Chapter 8

Pesticides: Environmental Impacts and Management Strategies

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Additional information is available at the end of the chapter

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1. Introduction

Increase in food production is the prime-most objective of all countries, as world population is expected to grow to nearly 10 billion by 2050. Based on evidence, world population is increasing by an estimated 97 million per year (Saravi and Shokrzadeh, 2011). The Food and Agricultural Organization (FAO) of the United Nations has in-fact issued a sobering forecast that world food production needs to increase by 70%, in order to keep pace with the demand of growing population. However, increase in food production is faced with the ever-growing challenges especially the new area that can be increased for cultivation purposes is very limited (Saravi and Shokrzadeh, 2011). The increasing world population has therefore put a tremendous amount of pressure on the existing agricultural system so that food needs can be met from the same current resources like land, water etc. In the process of increasing crop production, herbicides, insecticides, fungicides, nematicides, fertilizers and soil amendments are now being used in higher quantities than in the past. These chemicals have mainly come into the picture since the introduction of synthetic insecticides in 1940, when organochlorine (OCl) insecticides were first used for pest management. Before this introduction, most weeds, pests, insects and diseases were controlled using sustainable practices such as cultural, mechanical, and physical control strategies.

Pesticides have now become an integral part of our modern life and are used to protect agricultural land, stored grain, flower gardens as well as to eradicate the pests transmitting dangerous infectious diseases. It has been estimated that globally nearly $38 billion are spent on pesticides each year (Pan-Germany, 2012). Manufacturers and researchers are designing new formulations of pesticides to meet the global demand. Ideally, the applied pesticides should only be toxic to the target organisms, should be biodegradable and eco-friendly to some extent (Rosell et al., 2008). Unfortunately, this is rarely the case as most of the pesticides are non-specific and may kill the organisms that are harmless or useful to the ecosystem. In general, it has been estimated that only about 0.1% of the pesticides reach the target organisms and the remaining bulk contaminates the surrounding environment (Carriger et al., 2006). The repeated use of persistent and non-biodegradable pesticides has polluted various components of water, air and soil ecosystem. Pesticides have also entered into the food chain and have bioaccumulated in the higher tropic level. More recently, several human acute and chronic illnesses have been associated with pesticides exposure (Mostafalou and Abdollahi, 2012). Below, we have detailed the effect of pesticides on target and non-target organisms including earthworms, predators, pollinators, humans, fishes, amphibians, and birds. Additionally, impact of pesticides on soil, water and air ecosystems is also discussed. Furthermore, an eco-friendly practice (Integrated Pest Management (IPM) approach) has been detailed as a strategy that could minimize the use of pesticides.

2. Effects of pesticides on target organisms

Over the past era there has been an increase in the development of pesticides to target a broad spectrum of pests. The increased quantity and frequency of pesticide applications have posed a major challenge to the targeted pests causing them to either disperse to new environment and/or adapt to the novel conditions (Meyers and Bull, 2002; Cothran et al., 2013). The adaptation of the pest to the new environment could be attributed to the several mechanisms such as gene mutation, change in population growth rates, and increase in number of generations etc. This has ultimately resulted in increased incidence of pest resurgence and appearance of pest species that are resistant to pesticides.

2.1. Pesticide resistance

"Resistance may be defined as a heritable change in the sensitivity of a pest population that is reflected in the repeated failure of a product to achieve the expected level of control when used according to the label recommendation for that pest species" (IRAC, 2013). Resistant individuals tend to be rare in a normal population, but indiscriminate use of chemicals can eliminate normal susceptible populations and thereby providing the resistant individuals a selective advantage in the presence of a pesticide. Resistant individuals continue to multiply in the absence of competition and eventually become the dominant portion of the population over generations. As majority of the individuals of a population are resistant, the insecticide is no longer effective thus causing the appearance or development of insecticide resistance.

Resistance is the most serious bottleneck in the successful use of pesticides these days. The intensive use of pesticides has led to the development of resistance in many targeted pest species around the globe (Tabashnik et al., 2009). Number of resistant insects and mite species had risen to 600 by the end of 1990, and increased to over 700 by the end of 2001. This trend is likely to be continued in 21st century as well. Resistance has been found in different insecticides groups e.g., 291 species have developed cyclodiene resistance, followed by DDT (263 species), organophosphates (260 species), carbamates (85 species), pyrethroids (48 species), fumigants (12 species), and other (40 species) (Dhaliwal et al., 2006). Important crop pests, parasites of livestock, common urban pests and disease vectors in some cases have developed resistance to such an extent that their control has become exceedingly challenging (Van Leeuwen et al., 2010; Gondhalekar et al., 2011). However, many factors such as genetics, biology/ecology and control operations influence the development of pesticide resistance (Georghiou and Taylor, 1977).

Insecticide bioassays using whole insects continue to be one of the most widely used approaches for detecting resistance (Brown and Brogdon, 1987; Gondhalekar et al., 2013) despite some associated drawbacks. In the past two decades, however, several new methods employing advanced biochemical and molecular techniques, and combination of insecticide bioassays have been developed for detecting insecticide resistance (Symondson and Hemingway, 1997; Scharf et al., 1999; Zhou et al., 2002). Some examples of these techniques are enzyme electrophoresis, enzyme assays, immuno-assays, allele-specific polymerase chain reaction (PCR) etc.

2.2. Pest resurgence

Pest resurgence is defined as the rapid reappearance of a pest population in injurious numbers following pesticide application. Use of persistent and broad spectrum pesticides that kills the beneficial natural enemies is thought to be the leading cause of pest resurgence. However, resurgence is known to occur due to several reasons, for example, increase in feeding and reproductive rates of insect pests, due to application of sub-lethal doses of pesticides, and sometimes elimination of a primary pest provides favorable conditions for the secondary pests to become primary/key pests (Dhaliwal et al., 2006). There are many pesticide-induced pest outbreaks reported in walnut (*Juglans regia*) (Bartlett and Ewart, 1951), hemlock (*Conium maculatum*) (McClure, 1977), soybeans (*Glycine max*) (Shepard et al., 1977), and cotton (*Gossypium hirsutum*) (Bottrell and Rummel, 1978). Among these, brown plant hopper (BPH) (*Nilaparvata lugens* (Stal)) in rice (*Oryza sativa* L.) cultivation has gained a major importance in Asian countries (Chelliah and Heinrichs, 1984). In general, natural BPH populations were kept under check by natural enemies including mirid bugs, ladybird beetles, spiders and various pathogens. However, pesticides have not only destroyed the natural enemies (Fabellar and Heinrichs, 1986), but have influenced the fecundity of BPH females (Wang et al., 2010) further enhancing their resurgence. Additionally, the resurgence of bed bug, *Cimex lectularius* (Davies et al., 2012) and cotton bollworm *Helicoverpa armigera* (Mironidis et al., 2013) have been reported due to insecticide resistance and indiscriminate use of pesticides.

3. Effects of pesticides on non-target organisms

The effect of pesticides on non-target organisms has been a source of worldwide attention and concern for decades. Adverse effects of applied pesticides on non-target arthropods have been widely reported (Ware, 1980). Unfortunately, natural insect enemies e.g., parasitoids and predators are most susceptible to insecticides and are severely affected (Aveling, 1977; Vickerman, 1988). The destruction of natural enemies can exacerbate pest problems as they play an important role in regulating pest population levels. Usually, if natural enemies are absent, additional insecticide sprays are required to control the target pest. In some cases, natural enemies that normally keep minor pests under check are also affected and this can result in secondary pest outbreaks. Along with natural enemies, population of soil arthropods is also drastically disturbed because of indiscriminate pesticide application in agricultural systems. Soil invertebrates including nematodes, springtails, mites, micro-arthropods, earthworms, spiders, insects and other small organisms make up the soil food web and enable decomposition of organic compounds such as leaves, manure, plant residues etc. They are essential for the maintenance of soil structure, transformation and mineralization of organic matter. Pesticide effects on above mentioned soil arthropods therefore negatively impact several links in the food web. The following are the examples of non-target organisms that are adversely impacted by pesticides.

3.1. Earthworms

Earthworms represent the greatest proportion of terrestrial invertebrates (>80%) (Yasmin and D'Souza, 2010) and play a significant role in improving soil fertility by decomposing the organic matter into humus. Earthworms also play a major role in improving and maintaining soil structure, by creating channels in soil that enable the process of soil aeration and drainage. However, their diversity, density and biomass are strongly influenced by soil management. They are considered as an important indicator of soil quality in agricultural ecosystems (Paoletti, 1999). Earthworms are affected by various agricultural practices and indiscriminate use of pesticides is one of the leading practices affecting them (Pelosi et al., 2013).

Pesticide applications can cause decline in earthworm populations. For example, carbamate insecticides are very toxic to earthworms and some organophosphates have been shown to reduce earthworm populations (Edwards, 1987). Similarly, a field study conducted in South Africa has also reported that earthworms were influenced detrimentally due to chronic and intermittent exposures to chlorpyrifos and azinphos methyl, respectively (Reinecke and Reinecke, 2007). Various scientific studies reported that pesticides influence earthworm growth, reproduction (cocoon production, number of hatchlings per cocoon, and incubation period) in a dose-dependent manner (Yasmin and D'Souza, 2010). Earthworms exposed to different kind of pesticides showed rupturing of cuticle, oozing out of coelomic fluid, swelling, and paling of body that led to softening of body tissues (Solaimalai et al., 2004). Similarly a study carried out in France showed that the combination of insecticides and fungicides at different concentrations caused neurotoxic effects in earthworms (Schreck et al., 2008). Increased exposure period and higher dose of insecticides can also cause physiological damage (cellular dysfunction and protein catabolism) to earthworms (Schreck et al., 2008).

3.2. Predators

Predators are organisms that live by preying on other organisms and they play a very crucial role in keeping pest populations under control. Predators (beneficial organisms) are also an important part of the "biological control" approach which is one component of the integrated pest management strategy discussed later. In some of the examples cited below, pesticides were the main cause for decline in predator population:

- In brinjal (*Solanum melongena* L.) ecosystem, spraying with cypermethrin and imidacloprid caused higher mortality of coccinellids, braconid wasps and predatory spiders compared to when sprayed with bio-pesticides and neem (*Azadirachta indica*) based insecticides (Ghananand et al., 2011).

- Species diversity, richness and evenness of collembola, and numbers of spiders were found to be lower in chlorpyrifos treated plots compared with control, in grassland pastures in UK (Fountain et al., 2007).

- Studies were carried out to investigate the effects of chemicals on soil arthropods in agricultural area near Everglades National Park, USA. It was found that higher number of arthropods (including predators such as coccinelids and spiders) were present in non-sprayed fields compared to fields sprayed with insecticides and herbicides (Amalin et al., 2009).

- In foliar application, all the systemic neonicotinoids such as imidacloprid, clothianidin, admire, thiamethoxam and acetamiprid were found highly toxic to natural enemies in comparison with spirotetramat, buprofezin and fipronil (Kumar et al., 2012).

Additionally, pesticides can also affect predator behavior and their life-history parameters including growth rate, development time and other reproductive functions. For example, in the eastern USA, glyphosate-based herbicides affected behavior and survival of spiders and ground beetles, apart from affecting arthropod community dynamics that can also influence biological control in an agroecosystem (Evans et al., 2010). Similarly, dimethoate was shown to significantly decrease the body size, haemocyte counts and reduction of morphometric parameters on carabid beetle (*Pterostichus melas italicus*), in Calabria, Italy (Giglio et al., 2011).

3.3. Pollinators

Pollinators are biotic agents that play a very important role in pollination process. Some of the recognized pollinators are different species of bees, bumble bees (*Bombus* spp.), honey bees (*Apis* spp.), fruit flies, some beetles, and birds (e.g., hummingbirds, honeyeaters, and sunbirds etc.). Pollinators can be used as bioindicators of ecosystemic processes (process by which physical, chemical, biological events help connecting organisms with their environment) in many ways as their activities are affected by environmental stress caused by parasites, competitors, diseases, predators, pesticides and habitat modifications (Kevan, 1999). However, using pesticides causes direct loss of insect pollinators and indirect loss to crops because of the lack of adequate populations of pollinators (Fishel, 2011).

Pesticide application also affects various activities of pollinators including foraging behaviour, colony mortality and pollen collecting efficiency. Most of our current knowledge about effects of pesticides on change in pollinator behaviour has come from various bee studies as they comprise 80% of the insect pollinator population. For instance, many laboratory studies have demonstrated the lethal and sub-lethal effects of neonicotinoid insecticides (imidacloprid, acetamiprid, clothianidin, thiamethoxam, thiacloprid, dinotefuran and nitenpyram) on foraging behavior, learning and memory abilities of bees (Blacquie`re et al., 2012). Worker bee (female bees that lack full reproductive capacity and play many other roles in bee colony) mortality, decreased pollen collecting efficiency and eventually colony collapse occur due to pesticides (neonicotinoid and pyrethroid) application (Gill et al., 2012). In addition to this, non-lethal exposure of honey bees to neonicotinoid insecticide (thiamethoxam) causes high mortality due to homing failure at a level that could put a risk of colony collapse (Henry et al., 2012). Sub-lethal doses of imidacloprid (the most commonly used pesticide worldwide) affected longevity and foraging in honey bees (*A. mellifera*). *Nosema ceranae* (*Nosema* invades the intestinal tracts of adult bees causing colony collapse disorder (CCD) and nosema disease/ nosemosis, which consequently lead to decrease in honey production). Microsporidial infections increased significantly in gut of bees from imidacloprid treated hives. It has been anticipated that interactions between pathogens and imidacloprid pesticide could be a main reason for worldwide honey bee colony mortality, including CCD (Pettis et al., 2012; Wu et al., 2012). There are also reports that imidacloprid reduced brood production due to decline in the fecundity of bumble bees (*B. terrestris*) (Laycock et al., 2012; Whitehorn et al., 2012). On the other hand, little work has been done on the impact of pesticides on wild pollinators. For example, a field study carried out in Italy on an agricultural field found lower bumblebee and butterfly species richness associated with pesticide application. They also found that bees (insect pollinators) were at higher risk from pesticide use (Brittain et al., 2010).

3.4. Humans

The deleterious effects of pesticides on human health have started to grow due to their toxicity and persistence in environment and ability to enter into the food chain. Pesticides can enter the human body by direct contact with chemicals, through food especially fruits and vegetables, contaminated water or polluted air. Both acute and chronic diseases can result from pesticide exposure and these are summarized below:

3.4.1. Acute illness

Acute illness generally appears a short time after contact or exposure to the pesticide. Pesticide drift from agricultural fields, exposure to pesticides during application and intentional or unintentional poisoning generally leads to the acute illness in humans (Dawson et al., 2010; Lee et al., 2011b). Several symptoms such as headaches, body aches, skin rashes, poor concentration, nausea, dizziness, impaired vision, cramps, panic attacks and in severe cases coma and death could occur due to pesticide poisoning (Pan-Germany, 2012). The severity of these risks is normally associated with toxicity and quantity of the agents used, mode of action, mode of application, length and frequency of contact with pesticides and person that is exposed during application (Richter, 2002). About 3 million cases are reported worldwide every year that occur due to acute pesticides poisoning. Out of these 3 million pesticide poisoning cases, 2 million are suicide attempts and the rest of these are occupational or accidental poisoning cases (Singh and Mandal, 2013). Suicide attempts due to acute pesticide poisoning are mainly the result of widespread availability of pesticides in rural areas (Richter, 2002; Dawson et al., 2010). Several strategies have been proposed to reduce the incidences that occur due to acute pesticide poisoning such as restricting the availability of pesticides, substituting the pesticide with a less toxic but with an equally effective alternative and by promoting use of personal protection equipment (Murray and Taylor, 2000; Konradsen et al., 2003). Strict laws regulating pesticide sales along with preventive health programs and community development efforts are needed to enforce such strategies.

3.4.2. Chronic illness

Continued exposure to sub-lethal quantities of pesticides for a prolonged period of time (years to decades), results in chronic illness in humans (Pan-Germany, 2012). Symptoms are not immediately apparent and manifest at a later stage. Agricultural workers are at a higher risk to get affected, however general population is also affected especially due to contaminated food and water or pesticides drift from the fields (Pan-Germany, 2012). Incidences of chronic diseases have started to grow as pesticides have become an increasing part of our ecosystem. There is mounting evidence that establish a link between pesticides exposure and the incidences of human chronic diseases affecting nervous, reproductive, renal, cardiovascular, and respiratory systems (Mostafalou and Abdollahi, 2012). The list of chronic diseases that are linked to prolonged pesticide exposure by various studies is summarized in Table 1.

Diseases	References
Cancer (Childhood and adult brain cancer; Renal cell cancer; lymphocytic leukaemia (CLL); Prostate Cancer)	Lee et al., 2005; Shim et al., 2009; Heck et al., 2010; Xu et al., 2010; Band et al., 2011; Cocco et al., 2013
Neuro degenerative diseases including Parkinson disease, Alzheimer disease	Elbaz et al., 2009; Hayden et al., 2010;Tanner et al., 2011
Cardio-vascular disease including artery disease	Abdullah et al., 2011; Andersen et al., 2012
Diabetes (Type 2 Diabetes)	Son et al., 2010; Lee et al., 2011a
Reproductive disorders	Petrelli and Mantovani, 2002; Greenlee et al., 2003
Birth defects	Winchester et al., 2009; Mesnage et al., 2010
Hormonal imbalances including infertility and breast pain	Xavier et al., 2004
Respiratory diseases (Asthma, Chronic obstructive pulmonary disease (COPD))	Chakraborty et al., 2009; Hoppin et al., 2009

Table 1. The List of chronic diseases that are linked to the exposure to pesticides

Several mechanisms have been illustrated that link development of chronic diseases with pesticide exposure. Direct interaction of pesticides with genetic material resulting in DNA damages and chromosomal aberration is considered to be one of the primary mechanisms that lead to the chronic diseases such as cancer etc (Mostafalou and Abdollahi, 2012). In this context, several studies report an increase in frequency of chromosomal aberration, sister chromatid exchange, and breakage in DNA strand in pesticide applicators who worked in agricultural fields (Grover et al., 2003; Santovito et al., 2012). Similar to this, pesticides are also known to induce epigenetic changes (heritable changes without any alteration in DNA sequences) through DNA methylation, histone modifications and expression of non-coding RNAs. For example, neurotoxic pesticide paraquat has been implicated to induce the Parkinson's disease (PD) through epigenetic changes by promoting histone acetylation (Song et al., 2010). Pesticides may also induce oxidative stress by increasing reactive oxygen species (ROS) through altering levels of antioxidant enzymes such as superoxide dismutase, glutathione reductase and catalase (Agrawal and Sharma, 2010). Several health problems such as Parkinson disease, disruption of glucose homeostasis have been linked with pesticides induced oxidative stress (Mostafalou and Abdollahi, 2012).

4. Pesticides and soil environment

A major fraction of the pesticides that are used for agriculture and other purposes accumulates in the soil. The indiscriminate and repeated use of pesticides further aggravates this soil accumulation problem. Several factors such as soil properties and soil micro-flora determine the fate of applied pesticides, owing to which it undergoes a variety of degradation, transport, and adsorption/desorption processes (Weber et al., 2004; Laabs et al., 2007; Hussain et al., 2009). The degraded pesticides interact with the soil and with its indigenous microorganisms, thus altering its microbial diversity, biochemical reactions and enzymatic activity (Hussain et al., 2009; Munoz-Leoz et al., 2011). A summary of the effects of pesticides on its various components are given below:

1. Pesticides that reach the soil can alter the soil microbial diversity and microbial biomass. Any alteration in the activities of soil microorganisms due to applied pesticides eventually leads to the disturbance in soil ecosystem and loss of soil fertility (Handa et al., 1999). Numerous studies have been undertaken which highlight these adverse impacts of pesticides on soil microorganisms and soil respiration (Dutta et al., 2010; Sofo et al., 2012). In addition to this, exogenous applications of pesticides could also influence the function of beneficial root-colonizing microbes such as bacteria and arbuscular mycorrhiza (AM), fungi and algae in soil by influencing their growth, colonization and metabolic activities etc (Debenest et al., 2010; Menendez et al., 2010; Tien and Chen, 2012).

The pesticides that reach the soil can interact with soil microflora in several ways:

a. It can adversely affect the growth, microbial diversity or microbial biomass of the soil microflora. For example, sulfonylurea herbicides- metsulfuron methyl, chlorsulfuron and thifensulfuron methyl were reported to reduce the growth of the fluorescent bacteria *Pseudomonas* strains that were isolated from an agricultural soil (Boldt and Jacobson, 1998). The *Pseudomonas* spp. is known to play an important ecological role in the soil habitat (Boldt and Jacobson, 1998), and hence its reduction can adversely affect soil fertility. Similarly, benomyl, captan and chlorothalonil were reported to suppress the peak soil respiration (an indicator of microbial biomass) in an unamended soil by 30–50% (Chen et al., 2001b).

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b. Pesticide application may also inhibit or kill certain group of microorganisms and outnumber other groups by releasing them from the competition (Hussain et al., 2009). For example, increase in bacterial biomass by 76% was reported in response to endosulfan application and that reduced the fungal biomass by 47% (Xie et al., 2011).

c. Applied pesticide may also act as a source of energy to some of the microbial group which may lead to increase in their growth and disturbances in the soil ecosystem. For example, bacterial isolates collected from wastewater irrigated agricultural soil showed the capability to utilize chlorpyriphos as a carbon source for their growth (Bhagobaty and Malik, 2010).

d. Pesticides can alter and/or reduce the functional structure and functional diversity of microorganisms, but increase the microbial biomass (Lupwayi et al., 2009). In contrast, application of pesticides can also reduce the microbial biomass while increasing the functional diversity of microbial community. For example, methamidophos and urea decreased the microbial biomass and increased the functional diversity of soil as determined by microbial biomass and community level physiological profiles (Wang et al., 2006).

2. Pesticides may also adversely affect the soils vital biochemical reactions including nitrogen fixation, nitrification, and ammonification by activating/deactivating specific soil microorganisms and/or enzymes (Hussain et al., 2009; Munoz-Leoz et al., 2011). The synergistic and additive interactions between pesticides, micro-organisms and soil properties ultimately govern increase or decrease in rate of soil biochemical reactions. For example, populations of the *Azospirillum* spp. bacteria and the rate of ammonification was reported to increase at a particular pesticide concentration (i.e 2.5 to 5.0 kg ha^{-1}) in both laterite and vertisol soils planted to groundnut (*Arachis hypogaea* L.). But the tested pesticides exerted antagonistic interactions on the population of *Azospirillum* spp. and ammonification at higher concentrations (7.5 and 10.0 kg ha^{-1}) (Srinivasulu et al., 2012a).

3. Pesticides have also been reported to influence mineralization of soil organic matter, which is a key soil property that determines the soil quality and productivity. For example, a significant reduction in soil organic matter was found after the application of four herbicides (atrazine, primeextra, paraquat, and glyphosate) (Sebiomo et al., 2011). However, soil organic matter then increased after continuous application from the second to the sixth week of herbicide treatment.

4. Pesticides that reach the soil may also disturb local metabolism or can alter the soil enzymatic activity (Gonod et al., 2006; Floch et al., 2011). Soil in general contains an enzymatic pool which comprises of free enzymes, immobilized extracellular enzymes and enzymes excreted by (or within) microorganisms that are indicator of biological equilibrium including soil fertility and quality (Mayanglambam et al., 2005; Hussain et al., 2009). Degradation of both pesticides and natural substances in soil is catalyzed by this enzymatic pool (Floch et al., 2011; Kizilkaya et al., 2012). Due to this, measuring the change in enzymatic activity has now been classified as a biological indicator to identify the impact of chemical substances including pesticides on soil biological functions (Garcia et al., 1997; Romero et al., 2010). In fact, it has generally been assumed that measuring the change in enzyme activity is an earlier indicator of soil degradation as compared to the chemical or physical parameters (Dick et al., 1994). Several studies have already been undertaken which indicate both increase and decrease in activities of soil enzymes such as hydrolases, oxidoreductases, and dehydrogenase (Ismail et al., 1998; Megharaj et al., 1999). A description of pesticides interactions with soil enzymes has been summarized in Table 2.

Enzyme (Function in soil)	**Examples of the pesticides applied**	**Comments**
Nitrogenase (An enzyme used by organisms to fix atmospheric nitrogen gas).	Carbendazim, Imazetapir, Thiram, Captan, 2,4-D, Quinalphos, Monocrotophos, Endosulfan, γ-HCH, Butachlors	Pesticide reduced or inhibited the nitrogenase activity in laboratory or field conditions (Chalam et al., 1996; Martinez-Toledo et al., 1998; Niewiadomska, 2004; Niewiadomska and Klama, 2005; Prasad et al., 2011)/ Pesticides stimulated the nitrogenase activity (Patnaik et al., 1995)
Phosphatase (hydrolyzes organic P compounds to inorganic P)	2,4-D, Nitrapyrin, Monocrotophos, Chlorpyrifos, Mancozeb and Carbendazim	Inhibited (Tu, 1981); Activity increased, but higher concentration or increasing incubation period has inhibitory effects (Madhuri and Rangaswamy, 2002; Srinivasulu et al., 2012b)
Urease (catalyzes the hydrolysis of urea into CO_2 and NH_3 and is a key component in the nitrogen cycle in soils)	Isoproturon, Benomyl, Captan, Diazinon, Profenofos	Increase in urease activity (Chen et al., 2001a; Nowak et al., 2004), Pesticide reduced/inhibited urease activity (Abdel-Mallek et al., 1994; Ingram et al., 2005)
Dehydrogenase (DHA): (an oxidoreductase enzyme that catalyzes the removal of hydrogen)	Azadirachtin, Acetamiprid, Quinalphos,Glyphosate	Positive/stimulatory influence on the DHA (Singh and Kumar, 2008; Kizilkaya et al., 2012)/Initially inhibited but later on activity was restored (Andrea et al., 2000; Mayanglambam et al., 2005)
Invertase (hydrolyzes sucrose to fructose and glucose)	Atrazine, Carbaryl, Paraquat	Inhibited invertase activity (Gianfreda et al., 1995; Sannino and Gianfreda, 2001)
β-glucosidase (hydrolyzes disaccharides in soil to form β-glucose)	Metalaxyl, Ridomil gold plus copper	Enzyme activity increased and then decreased (Sukul, 2006) or inhibited (Demanou et al., 2004)
Cellulase (hydrolyzes cellulose to D-glucose)	Benlate, Captan, Brominal	Inhibited enzyme activity (Arinze and Yubedee, 2000; Omar and Abdel-Sater, 2001)

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Enzyme (Function in soil)	Examples of the pesticides applied	Comments
Arylsulphatase (an enzyme that hydrolyzes aryl sulfates)	Cinosulfuron, Prosulfuron, Thifensulfuron methyl, Triasulfuron	Decreased enzyme activity (Sofo et al., 2012)

Table 2. A summary of the effects of pesticides on different soil enzymes

Several environmental factors control the bioavailability, degradation and effect of pesticides on soil microorganisms in addition to the persistence, concentration and toxicity of the applied pesticides. These include soil texture, presence of organic matter, vegetation and cultural practices (Murage et al., 2007). For instance, a mixture of compost and straw was found to have the capability of bio-degrading different mixtures of fungicides that are usually applied in vineyards when tested under laboratory conditions (Coppola et al., 2011). Similarly, persistence of the herbicide imazapyr was reported to be different in three Argentinean soils (Tandil, Anguil, and Cerro Azul sites) and its half-life was negatively associated with soil pH, iron and aluminum content, and positively related with clay content (Gianelli et al., 2013). Additionally, level of soil moisture is also one of the most important factors that regulates pesticide bioavailability and degradation, as water acts as solvent for pesticide movement and diffusion, and is essential for microbial functioning (Pal and Tah, 2012). For example, degradation of herbicide saflufenacil was found to be faster at field capacity for Nada, Crowley and Gilbert soils as compared to the saturated soil conditions (Camargo et al., 2013).

It is important to monitor the response of soil microbial communities and various enzymatic activities to pesticide exposure in order to reduce their deleterious effects. A combination of both cultivation-dependent (e.g., community-level physiological profiling (CLPP), measuring overall rates of microbial activity) and cultivation-independent (e.g., DNA sequence information, proteomics of environmental samples) methods can be applied to measure and interpret the effects of pesticide exposure (Imfeld and Vuilleumier, 2012). With the advent of efficient new sequencing techniques and metagenomics, the scope of deploying cultivation independent methods for measuring bacterial diversity and function in soil ecosystem has been further increased. Metagenomics approach has been applied already to measure microbial diversity for a range of soil systems including contaminated sites (Ono et al., 2007) and land managed with different cultural practices (Souza et al., 2013). Such high-tech approaches hold the key for future methods to measure the mode of adaptation ecosystem to different pesticides and in development of new methods to better manage pesticide applications.

A careful screening of pesticide effects on soil microflora should be done in laboratory before their field applications. This is because pesticides tend to accumulate in soil due to repeated applications over time and can pose adverse effects on soil microflora even though they are applied at recommended doses (Ahemad et al., 2009). For instance, Ahemad and Khan (2011) reported the highest toxicity to plant growth promoting characteristics of the *Bradyrhi zobium* sp. when its strain MRM6 was grown with three times the recommended field rates of glyphosate, imidacloprid and hexaconazole. Similarly, Dunfield et al. (2000) assessed the effects of the fungicides captan and thiram at rates of 0.25-2 g a.i. kg^{-1} on the survival and phenotypic characteristics of bacteria *Rhizobium leguminosarum* bv. *viceae*, strain C1. They found that even though both captan and thiram significantly reduced the numbers of rhizobia recovered from seed and altered the FAME (fatty acid methyl ester) and biological profiles of recovered rhizobia, it was only the highest concentrations of captan that affected nodulation and plant growth. Similarly, herbicide mesotrione affected soil microbial communities, but the effects were only detected at doses far exceeding the recommended field rates (Crouzet et al., 2010). Overall, it is crucial to comprehend the role of pesticides in perturbing soil environment, so that the risk of pesticide contamination and its consequent adverse impacts on soil environment can be evaluated.

5. Pesticides in water and air ecosystem

Pesticide residues in water are a major concern as they pose a serious threat to biological communities including humans. There are different ways by which pesticides can get into water such as accidental spillage, industrial effluent, surface run off and transport from pesticide treated soils, washing of spray equipments after spray operation, drift into ponds, lakes, streams and river water, aerial spray to control water-inhibiting pests (Carter and Heather, 1995; Singh and Mandal, 2013). Pesticides generally move from fields to various water reservoirs by runoff or in drainage induced by rain or irrigation (Larson et al., 2010). Similarly, the presence of pesticides in air can be caused by number of factors including spray drift, volatilization from the treated surfaces, and aerial application of pesticides. Extent of drift depends on: droplet size and wind speed. The rate of volatilization is dependent on time after pesticide treatment, the surface on which the pesticide settles, the ambient temperature, humidity and wind speed and the vapor pressure of the ingredients (Kips, 1985). The volatility or semi-volatility nature of the pesticide compounds similarly constitutes an important risk of atmospheric pollution of large cities (Trajkovska et al., 2009). For instance, organophosphorus (OP) pesticides were identified from environmental samples of air and surface following agricultural spray applications in California and Washington (USA) (Armstrong et al., 2013). In Italian forests, indiscriminate use of pesticides and its active metabolites has led to the contamination of water bodies and ambient air, possibly affecting the health of aquatic biota fishes, amphibians and birds (Trevisan et al., 1993). The following section describes the effect of pesticides on fishes, amphibians and birds.

5.1. Fishes

Fishes are an important part of marine ecosystem as they interact closely with physical, biological and chemical environment. Fishes provide food source for other animals such as sea birds and marine mammals and thus fishes form an integral part of the marine food web. A lot of research has been carried out to examine the impact of pesticides on decline in fish population (Scholz et al., 2012). Pesticides have been directly linked to causing fish mortality worldwide. For example, 27 freshwater fish species are found to be affected by “plant protection products” (PPP) in Europe (Ibrahim et al., 2013). Another pesticide pentachlorophenol

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(NaPCP) is reported to cause large numbers of fish mortality in the rice fields of Surinam (Vermeer et al., 1970). Pesticides not only impact the fish but also food webs related to them. The persistent pesticides (organochlorine pesticides and polychlorinated biphenyls) have already been found in the major Arctic Ocean food webs (Hargrave et al., 1992). A survey was conducted to examine the influence of pesticides on aquatic community in West Bengal, India. Many body tissues of the fish such as gills, alimentary canal, liver and brain of carp and catfish were found drastically damaged by pesticides. It was reported that such level of pesticides in fish could harm the fish consumers as well (Konar, 2011).

Several examples are available where pesticides impacted the vital fish organs and behavior. Organophosphate pesticide "Abate" has the potential to alter the vitellogenesis (the process whereby yolky eggs are produced) of catfish (*Heteropneustes fossilis* (Bloch.)), which can severely affect catfish farming (Kumari, 2012). Another major effect of toxic contaminants is on olfaction in fishes since it can affect activities such as mating, locating food, avoiding predators, discriminating kin and homing etc (Tierney et al., 2010). Simultaneous exposure of trematode parasite (*Telogaster opisthorchis*), freshwater fish (*Galaxias anomalus*) and snails to high glyphosate concentrations significantly reduced their survival and development. Within 24 hrs of exposure to higher glyphosate concentrations, 100% mortality of individuals was found (Kelly et al., 2010).

The impact of pesticides within an aquatic environment is influenced by their water solubility and uptake ability within an organism (Pereira et al., 2013). For example, Clomazone, a popular herbicide, is particularly water soluble; a property that increases its likelihood of contaminating surface and groundwater. The hydrophilic (water-loving) or lipophobic (fat-hating) nature of this pesticide makes it less available in the fatty tissues of an organism (Pereira et al., 2013). Further to this, the toxicity of chemical (e.g., endosulfan in this case) in juvenile rainbow trout (*Oncorhynchus mykiss*) was affected by alkalinity, temperature of water and size of the fish (Capkin et al., 2006).

Pesticides in natural water within the acceptable concentration range can still pose harmful effects. Kock-Schulmeyer et al. (2012) found that even if the pesticide levels found in Llobregat River basin of Spain were within the European Union Environmental Quality Standards, they still accounted for a low to high ecotoxicological risk for aquatic organisms, especially algae and macro-invertebrates. Proper measures should be taken while disposing of expired pesticides, so that their discharge into the water bodies does not danger the aquatic life. This is because the alteration in water pH by expired insecticides can lead to acute toxicity of different fish (Satyavani et al., 2011).

5.2. Amphibians

Amphibians are ectothermic, tetrapod vertebrates of class Amphibia. They inhabit a wide variety of habitats, with most species living within fossorial, arboreal, terrestrial, and freshwater aquatic ecosystems. The global decline in the amphibian population has become an environmental concern worldwide. Many amphibian species are on the brink of extinction with 7.4% listed as critically endangered, and at least 43.2% experiencing some sort of population decrease (Stuart et al., 2004). There could be multitude of reasons for decline in amphibian species diversity, but pesticides appear to be playing an important role. Global warming and climate change are leading to more variable and warmer temperatures which may have increased the impact of pesticides on amphibian populations (Relyea, 2003; Johnson et al., 2013).

Many studies showed that amphibians are susceptible to environmental contaminants due to their permeable skin, dual aquatic-terrestrial cycle and relatively rudimentary immune system (Kerby et al., 2010). Several studies showing the impact of pesticides on amphibians are being mentioned here. It has been reported that the world's most commonly used herbicide (Roundup (Glyphosate)) may have far reaching effects on non-target amphibians (Relyea, 2012). Roundup, a globally used herbicide caused high mortality of larval tadpoles (3 different species in North America) and juvenile frogs under natural conditions in an outdoor pond mesocosm (Relyea, 2005a). Most of the evidence supported the toxic effects of pesticides on juvenile European common frogs (*Rana temporaria*) in an agricultural field that was over sprayed. Mortality of frogs ranged from 100% after 1 hour to 40% after 7 days at the recommended concentrations of pesticides (Bruhl et al., 2013). It was found that population of the wood frog (*Lithobates sylyaticus*) near an agricultural area was more resistant to common insecticide (chlorpyrifos), but not to the common herbicide (Roundup). However, no evidence was reported that resistance carried a performance cost when facing competition and the fear of predation (Cothran et al., 2013).

Further to this, pesticides indirectly affect amphibian populations by influencing growth of aquatic communities such as fungi, zooplankton, and phytoplankton as they are one of their prime energy resources. Malathion is the most commonly used broad-spectrum insecticide in United States. It is legal to spray malathion over aquatic habitats to control mosquitoes (Family: Culicidae), that vector malaria and West Nile Virus. A study found that even low concentration of malathion caused direct and indirect effects on aquatic communities (Relyea, 2012). For example, indirect effect of malathion led to decrease in zooplankton diversity, that led to increase in phytoplankton, a decrease in periphyton, and finally decrease in growth of frog tadpoles (Relyea and Hoverman, 2008). Moreover, it was found that repeated applications of low doses had largest impacts than single high dose application of malathion on an aquatic system (Relyea and Diecks, 2008). A comprehensive study was conducted to examine the effect of globally used pesticides including insecticides (carbaryl, malathion, and herbicides (glyphosate, 2, 4-D)) on aquatic communities (algae, 25 animal species). Species richness reduced differentially, 15% with carbaryl, 30% with malathion, and 22% with roundup, whereas 0% with 2, 4-D. It was found that Roundup completely eliminated two species of tadpoles and led to 70% decline in tadpole species (Relyea, 2005b). Another study demonstrated that frogs (*Rana pipiens*) living in agricultural area, where they experienced higher exposure to chemicals were smaller in size and weight than frogs living in area exposed to low-levels of chemicals. It suggests that frogs living in agricultural areas might have more vulnerability to infections and diseases due to their smaller size and alternation in their immune system (decrease in number of splenocytes and phagocytic activity) (Christin et al., 2013).

5.3. Birds

Birds are a diverse group, and apart from their distinct songs and calls, showy displays and bright colors adding enjoyment to lives of humans, they play a very critical role in food chains and webs in our ecosystems. Birds are also called “aerial acrobats” consuming different kinds of insects such as mosquitoes, European corn borer moth (*Ostrinia nubilalis*), Japanese beetles (*Popillia japonica*), and many other insect species that are considered as some of the most serious agricultural and health pests. Birds are important biotic components of an ecosystem and help in maintaining a natural equilibrium of insect populations by predating on them. In absence of birds, outbreaks of insect pest populations would become more common, ultimately leading to increased pesticide use. Pesticides exposure by different means such as direct ingestion of pesticide granules and treated seeds, treated crops, direct exposure to sprays, contaminated water, or feeding on contaminated prey, and baits cause birds mortality (Fishel, 2011; Guerrero et al., 2012). In USA, almost 50 pesticides are known for killing song birds, game birds, seabirds, shorebirds, and raptors (BLI, 2004).

Pesticides have a potential to alter behavior and reproduction of birds. Some of the examples cited here, using different synthetic chemicals including carbamates, organochlorines, and organophosphates can cause a decline in the populations of raptorial birds by altering their feeding behavior and reproduction (Mitra et al., 2011). A large area in the world is under rice and therefore cultivation and volume of pesticides applied in rice field is quite significant. Many different kinds of organochlorines, cholinesterase-inhibiting insecticides including carbofuran, monocrotophos, phorate, diazinon, fenthion, phosphamidon, methyl parathion and azinphos-methyl along with fungicides, herbicides and molluscicides are being used in rice fields. Some of these chemicals are highly toxic to birds causing mortality and some chemicals even have the potential to affect their reproductive systems (Parsons et al., 2010). Indirect effects of pesticides, through food chain have been proposed as a possible factor in decline of farmland bird species. Insecticides applied in breeding season can affect breeding performance of corn bunting (*Miliaria calandra*) and yellowhammer (*Emberiza citrinella*) (Boatman et al., 2004).

Pesticides, especially insecticides such as carbamates and organophosphates have the potential to cause bird mortality due to their high toxicity (Hunter, 1995). Further to this, insecticides and fungicides pose a most prominent threat to ground-nesting farmland birds as compared to other agricultural practices. The decline of US grassland birds is attributed to acute pesticide toxicity and not agricultural intensification as previously thought (Mineau and Whiteside, 2013). An estimate suggests that 672 million birds are directly exposed to pesticides every year on farmlands, and 10% of these birds die due to acute toxic effects of pesticides (Williams, 1997). A study was conducted in rice fields of Surinam to examine the effects of pesticides, pentachlorophenol (NaPCP) on birds. NaPCP was sprayed for the purpose of killing *Pomacea* snails. Large numbers of dead sick/dead egrets, herons and jacana birds were found during the period of pesticide application. Pentachlorophenol and endrin levels in these birds suggested that ingestion of contaminated food was the probable cause of sickness and mortality (Vermeer et al., 1970).

6. Pesticides and biomagnification

The increase in concentration of pesticides due to its persistent and non-biodegradable nature in the tissues of organisms at each successive level of food chain is known as biomagnification. Due to this phenomenon, organisms at the higher levels of food chain experience greater harm as compared to those at lower levels. Several studies have been undertaken that demonstrate enhanced amount of toxic compounds with increase in trophic levels. For example, out of 36 species collected from three lakes of northeastern Louisiana (USA) that were found to contain residues of 13 organochlorines, tertiary consumers such as green-backed heron (*Butorides striatus*), and snakes etc., contained the highest residues as compared to secondary consumers (bluegill (*Lepomis macrochirus*), blacktail shiner (*Notopis venustus*)) (Niethammer et al., 1984). Similarly, significantly higher concentrations of dichlorodiphenyltrichloroethane (4,4′-DDE) were found in the top consumer fish in Lake Ziway, catflish (*Clarias gariepinus*) than in lower consumers, Nile tilapia (*Oreochromis niloticus*), tilapia (*Tilapia zillii*) and goldfish (*Carassius auratus*) (Deribe et al., 2013). Some of the adverse effects of pesticides on non-target organisms such as fish, amphibians and humans discussed in the above section have also occurred as a result of biomagnifications of the toxic compounds. For example, reproductive failure and population decline in the fish-eating birds (e.g., gulls, terns, herons etc.) was observed as a result of DDE induced eggshell thinning (Grasman et al., 1998). The extent of biomagnifications increases with increase in persistence and lipophilic (fat-loving) characteristics of the particular pesticide. As a result of this, organochlorines are known to have higher biomaginification rate and are more persistent in a wider range of organisms as compared to organophsphates (Favari et al., 2002). It is important to do the risk assessments associated with the pesticides on the basis of their bioaccumulation and biomagnifications before considering them for agricultural purposes.

7. Strategies for pesticide management

There are a relatively few pesticide resistance management tactics that have been proposed risk-free and have a reasonable chance of success under a variety of different circumstances. Headmost among these are: monitoring of pest population in field before any pesticide application, alteration of pesticides with different modes of action, restricting number of applications over time and space, creating or exploiting refugia, avoiding unnecessary persistence, targeting pesticide applications against the most vulnerable stages of pest life cycle, using synergists which can enhance the toxicity of given pesticides by inhibiting the detoxification mechanisms. The most difficult challenge in managing resistance is not the unavailability of appropriate methods but ensuring their adoption by growers and pest control operators (Denholm et al., 1998; Dhaliwal et al., 2006).

Pest resurgence is a dose-dependent process and there are ways to tackle this problem using correct dosage of effective and recommended pesticides. Resurgence problem occurs due to a number of reasons. One of them is due to farmers’ tendency to apply low-dose insecticides

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due to economic constraints that lead to inadequate and ineffective control of pests. Pest resurgence also occurs due to reduced biological control (most common with insects), reduced competition (most common with weeds; monocots vs. dicots), direct stimulation of pest (due to sub-lethal dose), and improved crop growth.

In the current scenario, optimized use of pesticides is important to reduce environmental contamination while increasing their effectiveness against target pest. This way we can reduce pesticide resistance as well as pest resurgence problems. This has led to the consideration of rational use of pesticides, and the physiological and ecological selectivity of pesticides. Physiological selectivity is characterized by differential toxicity between taxa for a given insecticide. However, ecological selectivity refers to the modification of operational procedure in order to reduce unnecessary destruction to non-target organisms (Dent, 2000). Farmers should focus to use insecticides that are more toxic to target species than their natural enemies which could help to reduce resurgence to some extent (Dhaliwal et al., 2006).

One should consider adopting an Integrated Pest Management (IPM) approach for controlling pests, as these practices are designed to have minimal environment disturbance. The aim of IPM is not only to reduce indiscriminate pesticide use but also to substitute hazardous chemicals with safe chemistries. IPM is a process of achieving long-term, environmentally safe pest control using wide variety of technology and other potential pest management practices. According to National Academy of Science, "IPM refers to an ecological approach in pest management in which all available necessary techniques are consolidated in a unified program so that populations can be managed in such a manner that economic damage is avoided and adverse side effects are minimized" (NAS, 1969). In European arable systems, applied multi-disciplinary research and farmer incentives to encourage the adoption of innovative IPM strategies are essential for development of sustainable maize-based cropping systems. These IPM strategies can contribute immensely to address the European strategic commitment to the environmentally sustainable use of pesticides (Vasileiadis et al., 2011). The added cost and time to do an IPM approach is sometimes a difficult task for growers, but government and extension services can help in convincing and encouraging growers to go for IPM strategy for eco-friendly and long term pest control. We have already discussed earlier that continuous use of pesticides leads to pesticide resistance and pest resurgence problem. To avoid these issues we can always go for other potential management options that include cultural and physical control, host plant resistance, biocontrol, and the use of biopesticides etc.

7.1. Cultural control

Historically, cultural control methods were the farmer's most important tool of preventing crop losses. Cultural control for pest management has been adopted by growers throughout the world for a long time due to its environmentally friendly nature and minimal costs (Gill et al., 2013). Cultural control practices are regular farm operations, which are used to destroy the pests or to prevent them from causing plant damage. Several methods of cultural control have been practiced, such as crop rotation, sanitation, soil solarization, timed planting and harvest, use of resistant varieties, certified seeds, allelopathy, intercropping or "companion planting", use of farmyard manure, and living and organic mulches (Altieri et al., 1978; Dent, 2000; Dhaliwal et al., 2006). Soil solarization (McSorley and Gill, 2010; Gill and McSorley, 2011b) and organic mulches (Gill and McSorley, 2011a) alone and their integration (Gill and McSorley, 2010) were reported as economical and eco-friendly technique for controlling soil-surface arthropods (various insects, and nematodes) (Gill et al., 2010; Gill et al., 2011) and weeds (Gill et al., 2009; Gill and McSorley, 2011b). More effective cultural control can be achieved by synchronizing existing practices with life cycles of pests. This way the weakest link in their life cycle is subjected to adverse climatic conditions.

Large insect populations are killed automatically by farmers when they expose them to adverse climatic conditions through agricultural practices like weeding, ploughing, and hoeing. Ploughing of agricultural field allows turnover of the upper layer of soil while burying the weeds and residues from last year. For example, in South Africa, about 70% of overwintering populations of spotted stalk borer (*Chilo partellus*) and maize stalk borer (*Busseola fusca*) in grain sorghum (*Sorghum bicolor* L.) and maize (*Zea mays* L.) fields were destroyed by slashing the plants. Ploughing and discing of plant residues after slashing further destroyed 24% population on grain sorghum and 19% on maize (Kfir, 1990). Planting dates (Goyal and Kanta, 2005a), and barrier crops (teosinte (*Zea* spp.) and pearl millet (*Pennisetum glaucum* (L.)) (Goyal and Kanta, 2005b) were found to be effective against maize stem borer (*Chilo partellus*) in India. The brown seaweeds *Spatoglossum asperum* and *Sargassum swartzii* can be used as manure to protect plants (tomato (*Solanum lycopersicum* L.) in this case) from root rotting fungi, (*Macrophomina phaseolina*, *Rhizoctonia solani* and *Fusarium solani*) and root-knot nematode (*Meloidogyne javanica*) and for providing necessary nutrients to plants (Sultana et al., 2012). In India, rodents are pests in agriculture, horticulture, forestry, animal husbandry as well as in human dwellings and rural and urban storage facilities. Cultural methods, such as clean cultivation, proper soil tillage and crop scheduling, barriers, repellents and proofing that reduce the rodent harbourage, food sources and immigration may have long lasting effects (Parshad, 1999).

7.2. Physical and mechanical control

Managing pest populations using devices which affect them physically or alter their physical environment is called physical control. Exposure to sun rays, steaming, moisture management especially for stored grain pests, and light traps for attracting various kinds of moths, beetles and other pests are different methods used in physical control. For example steaming woolen winter clothes help in eliminating population of the woolly bear moth, *Antherenus vorax* (waterhouse) (Dhaliwal et al., 2006). Hot water treatment of plant storage products like corns, and bulbs helps to kill many concealed pests such as eelworms and bulb flies. Superheating of empty grain storage godowns to a temperature of 50ºC for 10-12 hours helps killing hibernating stored grain pests. Exposure of cotton seeds to sun's heat in thin layers for 2-3 days during summer helps in killing diapausing larvae of pink bollworm (*Pectinophora gossypiella* Saunders) (Dhaliwal et al., 2006).

Mechanical control refers to suppression of pest population by manual devices. It includes various practices such as hand picking, trapping and suction devices, clipping, pruning and crushing of infested shoots and floral parts, and exclusion by screens and barriers to keep away house flies (*Musca domestica*), mosquitoes and other pests. In south-eastern Australia, the

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common starling (*Sturnus vulgaris*) is an established invasive avian pest that is now making incursions into Western Australia which is currently free of this species. Trapping with live-lure birds is suggested to be the most cost-effective and widely implemented starling control technique (Campbell et al., 2012). Numerous wildlife species such as coyotes (*Canis latrans* Say), squirrels (Sciuridae family), and birds are known pests of California agriculture in the United States. For these pests, different non-lethal control options including habitat modification, exclusionary devices, and baiting are generally preferred (Baldwin et al., 2013). Mechanical weed control is mainly associated with tillage practices which are performed with special tools such as harrows, hoes, and brushes in growing crops. Increased knowledge about side effects of herbicides has further driven the interest in adoption of mechanical weed control thus increasing the prevalence of organic farming (Rueda-Ayala et al., 2010; Jat et al., 2011). Trapping using yellow colored sticky traps is an effective way for controlling tephritid flies (Dhaliwal et al., 2006).

7.3. Host plant resistance

Host plant resistance (HPR) is the genetic ability of the plant to improve its survival and reproduction by a range of adaptations as compared to the other cultivars when exposed to the same level of pest infestation. HPR offers the most effective, economical and eco-friendly method of pest control (Sharma and Ortiz, 2002), and is considered to be a key element of the IPM strategy. Due to this, identifying and developing HPR has always been a major thrust area of plant breeding, and a number of breeding programs aiming to develop pest resistant crops have been deployed in almost all the cultivated crop species. For example, identification and/or development of resistant varieties in maize against European corn borer (*Ostrinia nubilalis* (Hubner)) (Dhaliwal et al., 2006) , brassica against cabbage butterfly (*Pieris brassicae* Linn.) (Chahil and Kular, 2013), wheat (*Triticum aestivum* L.) and rye (*Secale cereale* L.) against *Fusarium* diseases (Miedaner, 1997) *Brassica* sp. against Sclerotinia disease (Garg et al., 2008), and in rice against bacterial blight (Khush et al., 1989). Additionally, availability and access to various germplasm collections have increased the scope of widening the gene-pool of cultivated crops and further identifying and developing HPR. Wild species are especially known to possess a rich repository of genes against various defense traits as they have evolved under different geographic locations. Considerable progress has been made where identification and/or transfer of resistance gene from wild to cultivated species against various pest species has been achieved such as in potato (*Solanum tuberosum* L.) against late blight (*Phytophthora infestans*) from ten wild *Solanum sp.* (Colon and Budding, 1988), wheat against powdery mildew (*Erysiphe graminis*) from wild emmer wheat (*Triticum dicoccoides*) (Reader and Miller, 1991) and mustard (*Brassica juncea*) against *Sclerotinia sclerotiorum* from *Erucastrum cardaminoides* (Garg et al., 2010).

7.3.1. Use of biotechnology and molecular approaches for developing resistant genotype

The advent of new biotechnological and molecular approaches has opened the way to develop resistant genotype that could not only reduce the pesticides application, but it also has a potential to be a part of IPM. Development of resistant genotypes in classical breeding is met with several challenges such as it is time consuming, desired traits are linked with the undesirable traits (linkage drag) and most importantly lack of resistant genotypes in the gene pool. On the other hand, use of biotechnology in crop improvement ensures the development of pest-resistant genotypes in a comparatively short period of time and minimizes the effects of linkage drag. One of the classic examples where biotechnology was successfully deployed to develop resistant genotype is by the synthesis of transgenic plants which involves modifying plant traits by inserting foreign DNA from a different species (De la Pena et al., 1987). A number of different crops including cotton, rice, mustard, and maize have been modified up to now to engineer the genotypes against various biotic stresses (Ahmad et al., 2012). One of the most successful examples of synthesis of transgenic genotype against pest resistance is in cotton where the gene coding for Bt toxin from the bacterium *Bacillus thuringiensis* (Bt) was inserted leading cotton genotypes to produce Bt toxin in its tissue (Pray et al., 2002; Wu et al., 2008). The lepidopteran larvae that fed on the transgenic plants were killed due to Bt toxin eventually decreasing the amount of pesticide applied to the field. Examples of transgenic crops that have been developed with a potential to reduce pesticides use are abound and few of them include potato lines against potato tuber moth (*Phthorimaea operculella*) expressing Cry1Ab (Kumar et al., 2010), rice against yellow stem borer (*Scirpophaga incertulas*) expressing potato proteinase inhibitor 2 (Bhutani et al., 2006) and oilseed rape lines resistant to various fungal attack over-expressing tomato chitinase gene (Grison et al., 1996).

Another strategy where biotechnology and molecular approaches have been deployed to combat biotic stresses involves the use of RNA interference (RNAi) technique. This technique primarily uses transgenic plants expressing double stranded RNA (dsRNA) and that reduces the messenger RNA (mRNA) levels (with a high specificity and fidelity) of a crucial gene in the target pest upon feeding (Price and Gatehouse, 2008; Kos et al., 2009). This ultimately interferes with the development and survival of the target pest. RNAi has emerged as a powerful functional genomics approach and it has been used to engineer several crops against number of insect-pests. For example, RNAi technique was used in tobacco genotype that targeted the gene "integrase splicing factor" in root knot nematode, *Meloidogyne incognita* nematode eventually leading to the decrease in the number of nematodes 6-7 weeks post inoculation (Yadav et al., 2006). When such an advanced and effective approach is combined with IPM, it has a great potential to decrease chemical use in agricultural and other ecosystems.

7.4. Biological control

The process of using natural enemies of particular pests to reduce their populations to such a level where economic losses are either eliminated or suppressed is called biological control. Traditionally the most important biocontrol agents are parasitoids, predators and pathogens. Biological control involves three major techniques, *viz.*, introduction, conservation, and augmentation of natural enemies. Biocontrol agents include vertebrates, nemathelminthes (flatworms, and roundworms), arthropods (spiders, mites, and insects), pathogens like viruses, bacteria, protozoa, fungi and rickettsiae all of which play a dynamic role in natural regulation of insect and mite populations (Dhaliwal et al., 2006). In 1762, the Indian Mynah, *Acridotheres tristis* (Linnaeus), was introduced to control red locust in Mauritius. First signifi-

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cant success in controlling a pest was achieved on the suggestion of C. V. Riley of California (USA) in 1888. The Vedalia beetle (*Rodolia cardinalis* (Mulsant)), was introduced from Australia into California (USA) for the control of cottony-cushion scale (*Icerya purchasi* maskell) on citrus plants. This scale insect had been accidentally introduced earlier from Australia (Dhaliwal et al., 2006).

Biological control of weeds has been very successful worldwide. There are about 41 species of weeds which have been successfully controlled using insects and pathogens as biocontrol agents. Also, 3 weed species have been controlled using native fungi as mycoherbicides (Mcfadyen, 2000). A total of 12 insects were released in Australia against prickly pear (*Opuntia stricta*), out of these, *Dactylopius opuntiae* and *Cactoblastis cactorum* were responsible for the successful control of prickly pear weed (Julien and Griffiths, 1998). In the past decade, Australia has released 43 species of arthropods and pathogens in 19 different projects for successful biological control of many exotic weeds. Effective biological control was achieved in several projects and outstanding success was achieved in the control of rubber vine (*Cryptostegia grandiflora*), and bridal creeper (*Asparagus asparagoides*) (Palmer et al., 2010).

Examples of biological control are available for other organisms like helminthes, nematodes, fungi, bacteria etc. A nematophagous fungus (*Monacrosporium thaumasium*) was found to be effective in controlling cyathostomin, one of the most important helminthes in tropical region of southeastern Brazil (Tavela et al., 2011). *Trichoderma* species are free-living fungi that have been used to control a broad range of plant pathogenic fungi, viruses, bacteria and nematodes especially root-knot nematodes (*Meloidogyne javanica* and *M. incognita*) (Sharon et al., 2011).

7.4.1. Biorational pesticides

Biorational pesticides/ biopesticides are considered as third-generation pesticides that are rapidly gaining popularity. The word biorational is derived from two words, "biological" and "rational", which means pesticides of natural origin that have limited or no adverse effects on the environment or beneficial organisms. Biopesticides encompass a broad array of microbial pesticides, plant pesticides and biochemical pesticides which are derived from micro-organisms and other natural sources, and processes involving the genetic incorporation of DNA into agricultural commodities. The most commonly used biopesticides include biofungicides (e.g., *Trichoderma* spp.), bioherbicides (*Phytopthora* spp.), bioinsecticides (spore forming bacteria, *Bacillus thuringiensis*, and *B. popilliae*, Actinomycetes), naturally occurring fungi (*Beauveria bassiana*), microscopic roundworms (Entomopathogenic nematodes), Spinosad, insect hormones and insect growth regulators (Gupta and Dikshit, 2010; Singh et al., 2013).

Applications of microbial insecticide, *Chromobacterium subtsugae* for suppression of pecan weevil (*Curculio caryae* (Horn)), and combination of eucalyptus extract and microbial insecticide, *Isaria fumosorosea* (Wize) for control of black pecan aphid (*Melanocallis caryaefoliae* (Davis)) were found promising as alternative insecticides (Shapiro-Ilan et al., 2013). Entomopathogenic nematodes (EPNs) belonging to the families Heterorhabditidae and Steinernematidae are potentially used in South Africa as biocontrol agents against vine mealybug (*Planococcus ficus* (Signoret)) (le Vieux and Malan, 2013). Spinosad was found effective in controlling Colorado potato beetle (*Leptinotarsa decemlineata*) in Iran, and is recommended for use in IPM program for Colorado potato beetle (Soltani and Agricultural, 2011). In China, entomopathogenic fungus (*Beauveria bassiana*) has shown great potential for the management of some bark beetle species including red turpentine beetle (RTB) (*Dendroctonus valens* LeConte), a destructive invasive pest (Zhang et al., 2011).

The allelopathic properties of plants can be exploited successfully as a tool for weed and pathogen reduction. In a rice field, application of allelopathic plant material @ 1-2 tonne/ha reduced weed diversity by 70% and increased yield by 20%. Numerous growth inhibitors identified from these allelopathic plants are responsible for their allelopathic properties and may be a useful source for the future development of bio-herbicides and pesticides (Xuan et al., 2005). A combination of coleopteran-active toxin, *Bacillus thuringiensis* Cry3Aa protoxin and protease inhibitors, especially a potato carboxypeptidase inhibitor, have efficiency in preventing damage to stored products and grains by stored grain coleopteran pests (Oppert et al., 2011).

7.5. Chemical control

Sometimes cultural and other agro-technical practices are not sufficient to keep pest population below economic injury level (lowest pest population density that will cause economic crop damage). Therefore, the chemical control agents are resorted to both as preventive and curative measures to minimize the insect pest damage. A good pesticide should be potent against pests, should not endanger the health of humans and non-target organisms, and should ultimately break down into harmless compounds so that it does not persist in environment. Both relative and specific toxicities of the pesticide need to be estimated in order to determine its potency.

It is very important to know spray droplet size and density chemical dosage, application timing, which can provide adequate pest control. There is also a need for research into the development of suitable packaging and disposal procedures, as well as refining of the application equipment. All of these shall rationalize the use of pesticides, so that they can be used in an acceptable way.

Very strict laws should be enacted to protect wildlife and other non-target organisms. Following directions on the pesticide label can prevent injury to non-target organisms. However, when these directions are not followed, benefits from pesticides can be outweighed by the harm and risk associated with pesticides (Fishel, 2011). During pesticide application, things that need to be considered are timing of insecticide application, dosage and persistence, and selective placement of insecticides as discussed below.

7.5.1. Timing of pesticide application

The timing of pesticide application is an important factor to consider before doing any pesticide application. Appropriate application time can ensure not only maximum impact on the target organisms but also least impact on beneficial organisms. Pesticide application timing mainly depends on availability of weather window, time at which pests can be best controlled, and when least damage will be caused to non-target organisms and environment. Flowering period in crops and middle of the day are the times when bees are more prone to insecticides. Hence, insecticide application should not happen at those times to avoid decline in bee populations. Time of insecticide application should coincide with the most vulnerable stage of insect life cycle. Monitoring of insects in the field is thus extremely important for knowing the stage of

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insect pest in the field. Monitoring systems are available for most of the insect pests, but spray regime or experiments need to be carried out to determine the most appropriate time for insecticide application for insects for which monitoring systems are not available (Hull and Starner, 1983; Richter and Fuxa, 1984).

Time of the day and season of the year are also important to consider when making pesticide applications. The early morning and evening hours are often the best times for pesticide application because windy conditions are more likely to occur around midday when the temperature warms near the ground level. This causes hot air to rise quickly and mix rapidly with the cooler air above it, favoring drift. During stable conditions, a layer of warm air can stay overhead and not promote mixing with colder air that stays below and closer to the ground. Inversions tend to dissipate during the middle of the day when wind currents mix the air layers. It is very important that applicators recognize thermal inversions and do not spray under those conditions. A temperature or thermal inversion is a condition that occurs naturally and exists when the air at ground level is cooler than the temperature of the air above it. Wind speed is the most important weather factor influencing drift. High wind speeds will move droplets downwind and deposit them off the target. On the other hand, dead calm conditions are never recommended due to likelihood of temperature inversions (Fishel and Ferrell, 2013). Drifting of pesticides increases the possibility of injury to pollinators, humans, domestic animals and wildlife. It is recommended not to spray in wind speed above 2.5 miles/second which otherwise can cause excessive drift and eventually contamination of adjacent areas (Matthews, 1981). Pesticide application should not be made just before rain because pesticides can be washed off by the rain without any impact on the target pest.

7.5.2. Dosage and persistence

Pesticide dose should be sufficient but no greater than the level required for best results. The pesticide manufacturer sets the dose to ensure an acceptable level of control, producing acceptable residue levels, and maximizing returns per unit of formulated insecticide. Persistent pesticides have their benefit of longer persistence on the target and therefore requires less frequent spraying compared to non- persistent pesticides. But care should be taken while using persistent pesticides since these might diminish benefits from natural enemies even at lower doses. If an insecticide is persistent in nature, chances of insecticide residues being harmful to natural enemies are greatly increased (Dent, 2000).

7.5.3. Selective placement

Distribution of pesticides in the field should be such that maximum target cover is achieved. Usually only about 1% of the applied pesticides is able to reach its target, while a large amount of it is wasted. Understanding the pest biology and behavior is critical as it can provide information on pest's habitat, fecundity, feeding etc., which can be important considerations before applying pesticides. Most of the pesticides are applied in liquid form and thus the droplet size is very important in determining their effectiveness. Small droplets provide better coverage and greater likelihood of coming in contact with the target compared to larger droplets that can bounce off the plant surface very easily. The disadvantage with smaller and bigger droplets is the increased chance of drift and therefore a balance has to be considered between smaller droplets to obtain the maximum effectiveness and reduced drift.

In situations where crops are grown on beds covered with plastic mulch, pesticides should be injected into soil at the time the plastic is laid or injected afterward through drip irrigation system to achieve maximum pesticide effectiveness. For termite (Order: Isoptera) treatments, sometimes perimeter application of insecticides is required around structures/buildings. Additionally, liquids that form foams following injections can be injected into small spaces that are or might be inhabited by termites or other small creatures.

8. Conclusion

Although, pesticides were used initially to benefit human life through increase in agricultural productivity and by controlling infectious disease, their adverse effects have overweighed the benefits associated with their use. The above discussion clearly highlights the severe consequences of indiscriminate pesticide use on different environmental components. Some of the adverse effects associated with pesticide application have emerged in the form of increase in resistant pest population, decline in on beneficial organisms such as predators, pollinators and earthworms, change in soil microbial diversity, and contamination of water and air ecosystem. The persistent nature of pesticides has impacted our ecosystem to such an extent that pesticides have entered into various food chains and into the higher trophic levels such as that of humans and other large mammals. Some of the acute and chronic human illnesses have now emerged as a consequence of intake of polluted water, air or food.

This is the time that necessitates the proper use of pesticides to protect our environment and eventually health hazards associated with it. Alternative pest control strategies such as IPM that deploys a combination of different control measures such as cultural control, use of resistant genotype, physical and mechanical control, and rational use of pesticide could reduce the number and amount of pesticide applications. Further, advanced approaches such as biotechnology and nanotechnology could facilitate in developing resistant genotype or pesticides with fewer adverse effects. Community development and various extension programs that could educate and encourage farmers to adopt the innovative IPM strategies hold the key to reduce the deleterious impact of pesticides on our environment.

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