Journal of Integrated Pest Management, (2019) 10(1): 12; 1–9
doi: 10.1093/jipm/pmz010
Issues

The New Integrated Pest Management Paradigm for the Modern Age

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Subject Editor: Thomas Kuhar

Received 14 December 2018; Editorial decision 31 March 2019

Abstract

Earlier models of integrated pest management (IPM) focused on ecological aspects of pest management. With the recent developments in agricultural technology, modern communication tools, changing consumer trends, increased awareness for sustainably produced food systems, and globalization of trade and travel, there seems to be a need to revisit the IPM paradigm as appropriate for modern times. A new model, built on earlier models based on ecological and economic aspects, is expanded and reconfigured to include management, business, and sustainability aspects and emphasize the importance of research and outreach. The management aspect contains four components of IPM that address the pest management options, the knowledge and resources to develop management strategies, the management of information and making timely decisions, and the dissemination or sharing of information. With the business aspect that includes the producer, consumer, and seller, and the sustainability aspect that covers economic viability, environmental safety, and social acceptability, the new model presents the human, environmental, social, and economic factors that influence the food production.

Key words: economic viability, environmental safety, IPM, new model, pest management

The concept of integrated pest management (IPM), a sustainable strategy for managing pests, has been in practice for a long time. Although multiple sources define IPM in different ways, previous models primarily focused on the ecological, and to some extent on the evolutionary, aspects of pest management (Peterson et al. 2018). A recent IPM pyramid presented by Stenberg (2017) identified a lack of a holistic IPM approach that uses both traditional and modern tools. However, his conceptual framework mainly dealt with the ecological aspects of pest management with an emphasis on interdisciplinary research approach. Several reports indicated that IPM implementation depends on numerous factors including the level of education, economic and social conditions, environmental awareness, rational thinking, moral values, regulatory aspects, government policies, availability of IPM tools, extension education, consumer preference, and retail marketing (Parsa et al. 2014, Lefebvre et al. 2015, Jayasooriya and Aheeyar 2016, Rezaei et al. 2019). However, there is no IPM model that encompasses all these factors and provides a comprehensive description.

The interpretation of IPM also varies among those who develop, promote, or practice IPM strategies. For example, according to the United States Department of Agriculture-Agricultural Research Service (USDA-ARS 2018), IPM is a sustainable, science-based, decision-making process that combines biological, cultural, physical, and chemical tools to identify, manage, and reduce risk from pests and pest management tools and strategies in a way that minimizes overall economic, health, and environmental risks. Several other definitions also focus on minimizing or eliminating the reliance on chemical control options, adopting a number of other options with the emphasis on environmental and human health. However, some practitioners interpret IPM as rotating chemicals from different mode of action groups to maintain pest control efficacy and reduce pesticide resistance with an emphasis on reducing pest damage. These definitions and interpretations represent a variety of objectives and strategies for managing pests including vertebrate and invertebrate pests, diseases, and weeds. IPM is not a principle that strictly and uniformly applies to every situation, but a philosophy that can guide the practitioner to use it as appropriate for their situation. For example, host plant resistance is effectively used in some crops with pest and disease resistant or tolerant varieties, but not in other crops. Pheromones are widely used for mating disruption, mass trapping, or monitoring of certain lepidopteran and coleopteran pests, but not for several hemipteran pests. Biological control is commonly used for greenhouse pests, but not to the same extent in the field. Mechanical tools such as bug vacuums are used in high-value crops such as strawberry, but they are not an economical option in nonspecialty crops and are not carbon efficient because of fossil fuel consumption. While chemical pesticides should be used as the last resort, in principle, sometimes they are the first line of defense to prevent the area-wide spread of certain endemic or invasive pests and diseases or to protect the seed and transplants from common and persistent pest problems. Seed treatment with chemical pesticides, e.g., has become a popular prophylactic measure in many crops in recent years.

Crop production is an art, a science, and an enterprise, and by adding environmental and social factors, IPM—an approach used in crop production—is also influenced by a number of factors. Each grower has their own strategy for producing crops, minimizing losses, and making a profit in a manner that is acceptable to the retailer, safe for the consumers, and less disruptive to the environment. In other words, IPM is an approach to manage pests in an economically viable, socially acceptable, and environmentally safe manner. Keeping this short, but complex, definition in mind and considering recent advances in crop production and protection, communication technology, and globalization of agriculture and commerce, a new paradigm of IPM (Fig. 1) is presented with its management, business, and sustainability aspects having the following direct or indirect objectives:

- Update the IPM concept as appropriate for modern times and encourage re-evaluation of what is perceived as sustainable
- Build consumer confidence and education in an IPM-based production system that is ideal for all crops and situations, ensures global food security, and eliminates food-based social inequality
- Ensure profitability for the producers while allowing informed consumers, rather than special interest groups or retailers, to make their food choice
- Minimize potential negative impact of the non-IPM-based conventional practices or those perceived to be sustainable alternatives on the environment and challenges associated with managing certain pests

Management Aspect

There are four major components in the new IPM model that address various pest management options, the knowledge, and resources the grower has to address the pest issue, planning and organization of information to take appropriate management actions, and maintaining good communication to acquire and disseminate knowledge about pests and their management.

Pest Management

The concept of pest control has changed to pest management over the years knowing that a balanced approach to managing pest populations to levels that do not cause economic losses is better than eliminating or eradicating (except for newly introduced invasive pests), for environmental and economic reasons. Although the term control is frequently used in literature and conversations, it generally refers to management. A thorough knowledge of general IPM principles and various management options for all possible pest problems is important as some are preventive and others are curative.

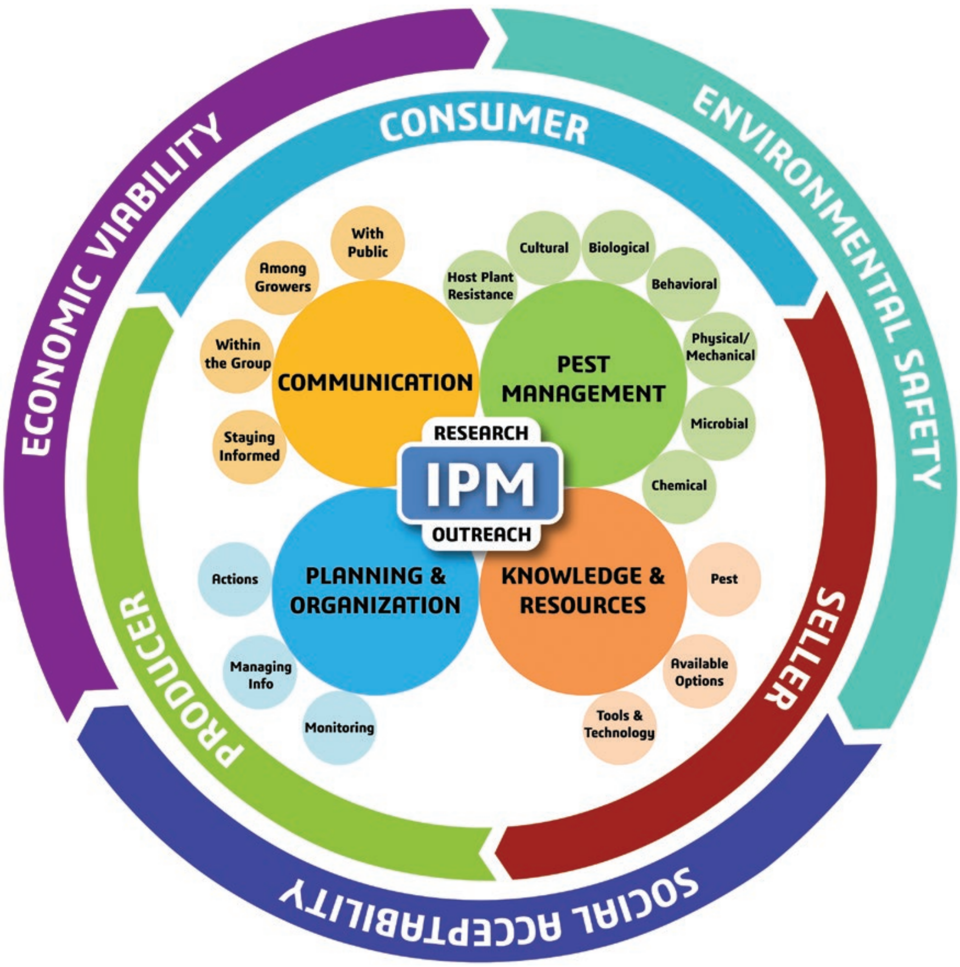

Fig. 1. New IPM paradigm with its various components and influencing factors for economically viable, socially acceptable, and environmentally safe pest management.

Some of the recommended practices may not be practical in all situations and the grower or the pest control professional has to choose the option(s) appropriate for their situation. It is also essential to understand inherent and potential interactions among these management options to achieve desired control. The following are common control options that can be used at different stages of crop production to prevent, reduce, or treat pest infestations. Each of them may provide a certain level of control, but their additive effect can be significant in preventing yield losses.

Host Plant Resistance

A strategy that involves the use of pest-resistant and pest-tolerant cultivars developed through traditional breeding or genetic engineering (Douglas 2018, Kennedy 2008, Nelson et al. 2018). These cultivars possess physical, morphological, or biochemical characters that reduce the plant's attractiveness or suitability for the pest to feed, develop, or reproduce successfully. These cultivars resist or tolerate pest damage and thus reduce the yield losses. This option is the first line of defense in IPM.

Cultural Control

Adopting good agronomic practices that avoid or reduce pest infestations and damage refers to cultural control. Choosing clean seed or plant material is critical to avoid the chances of introducing pests right from the beginning of the crop production. Adjusting planting dates can help escape pest occurrence or avoid most vulnerable stages. Early planting of cowpea reduced aphid, thrips, and pod bug infestations in Uganda (Karungi et al. 2000) and the legume podborer (*Maruca vitrata*), the legume flower thrips (*Megalurothrips sjostedti*), and the pod sucking bug (*Clarigralla tomentosicollis*) in Nigeria (Asante et al. 2001). Plant density or row spacing will also have an impact on pest infestations. High plant density reduced root maggot (*Delia* spp.) infestations in canola in Canada (Dosdall et al. 1996) and aphid infestations in cowpea in Uganda (Karungi et al. 2000). Modifying irrigation practices, fertilizer program, and other agronomic practices can create conditions that are less suitable for the pest. Micro-sprinklers are installed on the strawberry beds as a spider mite control strategy especially in organic strawberries in California (personal observation). Strawberry plots with micro-sprinklers also appeared to have less severe powdery mildew (caused by *Podosphaera aphanis*) and botrytis fruit rot (caused by *Botrytis cinerea*) infections compared with the plots with overhead aluminum sprinklers (Dara et al. 2016). Low potassium content in plants induces jasmonic acid synthesis in plants and helps with plant's ability to withstand insect pests and certain diseases (Davis et al. 2018). Increased plant nitrogen can exacerbate arthropod infestations (Hodson and Lampinen 2018). High (Mitchell et al. 2003) or low nitrogen (Snoeijers et al. 2000) content in the plant can also contribute to some disease problems. Destroying crop residue and thorough cultivation will eliminate breeding sites and control soil-inhabiting stages of the pest. Sanitation practices to remove infected/infested plant material, regular cleaning field equipment, avoiding accidental contamination of healthy fields through human activity are also important to prevent the pest spread. For example, winter plowing of orchard floors reduced the pistachio psyllids (*Agonoscena pistaciae*) overwintering in the leaf litter and weeds in Iran (Mehrnejad 2018). Plowing is also an important control option to destroy the crop residue and expose the soil-inhabiting stages of several vegetable pests (Kunjwal and Srivastava 2018). Sanitation practices such as bagging unmarketable berries or even changing the harvest schedule from every 3 d to 1–2 d reduced spotted-wing drosophila (*Drosophila suzukii*) infestations (Leach et al. 2017). Crop rotation with non-host or tolerant crops will break the pest cycles and reduce their buildup year after year. Crop rotation tactic has been used for insect, disease, and weed management in many cropping systems (Curl 1963, Wright 1984, Liebman and Dyck 1993, Mohler and Johnson 2009). Intercropping of non-host plants or those that deter pests or using trap crops to divert pests away from the main crop are some of the other cultural control strategies in IPM (Pretty and Bharucha 2015, Nielsen et al. 2016).

Biological Control

Natural enemies such as predatory arthropods and parasitic wasps can be very effective in causing significant reductions in pest populations in certain circumstances (Hajek and Eilenberg 2018). Periodical releases of commercially available natural enemies or conserving natural enemy populations by providing refuges or avoiding practices that harm them are some of the common practices to control endemic pests. Biological control has been successfully used in greenhouses (van Lenteren 1988) and specialty crops such as strawberries grown in the field (Zalom et al. 2018). To address invasive pest issues, classical biological control approach is typically used where natural enemies from the native region of the invasive pest are imported, multiplied, and released in the new habitat of the pest (Kenis et al. 2017, Heimpel and Cock 2018). The release of irradiated, sterile insects is another biological control technique that has been effectively used against a number of pests (Klassen and Curtis 2005).

Behavioral Control

The behavior of the pest can be exploited for its monitoring and control through baits, traps, and mating disruption techniques (Heinz et al. 1992, Shorey and Gerber 1996, Foster and Harris 1997, Vladés et al. 2005, El-Sayed et al. 2009, Morrison et al. 2016). Baits containing poisonous material will attract and kill the pests when distributed in the field or placed in traps. Pests are attracted to certain colors, lights, odors of attractants or pheromones. Devices that use one or more of these can be used to attract, trap or kill pests. Pheromone lures confuse adult insects and disrupt their mating potential, and thus reduce their offspring.

Physical or Mechanical Control

This approach refers to the use of a variety of physical or mechanical techniques for pest exclusion, trapping (in some cases similar to the behavioral control), removal, or destruction (Webb and Linda 1992, Gamliel and Katan 2012, Gogo et al. 2014, Dara et al. 2018). Pest exclusion with netting or row covers, handpicking or vacuuming to remove pests, mechanical tools for weed control, traps for rodent pests, modifying environmental conditions such as heat or humidity in greenhouses, steam sterilization or solarization, visual or physical bird deterrents such as reflective material or sonic devices are some examples of physical or mechanical control.

Microbial Control

Using entomopathogenic bacteria, fungi, microsporidia, nematodes, or viruses, and fermentation byproducts of some microbes against arthropod pests, plant parasitic nematodes, and plant pathogens generally come under microbial control (Mankau 1981, Paulitz and Bélanger 2001, Dong and Zhang 2006, Lacey 2017).

Chemical Control

Chemical control typically refers to the use of synthetic chemical pesticides (Pimental 2009). However, to be technically accurate, chemical control should include synthetic chemicals as well as chemicals of microbial or botanical origin. Although botanical extracts such as azadirachtin and pyrethrins, and microbe-derived toxic metabolites such as avermectin and spinosad are regarded as biologicals (Lasota and Dybas 1991, Sarfraz et al. 2005, Dodia et al. 2010), they are still chemical molecules, similar to synthetic chemicals, and possess many of the human and environmental safety risks as chemical pesticides. Chemical pesticides are categorized into different groups based on their mode of action (IRAC 2018) and rotating chemicals from different mode of action groups is recommended to reduce the risk of resistance development (Sparks and Nauen 2015). Government regulations restrict the time and amount of certain chemical pesticides and help mitigate the associated risks.

The new ribonucleic acid interference (RNAi) technology where double-stranded RNA is applied to silence specific genes in the target insect is considered as biopesticide application (Gordon and Waterhouse 2007). Certain biostimulants based on minerals, microbes, plant extracts, seaweed or algae impart induced systemic resistance to pests, diseases, and abiotic stressors, but are applied as amendments without any claims for pest or disease control (Larkin 2008, Vleesschauwer and Höfte 2009, Sharma et al. 2014, López-Bucio et al 2015, Dara 2018a). These new products or technologies can fall into one or more abovementioned categories of pest management.

All the pest management options need careful consideration and application to avoid potential risks. For example, several pests developed resistance to transgenic crops with *Bacillus thuringiensis* toxic proteins (Tabashnik et al. 2013) and planting non-transgenic plants along with resistant plants has been recommend, among other strategies, to reduce the resistance development (Tang et al. 2001, Huang et al. 2011). The western corn rootworm, *Diabrotica virgifera virgifera*, adapted to the cultural practice of rotating soybean with corn (Gray et al. 2013) and gut bacteria, among other factors, appears to facilitate this adaptation (Chu et al. 2013). Pests can also develop resistance to botanical and microbial pesticides if they are overused (Dara 2017). While mating disruption is successfully used for controlling several pests, factors such as migration of mated females and alternative mate recruitment strategies of some species could affect the efficacy of this technique (Cardé and Minks 1995). Pesticide resistance in arthropod pests is a longtime problem in pest management (Georghiou 1983) and one of the key factors for developing IPM strategies. As required by the crop and pest situation, one or more of the control options can be used throughout the production period for effective pest management. When used effectively, nonchemical control options delay, reduce, or eliminate the use of chemical pesticides.

Although pest management decisions are supposed to be based on economic injury levels and thresholds, in many situations they are either not available, difficult to determine, not applicable to all geographic regions or seasons, or existing ones need revalidation (Poston et al. 1983). Some of the established thresholds are also questionable. Because crop production is highly precise due to modern technologies on one hand, as well as highly variable depending on a myriad of biotic and abiotic factors and the proprietary practices of different farming operations, information management and decision-making parts play a critical role in IPM. One cannot offer a one-size-fits-all solution and the pest control efficacy depends on several factors in addition to the option used.

Knowledge and Resources

The knowledge of various control options, pest biology and damage potential, and suitability of available resources enables the grower to make a decision appropriate for their situation. Conversations with growers in different parts of United States and other countries revealed that IPM implementation is limited by the lack of sufficient knowledge, resources, or immediate economic benefit. It is also evident from many conversations with growers and pest control professionals in California that resistance management seen as rotating pesticides among different mode of action groups is commonly perceived as IPM, although resistance management is only a part of IPM. IPM implementation is especially a challenge in developing countries or with low-income growers in developed countries. Socio-psychological factors including rational and moral considerations were found to the drivers in IPM implementation in Iran (Rezaei et al. 2019). A survey of vegetable growers in Sri Lanka showed that nearly 50% of them practiced calendar-based chemical pesticide applications before pest or disease occurrence and only 20% had some understanding of IPM (Jayasooriya and Aheeyar 2016). A survey conducted by Parsa et al. (2014) also showed that a lack of qualified IPM experts and extension educators was an impediment for IPM implementation in developed countries.

Pest

Identification of the pest, understanding its biology and seasonal population trends, damaging life stages and their habitats, nature of the damage and its economic significance, the vulnerability of each life stage for one or more control options, host preference and alternate hosts, predictability of pest occurrence based on the environment, cropping trends, farming practices, and other influencing factors, and all the related information is critical for identifying an effective control strategy.

Available Control Options

Because not all control options can be used against every pest, the grower has to choose the ones that are ideal for the situation. For example, systemic insecticides are more effective against pests that mine or bore into the plant tissue. Pests that follow a particular seasonal pattern can be controlled by adjusting planting dates. Commercially available natural enemies can be released against some, while mating disruption works well against others. Entomopathogenic nematodes can be used against certain soil pests, bacteria, and viruses against pests with chewing mouthparts such as Lepidoptera and Coleoptera, while fungi are effective against a variety of pests. Although planting alfalfa strips in strawberry fields to attract and vacuum the western tarnished plant bug, *Lygus hesperus*, has been recommended as an IPM tactic by Swezey et al. (2007), the idea did not take off because growers were not ready for such an intercropping arrangement. Growers are reluctant to lose some of the land for alfalfa and concerned that alfalfa might attract more *L. hesperus* into strawberry fields. In some areas, where agricultural land is in shortage or there is a continuous demand for specialty crops, certain IPM practices such as allocating space for natural enemy habitats or crop rotation are not always possible. For example, on some farms, strawberries are grown year after year without a rotation with vegetables or cover crops on the California Central Coast (personal observations).

Tools and Technology

A particular pest can be controlled by certain options, but they may not all be available in a particular place, for a particular crop, or within the available financial means. For example, the release of natural enemies may be possible in high-value specialty crops, but not in large acreage field crops. A particular pesticide might have been registered for a pest on some crops, but not on all. Use of netting, row covers, or tractor-mounted vacuums can be effective, but very expensive limiting their availability to those who can afford.

This is an important component where diagnostic and preventive or curative decisions are made based on available and affordable control options. With more regulations on pesticide use and a reduction in the number of active ingredients in some crops, there is a higher emphasis on better understanding of available control options (Hillocks 2012). Regulatory guidelines that limit the use of certain pesticides or promote the use of others can have a major influence on IPM implementation. Many countries have phased out broad-spectrum pesticides and fumigants. Recent concern for pollinator health has also led to restrictions on the use of certain pesticides.

While these factors in the knowledge and resources component cover the implementation part of IPM, having sufficient resources to develop IPM strategies is a critical part in the whole equation that is often ignored. Shortage of IPM specialists, limited financial resources for research and extension, and inherent challenges in conducting time-consuming applied agricultural research are some of the hurdles in developing and disseminating IPM strategies. Too often, many of the IPM tools and technologies do not reach the implementation stage due to practical limitations such as a high cost of commercialization or lack of interest in its adoption.

Planning and Organization

This component deals with the management aspect of the new IPM model for data collection, organization, and actual actions against pest infestations.

Pest Monitoring

Regularly monitoring the fields for pest occurrence and spread is a basic step in crop protection. Early detection in many cases can help address the pest situation by low-cost spot treatment or removal of pests or infested or infected plant material. When pest infestations continue to grow, regular monitoring is necessary to assess the damage and determine the time to initiate farm-wide control. Monitoring is also important to avoid calendar-based pesticide applications especially at lower pest populations that do not warrant treatments. For example, sampling-based fumigation along with improved sanitation and other practices can be an economical alternative to calendar-based fumigation of wheat in elevators (Adam et al. 2010). During many conversations with growers and colleagues in extension, it appeared that thorough scouting or decision-making solely based on scouting are not possible due to the lack of resources. However, drone-assisted aerial imagery for pest detection and identification or to locate areas that are exposed to biotic or abiotic stressors can improve the monitoring efficiency and precision (Vanegas et al. 2018, Yue et al. 2018). Some of these tools are already available for commercial use.

Managing Information

A good recordkeeping about pests, their damage, effective treatments, seasonal fluctuations, interactions with environmental factors, irrigation practices, plant nutrition, and other related information from year to year will build the institutional knowledge on a farm and prepares the grower to take preventive or curative actions.

Corrective Actions

Taking a timely action is probably the most important aspect of IPM. Even with all the knowledge about the pest and availability of resources for its effective management, losses can be prevented only when corrective actions are taken at the right time. Good farm management will allow the grower to act in a timely manner. These actions are not only necessary to prevent damage on a particular farm, but also to prevent the spread to neighboring farms. When pest management is neglected on a farm, it can spread to neighboring farms and become an area-wide problem with larger regulatory, social, and economic implications.

Communication

Good communication to transfer the individual or collective knowledge for the benefit of everyone is the last component of the new IPM model. Modern and traditional communication tools can be used for outreach as researchers develop information about endemic and invasive pests, emerging threats, and new control strategies.

Staying Informed

Growers and pest control professionals should stay informed about existing and emerging pests and their management options. Science-based information can be obtained by attending extension meetings, webinars, or workshops, reading the newsletter, trade, extension, or scientific journal articles, and keeping in touch with researchers and other professionals through various communication channels. There are several online resources from universities and other reputed institutions and smartphone applications that provide regular updates (Dara 2016). Well-informed growers can be well prepared to address pest issues. Keeping abreast with pest issues and their management trends is also very important for researchers and extension professionals as they develop and disseminate new strategies.

Communication Within the Group

Educating farm crew through periodical training or communication will help with all aspects of pest management, proper pesticide handling, ensuring worker safety, and preventing environmental contamination. Knowledgeable field crews will be able to identify and monitor pest problems and effectively execute the management strategies.

Communication Among Growers

Although certain crop production and protection strategies are considered proprietary information, sharing knowledge and resources with each other will improve pest control efficacy and benefit the entire grower community. Pests do not have boundaries and can spread to multiple fields when they are not effectively managed throughout the region. Growers in developing countries feel that collective action is required for IPM implementation as there is a lack of sufficient knowledge (Parsa et al. 2014).

Communication With the Public

Public demand is influenced by retail marketing strategies, concerns for food safety based on pesticide regulations in their region, and a lack of knowledge on food production among other factors. During multiple outreach meetings and field tours organized exclusively for the public in Southern California during the past few years, it was evident that a majority was not aware of farming systems, had misunderstanding about sustainable agriculture, and believed that organic food is pesticide-free (Dara personal observations and unpublished survey data). They indicated a change in their knowledge and a potential change in their behavior in making food choices following the discussions and field tours. Educating public will help their understanding of and preference for organic, conventional, or sustainably produced food as well as influence policy and regulatory decisions in their regions to ensure food safety and security.

Research and Outreach

Research and outreach are an integral part of the IPM model to identify and anticipate pest problems, develop preventive and curative strategies, and effectively disseminate the information through traditional and modern communication tools and strategies. United States Environmental Protection Agency (US EPA 2018) recognizes education and outreach as the key factors in IPM implementation. A study conducted by Parsa et al. (2014) involving IPM professionals and practitioners from 96 countries revealed that inadequate training and technical support as major obstacle for IPM implementation. Cameron (2007) identified that science-based solutions and extension services are critical for IPM implementation in vegetables and fruits in New Zealand. Developing science-based information through applied research, effective outreach based on the socioeconomic and demographic structure of the clientele, networking and communication skills of extension educators, and reputation of researchers and extension educators play an important role in educating IPM practitioners.

In addition to the research and outreach foundation and the four components of management, factors that influence profitable, safe, and affordable food production at a larger scale and their implications for global food security should also be included in an IPM model. There are two layers surrounding these four components addressing the business and sustainable aspects of food production.

Business Aspect

Consumers want nutritious, healthy, and tasty produce that is free of pest damage at affordable prices. Growers try to meet this demand by producing food that meets all the consumer needs, while maintaining environmental and human safety, and still being able to make a profit. Sellers evaluate the market demand and strategize their sales to satisfy consumers while making their own profit to stay in the business. In an ideal system, consumer, producer, and seller would maintain a harmonious balance of food production and sale. In such a system, food is safe and affordable to everyone, there will be food security all over the world, and both growers and sellers make a good profit with minimal risk to the environment in the process of food production. However, this balance is frequently disrupted due to 1) consumers' misunderstanding of various food production systems, their demand for perfectly shaped fruits and vegetables at affordable prices, or their willingness to pay a premium price for food items that are perceived to be safe, 2) growers trying to find economical ways of producing high-quality food while facing with continuous pest problems and other challenges, and 3) sellers trying to market organic food at a higher price as a safer alternative to conventionally produced food. If growers implement good IPM strategies to produce safe food and consumers are aware of this practice and have confidence in food produced in an IPM-based system, then sellers would be able to market what informed-consumers demand. Extension traditionally focused on educating the growers and those involved in food production, but public education on the importance of IPM can have a significant influence on the way food is produced.

Sustainability Aspect

IPM is an approach to ensure economic viability at both consumer and producer level (seller is always expected to make a profit), environmental safety through a balanced use of all available pest control options, and social acceptability since IPM-based food is safe and affordable.

Although organic food production is generally perceived as safe and sustainable, the following examples can explain why it is not necessarily true. Organic food production is not pesticide-free and some of the pesticides used in an organic system are as harmful to humans and nontarget organisms as some chemical pesticides. For example, pyrethrins are highly toxic to honey bees, fish, and aquatic invertebrates (NPIC 2014). Certain organically accepted pesticides have toxins or natural chemical molecules that are very similar to those in synthetic pesticides. In fact, some synthetic pesticides (e.g., synthetic pyrethroids vs pyrethrins and neonicotinoids vs nicotine) are manufactured imitating the pesticidal molecules of natural origin. Pests develop resistance to biopesticides just as they develop resistance to chemical pesticides. Arthropod resistance to abamectin (Stumpf and Nauen 2002), *B. thuringiensis* formulations or its *cry* toxins in genetically modified crops (Hama et al. 1992, Tabashnik et al. 2013), spinosad (Scott 2008), and other biopesticides (Dara 2017) are well documented. Kaolin particle films used in organic farming might control some pests, but can negatively impact natural enemies and cause other pests to proliferate (Markó et al. 2008). Organic farming practices might encourage natural enemy populations, but a higher number of natural enemies does not always result in pest suppression (Dara 2014). Mechanical pest control practices such as vacuuming or tilling utilize fossil fuels and indirectly have a negative impact on the environment. For example, diesel-powered tractors are operated for vacuuming western tarnished bug in strawberry 2–3 times or more each week while a pesticide application typically requires the use of tractor once every 7–14 d. To control certain pests, multiple applications of organic pesticides might be necessary with associated costs and risks, while similar pest populations could be controlled by fewer chemical pesticide applications. It is very difficult to manage certain plant diseases and arthropod pests through nonchemical means in some crops (Flinckh et al. 2006). Inadequate control not only leads to crop losses, but can result in their spread to larger areas making their control even more difficult. Manure commonly used in organic farms can have a bigger carbon footprint, and nitrate shortage in the root zone and nitrate leaching are common in organic farms (Tal 2018). A meta-analysis of European research by Tuomisto et al. (2012) identified both positive and negative impacts of organic farming in terms of nutrient management and emphasized the need to improve both organic and conventional systems for reducing negative environmental impacts and increasing yields. Many growers prefer a good IPM-based production to an organic production for the ease of operation and profitability. However, they continue to produce organic food to stay in business. Multiple conversations with the strawberry and vegetable growers in the Central Coast region of California indicated that they produce organically to meet the market demand, but they prefer a system where they can use nonorganic options when and as needed (Dara unpublished data). Growers in Bangladesh, Haiti, Moldova, and Myanmar, during training programs organized by the U.S. Agency for International Development, shared that organic farming is more challenging than conventional farming especially for pest management, but they produce organically because of high returns (personal communication). A small study conducted in the United Kingdom reported that organic growers had ecocentric reasons for protecting the environment while conventional growers had anthropocentric reasons to ensure food security (Kings and Ilbery 2011). However, a more recent review article thoroughly compared organic and conventional farming approaches at the global level (Tal 2018). When the productivity, biodiversity, water quality, off-site environmental impacts, carbon footprint, climate change, and other aspects were compared, carefully run conventional farming appears to be more sustainable than organic farming. Compared to organic farming or a conventional farming with non-ecocentric approach, a conventional system based on IPM principles and focused on sustainability is safe, profitable, and practical (Dara 2018b).

While middle and upper-class consumers may be willing to pay higher prices for organically produced food, many of the low-income groups in developed and underdeveloped countries cannot afford such food. Organic food production can lead to social inequality and a false sense of well-being for those can afford. Nutritional quality of organic foods is more for certain nutrients, while it is more for conventional foods for others (Worthington 2001, Dangour et al. 2009, Bourn and Prescott 2010, Popa et al. 2018). Although subjective well-being is reported from organic food consumption (Apaolaza et al. 2018), the evidence of health benefits from the nutritional quality of organic foods is yet to be validated (Dangour et al. 2009, Bourn and Prescott 2010). Food security for the growing world population is necessary through optimizing input costs, minimizing wastage, grower adoption of safe and sustainable practices, and consumer confidence in food produced through such practices. IPM addresses all the economic, environmental, and social aspects and provides safe and affordable food to the consumers and profits to producers and sellers, while maintaining environmental health.

Conclusions

Earlier IPM models are designed from the scientific perspective with a focus on ecological, environmental and evolutionary aspects of pest management to reduce or prevent economic losses. There was limited scope to include the human, social, business, and communication aspects of the total equation in the previous models that may be deficient in effective promotion and implementation of IPM. Several examples discussed in this paper showed the influence of these factors on development, outreach, and successful implementation of IPM practices around the world. Since IPM is a part of agriculture, which is a consumer-oriented enterprise, and agriculture is a part of global trade, which is influenced by several other factors, IPM is redefined for the modern times where advanced agricultural technologies and communication tools play a critical role in food production and consumption. Although the two outer layers in the new model can be applicable to more than pest management, they do have a significant influence on IPM within the entire crop production and are the driving force for farming operations. Agricultural researchers, educators, sociologists, economists, business analysts, managers, growers, pest management professionals, agricultural input manufacturers, retailers, and consumers play a critical role in food production. By reconfiguring the components and including various factors that influence them, the new IPM model provides a template for focusing on different areas of the paradigm and to encourage collaboration among different disciplines. This new model is expected to guide IPM strategies around the world to develop and implement sustainable agricultural practices to ensure profitability for the growers, affordability to consumers, and food security to the growing world population.

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