 billion kg, equivalent to taking about 10.2 million cars off the road in 2011 alone. Transgenic cotton alone has helped to alleviate poverty by making significant contribution to the income of about 16 million small resource-poor farmers in 2012. This can be enhanced substantially in the remaining years of the second decade of commercialization, principally with transgenic cotton, maize and rice (James, 2012; Brookes and Barfoot, 2013).

Thus, in addition to higher yield, the benefits to farmers of transgenic crops include the lower input costs in terms of pesticide use, and ease of crop management. The reduction in pesticide usage would lead to reduced exposure of farm labour to pesticides, reduction in harmful effects of pesticides on non-target organisms, and reduced amounts of pesticide residues in food and food products. The additional benefits to farmers would be to control insect pests which have become resistant to commonly used pesticides, and reduction in crop protection costs. These factors are likely to have substantial impact on the livelihood of farmers in both developed and developing countries. In many developing countries, small-scale farmers suffer pest-related yield losses because of technical and economic constraints. Pest-resistant genetically modified crops can contribute to increased yields and agricultural growth in such situations. Available impact studies of insect-resistant and herbicide-tolerant crops show that these technologies are beneficial to farmers and consumers, producing large aggregate welfare gains as well as positive effects for the environment and human health. The advantages of future applications could be even much bigger. Transgenic crops can contribute significantly to global food security and poverty alleviation (Sharma, 2012).

In late 1990s, the manipulation of the post-transcriptional gene silencing phenomenon known as RNA interference (RNAi) was demonstrated in the genetic model systems of *Caenorhabditis elegans* Maupus (Fire *et al*., 1998) and *Drosophila melanogaster* (Meigen) (Kennerdell and Carthew, 1998). This genetic system has provided a powerful reverse genetic tool for the elucidation of gene function. Since its discovery, many reports have been published describing efforts to apply RNAi approaches in insect species lacking well developed genetics or characterized genomes. Recent progress in this area, focusing in particular on several recent landmark studies, demonstrate the potential practical value of this gene silencing technique for the development of new tools for the management of insect pests of agriculture. This can be achieved by disrupting the expression of essential genes. A desirable feature of RNAi approaches for crop protection is the exquisite selectivity of RNAi based on the sequence identity of the dsRNA with the sequence of its target transcript. This selectivity can be exploited to devise RNAi-based pest management strategies that have no effect on non-target species, thus permitting their integration into existing integrated pest management programs (Jindal *et al.*, 2012; Gu and Knipple, 2013).

Despite numerous future promises, there are number of ecological and economic issues that need to be addressed when considering the development and deployment of transgenic crops for pest management. There is a multitude of concerns about the real or conjectural effects of transgenic plants on non-target organisms, including human beings, and evolution of resistant strains of insects. As a result, caution has given rise to doubt because of lack of adequate information. One of the risks of growing transgenic plants for pest management is the potential spread of the transgene beyond the target area. There is a feeling that the genes introduced from outside the range of sexual compatibility might present new risks to the environment and humans, and will lead to development of resistance to herbicides in weeds, and to antibiotics. The biosafety issues related to the development of transgenic plants include risks for animal and human health, such as allergies, toxicity, and food quality and safety. While some of these concerns may be real, others seem to be conjectural and highly exaggerated.

Future research on development and deployment of transgenic crops should focus on the following issues:

- Effects of transgenic plants on the activity and abundance of non-target herbivore arthropods, natural enemies, and fauna and flora in the rhizosphere and aquatic systems should be thoroughly investigated. Development of transgenic crops with wide spectrum of activity against insect pests feeding on a crop, but harmless to natural enemies and other non-target organisms should be given top priority.

- There is a need for having a detailed understanding of resistance mechanisms, insect biology, and plant molecular biology to tailor gene expression in transgenic plants for efficient pest management. Future researches should focus on pyramiding of novel genes with different modes of action with conventional host plant resistance, and multiple resistance to insect pests and diseases.
- The potential of RNAi, a technique to study the function of particular gene by silencing that gene in an organism, has been established in insects. The research efforts must be intensified to identify the potential insect genes which are important for biological functions of the target insects and use identified potential genes for development of transgenic plants against that particular insect.
- One of the risks of growing transgenic crops is gene flow to the environment. There is a feeling that genes introduced from outside the range of sexual compatibility might present new risks to the environment. Therefore, studies should be undertaken to determine the extent and implications of gene transfer. Appropriate measures should be devised to contain gene flow where its likely consequences may be deleterious to the environment.
- The need for identification and detection of transgenic crops and food products derived from them has increased with the rapid expansion in cultivation of transgenic crops over the past decade. Labeling and traceability of transgenic material is important to address the concerns of the consumer. Establishment of reliable and economical methods for detection, identification and quantification of genetically modified food continues to be a great challenge at the international level.

INTEGRATED PEST MANAGEMENT

Integrated pest management (IPM) programmes were initially evolved as a result of the pest problems caused by repeated and excessive use of pesticides and increasing cases of pest resistance to these chemicals. It is only during the past two decades that economic and social aspects of IPM have also received increasing attention. If the environmental and social costs of pesticide use are taken into account, IPM appears to be more attractive alternative with lower economic costs. Production, storage, transport, distribution and application of pesticides involves greater health hazards than the safer inputs used in IPM. The IPM programmes do not endanger non-target organisms nor do they pollute soil, water and air. IPM builds upon indigenous farming knowledge, treating traditional cultivation practices as components of location-specific IPM practices. The incorporation of IPM into traditional practices helps the farmers to modernize while maintaining their cultural roots. The inputs used in IPM are usually based on local resources and outside dependence is minimized. This helps in maintaining social and political stability. It is now being increasingly realized that modern agriculture cannot sustain the present productivity levels with the exclusive use of pesticides. Increasing pest problems and disruption in agroecosystems can only be corrected by use of holistic pest management programmes (Koul *et al.*, 2004). Pest management practices may not be sustainable for a variety of reasons:

(i) The control tactic may no longer be effective over time due to selection against pests that are susceptible to the tactic.

(ii) The control tactic leads to distruption in the ecosystem that may result in further outbreak of the target pest or outbreaks of new pests.

(iii) The cost of the practice may be too expensive to maintain indefinitely.

(iv) The practice may degrade the quality of human health, environment or agronomic resources over time.

(v) New pest problems may arise due to introduction of pests or natural enemies that attack existing biological control agents and thereby increase pest populations.

(vi) As the types and the abundance of pests change due to crop intensification, the previous management tactics may not adequately control pest population.

Therefore, pest management decisions will have to be taken, keeping in view the dynamics of pest population, sustainability of the management tactics, compatibility of the tactics and stability of the agroecosystem. As control measures are generally disruptive to the ecosystems, preventing the pest problem from arising in the first place is preferable to control and promote sustainability. If pesticides are part of the IPM system, a pesticide resistance management strategy is essential, so that the target pest's susceptibility to pesticide does not decline over time. Other management tactics like pest-resistant cultivars, biological control agents and cultural practices are not necessarily sustainable over time, which may require periodical monitoring. Farmers' own management practices need to be incorporated in IPM systems to make them more acceptable and sustainable (Dhaliwal and Koul, 2010).

Pest surveillance and forecasting form an important component of IPM and provide information for pest control decision making. Nation-wide surveillance networks need to be created for the major pests. Mathematical models and computer-based programmes will help to predict population dynamics of major pests based on weather data, incidence and damage over represented sites across the country. In the long term, forewarning models in different agroclimatic zones may be evolved by establishing a network for collection of the required data. In case of highly mobile pests, regional/ international programmes involving all the affected countries may be undertaken.

Many of the IPM strategies can be implemented effectively only on an area-wide basis. This is possible through increased farmers' awareness and enactment of suitable legislative measures. IPM also needs to be integrated with other components of crop production and rural development. Ultimately, IPM is to be used at the farmers' level and, therefore, it needs to be converted from a scientist-oriented to a farmer-oriented concept. The recent advances in information and communication technology have provided us a unique opportunity to achieve these objectives. Computer-based interaction systems installed at the village level can help the farmers in pest identification, forecasting of pest populations, range of options available for pest management with advantages and limitations of each of these options. This will help the farmers in identifying the pest option based on their requirements and resources (Koul *et al.*, 2008; Dhaliwal and Arora, 2012).

According to a recent survey, only less than 5% of the farmers follow IPM packages despite huge networks and efforts in various cropping systems. Virtually, there has been little effort to integrate the locally available and compatible management measures to develop economically viable IPM practices. India should formulate a National Pest and Pesticide Management Policy in order to achieve systematic reduction in the usage of pesticides over time, leading towards the larger goal of agricultural and environmental sustainability. Strict adoption of IPM in at least 75% of the gross cropped area in every state of India, along with declaration of some sensitive ecological zones as pesticide free zones, where no pesticide marketing or use is allowed, should be one of the main policy components. The policy should take into consideration all aspects of pest management, including environmental and human health risks, and hazards to applicators and other associated social and economic issues of agricultural sustainability (Shetty *et. al.,* 2008)

IPM programmes gained momentum during 1980s and since then many major food and fibre crops were covered under IPM technology in many countries. However, many crops of extreme importance to subsistence and resource-poor farmers around the world have not received due attention. These crops, often referred to as 'orphan crops' because of relative lack of research and development applied to them, include root and tuber crops such as cassava, sweet potato and yam; millets such as pearl millet, finger millet and foxtail millet; and several legumes and tree crops. Moreover, the package of practices in many developing countries still lay emphasis on pesticide based pest management programmes. Therefore, the future IPM programmes need to be ecologically based in order to achieve sustainable crop protection.

- IPM programmes have been developed and validated for almost all the major crops in different parts of the world. However, their widespread acceptance by the farmers in many developing countries is far from satisfactory. Therefore, farmers must be involved in devising and refining IPM schedules so that they are convinced of the benefits of the IPM technology. Viewing farmers as an equal partner in technology development and testing will foster ownership of IPM technologies and increase adoption.
- Different tactics of IPM may not always be complementary to each other. There have been situations where host plant resistance and chemical control, host plant resistance and biological control, chemical control and biological control, and transgenic crops and biological control have been incompatible. Therefore, the interactions among various tactics of IPM should be thoroughly investigated before applying them to IPM programmes.
- Generally IPM programmes have been devised taking into consideration the major target pest. Efforts should be made to follow a holistic approach by taking into consideration the entire insect pest and disease complex of the agroecosystem.
- A field-to-field approach is followed by individual farmer to manage pests on their farms. There are always chances of movement of insects from the adjoining untreated fields to colonise the treated crop after a few days of the control operation. Therefore, area-wide pest management approach should be followed where the farmers practice the IPM schedule in contiguous blocks.
- Pesticides have dominated the scene of pest management even after the concept of IPM became popular and widely accepted. There is a need to shift the IPM paradigm from focusing on pest management strategies relying on pest management to a system approach relying primarily on biological knowledge of pests and their ecological interactions with the crops. Digital technology and high-speed telecommunications can enable access to recent information in the Internet. The use of Global Positioning Systems (GPS) will compliment web networks by providing researchers and extension workers with tools that will enable them to define regions where production constraints are most acute, develop targeted technologies for those regions and monitor their use. Modeling and computer programmes can aid in understating the dynamics of pest populations and devising sustainable pest management strategies.

CONCLUSIONS

The global population reached 7 billion in 2011, increasing from 5 billion in 1987 to 6 billion in 1999. Although the overall growth rate has declined from 2.1% per year in late 1960s to 1.2% at present, the population is still growing, particularly in Asia and sub-saharan Africa. For example, according to 2011 census, India's population stood at 1.21 billion. It is entirely possible that that 8th billion in world population would be added in 12 years as well. This would place us squarely in the middle of history's most rapid population expansion. Therefore, strenuous efforts will have to be made to increase world food supplies to ensure environment and food security. Ecostrategies are likely to play a prominent role to achieve the above objectives. In this context, integrated pest management, which relies on suppression of pest problems while causing minimum disruption to the agroecosystem, is one of the viable alternatives.

The current methodology for assessing insect damage to undertake control measures is cumbersome, and the farmers are not able to properly understand and practice the methods. Simple techniques to assess insect damage and population density would be useful for timely application of appropriate control measures. There is a need to develop economical high-resolution environmental and biological monitoring systems to enhance our capabilities to predict pest incidence, estimate damage, and identify valid economic thresholds. Economic threshold levels (ETLs) are available for a limited number of insect species. ETLs developed without taking into consideration the potential of naturally occurring biological control agents and levels of resistance in the cultivars to the target pests are of limited value. The ETLs have to be developed for specific crop-pest-climatic situations. The ETLs developed in one region are not applicable in other areas where the crop-pest and socioeconomic conditions are different. Simple methods of assessing ETLs could help avoid unnecessary pesticide applications.

Nanotechnology is a promising field of research which has opened up a wide array of opportunities and is expected to give major impulse to technical innovations in future. These include enhancement of agricultural productivity involving nanoporous zeolites for slow release and efficient dosage of water and fertilizer, nanocapsules for herbicide delivery, and vector and pest management, and nanosensors for pest detection. Nanoparticles help to produce new pesticides and insect repellents. Nanoencapsulation (a process through which a chemical is slowly but efficiently released to a particular plant), with nanoparticles in the form of pesticides allows proper absorption of the chemical into plants unlike in the case of larger particles. This process can also deliver DNA and other desired chemicals into plant tissues for protection of host plants against insect pests. It is known that aluminosilicate filled monotube can stick to the plant surfaces while nanoingredients of nanotube have the ability to stick to the surface hair of insect pests, and ultimately enter the body and influence certain physiological functions. Nanoencapsulation is currently the most promising technology for protection of crop plants against insect pests. Research on nanoparticles and insect control should be directed towards production of faster and ecofriendly pesticides to deliver into the target host tissue through nanoencapsulation. This will control pests efficiently, prolong the protection time and lead to sustainable crop protection. Thus, nanotechnology is likely to revolutionize agriculture in general and pest management in particular in the near future (Goud *et al.*, 2011).

The relative efficacy of many of the pest management practices is likely to change as a result of the influence of climate change on extension of geographical range of insect pests, increased overwintering and rapid population growth, change in insect-host plant interaction, increased risk of invasion by migrant pests, impact on arthropod diversity and extinction of species, changes in synchrony between insect pests and their crop hosts, introduction of alternate hosts as green bridges, and reduced effectiveness of crop protection technology. Climate change would thus have serious consequences on diversity and abundance of arthropods, and the extent of losses due to insect pests, which will impact both crop production and food security. Prediction of changes in geographical distribution and population dynamics of insect pests will be useful to adapt the pest management strategies to mitigate the adverse effects of climate change on crop production. There is a need to have a concerted look at the likely effects of climate change on crop protection, and devise appropriate measures to mitigate the effects of climate change on food security (Sharma, 2010)

Foods derived from genetically modified plants are now appearing in the market and many more are likely to emerge in the future. It is important to ensure the safety of food derived from transgenic crops based on the principle of nutritional equivalence. All out efforts should be made to make this technology available to farmers who cannot afford the high cost of seeds and chemical pesticides in developing countries. Transgenic crops would play a significant role in integrated pest management in future reducing the number of pesticide applications and pesticide residues in food. Concerted efforts are required involving international and advanced research institutes, and the national research organizations to harmonize the regulatory requirements to assess the biosafety of the food derived from genetically engineered crops and their effects on non-target organisms for sustainable crop production and food security.

The goals of the future IPM programmes are to improve the economic benefits related to the adoption of IPM practices and to reduce potential human health risks and unreasonable environmental effects from pests and from the use of pest management practices.

- A major determining factor in the adoption of IPM programmes is whether the economic benefit outweighs the cost to implement an IPM practice. Conducting a "cost benefit" analysis of the proposed IPM strategies is not based solely on the monetary costs; it is based on four main parameters, i.e. monetary, environmental/ecological health and function, aesthetic benefits, and human health.
- IPM programmes need to be designed with the goal of reducing potential human health risks by reducing exposure of both the general public and workers to pests as well as high-risk pest management practices, whether mechanical, chemical or biological in nature. IPM protects human health through its contribution to food security by reducing potential health risks and enhancing worker safety.
- IPM programme should be designed to protect agricultural, urban and natural resource environments from the encroachment of native and non-native pest species while minimizing unreasonable adverse effects on soil, water, air and beneficial biological organisms.

Classical integrated management programmes for apple pests in Canada and cotton pests in Peru provided some of the early models for successful implementation of IPM in the field. The FAO subsequently provided the coordination to spread the IPM concept in developing countries. The success of an IPM programme in rice in Southeast Asia was based on linking outbreaks of the brown planthopper with application of broad-spectrum insecticides, and the realization of the fact that the brown planthopper populations were kept under check by the natural enemies in the absence of insecticide applications. Much of the impact of this programme was brought out through field demonstrations, training programmes, and farmers' field schools. Subsequently, many more developing countries launched their own national IPM programmes. The success of some of these programmes has led to the establishment of the Global IPM Facility, under the auspices of FAO, UNDP and the World Bank, which will serve as a coordinating and promoting entity for IPM worldwide. Currently many IPM programmes have been developed in which different control tactics are combined to suppress pest numbers below a threshold. These vary from judicious use of insecticides based on ETLs and regular scouting to ascertain pest population levels to sophisticated systems using computerized crop and population models to assess the need, optimum timing, and selection of insecticides for sprays. The increase in our knowledge about insect-plant-environment interactions and advances in modern technology like biotechnology and nanotechnology, would give further impetus to IPM in the future.

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