Effect of Agrichemicals on Biocontrol Agents of Plant Disease Control

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Abstract

Plant diseases need to be controlled to maintain the quality and abundance of food, feed, and fiber produced by growers around the world. Different approaches may be used to prevent, mitigate, or control plant diseases. Beyond good agronomic and horticultural practices, growers often rely heavily on chemical fertilizers and pesticides. Such inputs to agriculture have contributed significantly to the spectacular improvements in crop productivity and quality over the past 100 years. However, the environmental pollution caused by excessive use and misuse of agrochemicals, as well as fear-mongering by some opponents of pesticides, has led to considerable changes in people's attitudes toward the use of pesticides in agriculture. Consequently, some pest management researchers have focused their efforts on developing alternative inputs to synthetic chemicals for controlling pests and diseases. Among these alternatives biological control is the major emerging tool for disease control in sustainable agriculture. Biological control offers a novel approach when applied either alone or in combination with other management practices. Biocontrol and chemicals are important tools in IPM strategy wherein agrochemicals applied by any of the methods (seed treatment, soil application, and foliar spray) will ultimately reach soil and interact with the biocontrol agents. These agrochemicals drastically affect the growth, reproduction, and survivability of biocontrol agents in a particular cropping system and thereby on their biocontrol efficacy. The available literature on the effect

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of agrochemicals on biocontrol agents revealed that most of the agrochemicals (fungicides, insecticides, fertilizers, and herbicides) are reported to have adverse effect on the soil microflora including biocontrol agents. The need-based and judicious application of agrochemicals, checking the compatibility between the agrochemicals and biocontrol agents and developing the new pesticide resistant strains of biocontrol agents using biotechnology tool, will help to address the above Problems.

Keywords
Biocontrol agents · Environment · Fertilizers · Fungicides · Herbicides · Insecticides · Toxicity

1.1 Introduction

Plant diseases are of significant concern due to the intimate relationship between plant health and the welfare of people, animals, and the environment. The ability to provide adequate food and fiber is becoming increasingly strained, and continued improvement in sustainable plant disease management is required to help meet these demands. Plant diseases often substantially reduce quality and quantity of agricultural commodities (Cramer 1967). Also, infestation by microorganisms in the field or in postharvest storage can affect the health of humans and livestock, especially if the contaminating organism produces toxic residues in or on consumable products (Sinha and Bhatnagar 1998). Control of plant disease is vital in protecting the plants from diseases, reducing yield losses, and finally achieving the food security. In this concern agrochemicals (pesticides and fertilizers) are looked upon as a vehicle for improved crop production technology though it is a costly input. Balanced use, optimum doses, correct method, and right time of application of agrochemicals ensure increased crop production. Yet, chemical method of disease management, while effective in the control of plant pathogens, may negatively impact nontarget organisms; hence, it is time to look upon sustainable, eco-friendly approaches for disease management. At this juncture biological control plays a vital role in reducing the excess use of chemical pesticides and thereby prevents the adverse effect of pesticides. This chapter will highlight the role of environment on disease occurrence and on biocontrol agents, pros and cons of agrochemicals, adverse effect of agrochemicals on biocontrol agents, and strategies to mitigate adverse effect of agrochemicals.

1.2 Abiotic Environment

For a disease to occur and to develop optimally, a combination of three factors must be present: susceptible plant, infective pathogen, and favorable environment. However, although plant susceptibility and pathogen infectivity remain essentially unchanged in the same plant for at least several days, and sometimes for weeks or months, the environmental conditions may change more or less suddenly and to various degrees. Such changes may drastically influence the development of diseases in progress or the initiation of new diseases. Of course, a change in any environmental factor may favor the host, the pathogen, or both, or it may be more favorable to one than it is to the other. As a result, the expression of disease will be affected accordingly. Plant diseases generally occur over a fairly wide range of the various environmental conditions. The environmental factors that affect the initiation and development of infectious plant diseases most seriously are temperature and moisture on the plant surface. Soil nutrients also play an important role in some diseases and, to a lesser extent, light and soil pH. Environment and edaphic factors affect disease development through their influence on the growth and susceptibility of the host and on the multiplication and activity of the pathogen and biocontrol agents which finally relates to the severity of symptom development.

1.2.1 Abiotic Environment on Biocontrol Agents

As the crops are affected by abiotic stresses such as soil moisture-deficit stress, high temperature, soil salinity, and so forth, microbes are also known to be affected by these conditions. Reports from Madhya Pradesh and Chhattisgarh of India indicated that the free-living rhizobial population declines to lower than the minimum threshold levels required for nodulation due to high soil temperatures requiring inoculation every year (Gupta et al. 2000; Rao 1996–2000). Widden and Hsu (1987) observed that the ability of different species of *Trichoderma* to colonize pine or maple litter differed with temperatures. Mukherjee and Raghu (1997) reported that as temperature increases (>30° C), biocontrol efficacy of *Trichoderma* decreases drastically. Abiotic stresses greatly influence the performance of biocontrol agents. Sankaranarayanan and Rajeswari (2001) studied the effect of moisture and pH on the efficacy of VAM (*Glomus mosseae*) on *Meloidogyne incognita* in black gram. Among the moisture levels tested 70% moisture and among the pH levels, pH 7 was found suitable for the better mycorrhizal colonization, spore production, and well establishment of VAM to control root knot nematode. Higher moisture level (80–100%) was found detrimental to VAM fungus. Leo Daniel et al. (2011) evaluated *T. virid*e for its in vitro abiotic stress tolerance ability and its field bioefficacy against root rot disease in black gram, and it was reported that growth of *T. viride* decreased with increase in salinity, temperature, and drought. Reetha et al. (2014) studied the effect of temperature and pH on growth of *Trichoderma harzianum* and reported that *T. harzianum* was grown better at 25–30 °C and very slowly grown at 37 °C and not grown at 45 °C.

1.3 Agrochemicals

Agrochemicals cover a wide range of compounds including insecticides, fungicides, herbicides, rodenticides, molluscicides, nematicides, plant growth regulators, and others. The introduction of synthetic insecticides – organophosphate (OP) insecticides in the 1960s, carbamates in the 1970s, and pyrethroids in the 1980s – and the introduction of herbicides and fungicides in the 1970s–1980s contributed greatly to pest control and agricultural output. Ideally a pesticide must be lethal to the targeted pests, but not to nontarget species, including man. Unfortunately, this is not the case, so the controversy of use and abuse of pesticides has surfaced. The rampant use of these chemicals, under the adage, “if little is good, a lot more will be better,” has played havoc with human and other life forms.

1.3.1 Production and Usage of Pesticides

Modern agriculture depends on the four main factors, viz., water, fertilizers, seed, and pesticides. Pesticides are the integral part of modern agriculture. The production of pesticides started in India in 1952 with the establishment of a plant for the production of BHC near Calcutta, and India is now the second largest manufacturer of pesticides in Asia after China and ranks fourth globally (FICCI 2016). There has been a steady growth in the production of technical grade pesticides in India, from 5,000 metric tonnes in 1958 to 102,240 metric tonnes in 1998. In 1996–1997 the demand for pesticides in terms of value was estimated to be around Rs. 22 billion (USD 0.5 billion), which is about 2% of the total world market. The pattern of pesticide usage in India is different from that for the world in general. In India 76% of the pesticide used is insecticide, as against 44% globally (Mathur 1999). The use of herbicides and fungicides is correspondingly less heavy. The main use of pesticides in India is for cotton crops (45%), followed by paddy and wheat. The Indian domestic demand is growing at the rate of 8–9% and export demand at 15–16%. The per capita consumption of pesticides in India is 0.6 Kg/ha. The per capita pesticide consumption in China and the USA is 13 Kg/ha and 7 Kg/ha, respectively. India is the second biggest consumer of fertilizer in the world next only to China. The total consumption of fertilizer (NPK) in India is nearly about 255.4 thousand tonnes.

1.3.2 Positive Effects (Benefits) of Agrochemicals

1.3.2.1 Improving Productivity

A UN study on global population trends predicts that India will surpass China to become the most populous nation in the world by 2022. With a present size of 1.32 billion, India currently supports nearly 17.84% of the world population, with 2.4% land resources and 4 % of water resources (FICCI 2016). It is also noted that about 30–35% potential crop production is lost due to pests, weeds, and diseases.

Keeping pace with these growing numbers, the country will not only have to raise its agricultural production but also the productivity to ensure food and nutrition security of the nation. Crop protection and crop enhancement solutions, based on best global practices and the latest technologies available, are the answer. Tremendous benefits have been derived from the use of pesticides in agriculture. Food grain production, which stood at a mere 50 million tons in 1948–1949, had increased almost fourfold to 198 million tonnes in 1996–1997. This result has been achieved by the use of high-yield varieties of seeds, advanced irrigation technologies, and agricultural chemicals (Employment Information: Indian Labour Statistics 1997). Similarly outputs and productivity have increased dramatically in most countries, for example, wheat yields in the UK and corn yields in the USA. Increases in productivity have been due to several factors including use of fertilizer, better varieties, and use of machinery. Pesticides have been an integral part of the process by reducing losses from the weeds, diseases, and insect pests that can markedly reduce the amount of harvestable produce.

1.3.2.2 Protection of Crop Losses

About 30–35 % crop production is lost due to insects, weeds, and diseases. The total number of pests attacking major crops has increased significantly from the 1940s. For instance, the number of pests which are harmful for crops such as rice has increased from 10 to 17, whereas for wheat it has increased from 2 to 19, respectively. The increased damage to crops from pests and subsequent losses pose a serious threat to food security and further underscore the importance of agrochemicals. The use of pesticides helped to manage the weeds, insects, and diseases in agriculture resulting in scaling down the loss from these pests. Webster et al. (1999) stated that "considerable economic losses" would be suffered without pesticide use and quantified the significant increases in yield and economic margin that result from pesticide use.

1.3.2.3 Vector Disease Control

Most of the agriculture crops are prone to be infected by several viral diseases. These viral diseases are mainly transmitted by insect vectors (aphids, whitefly, leafhopper, etc.). The development of systemic insecticides has helped to control the insect vectors, thereby addressing the problem of plant viral disease management.

1.3.3 Negative Effects (Hazards of Pesticides)

1.3.3.1 Direct Impact on Humans

If the credits of pesticides include enhanced economic potential in terms of increased production of food and fiber, and amelioration of vector-borne diseases, then their debits have resulted in serious health implications to man and his environment.

There is now overwhelming evidence that some of these chemicals do pose a potential risk to humans and other life forms and unwanted side effects to the environment (Forget 1993; Igbedioh 1991; Jeyaratnam 1981). No segment of the population is completely protected against exposure to pesticides, and the potentially serious health effects, though a disproportionate burden, are shouldered by the people of developing countries and by high-risk groups in each country (WHO 1990). The high-risk groups exposed to pesticides include production workers, formulators, sprayers, mixers, loaders, and agricultural farmworkers.

1.3.3.2 Pesticide Residue in Food Commodities

The indiscriminate use of pesticides for controlling the insect pests and diseases resulted in pesticide residue problems in food commodities. Pesticide residue refers to the pesticides that may remain on or in food after they are applied to food crops. The maximum allowable levels of these residues in foods are often stipulated by regulatory bodies in many countries. In India the first report of poisoning due to pesticides was from Kerala in 1958, where over 100 people died after consuming wheat flour contaminated with parathion (Karunakaran 1958)**.** This prompted the Special Committee on Harmful Effects of Pesticides constituted by the ICAR to focus attention on the problem (Report of the Special Committee of ICAR 1972). In 2006, the Ministry of Agriculture initiated a program to monitor pesticide residues at the national level. Working through the Indian Council of Agricultural Research, the Ministry selected 20 laboratories to collect and analyze samples of vegetables, fruits, spices, pulses, cereals, milk, fish, tea, honey, meat, animal feed, and groundwater. In 2011–2012, 16948 food commodities were analyzed for pesticides, in which 1668 (9.8%) commodities were found positive, while 290 (1.7%) had pesticides above MRL (AINP Annual report 2013).

1.3.3.3 Impact on Environment

Pesticide sprays can directly hit nontarget vegetation or can drift or volatilize from the treated area and contaminate air, soil, and nontarget plants. Some pesticide drift occurs during every application, even from ground equipment (Glotfelty and Schomburg 1989). Drift can account for a loss of 2–25% of the chemical being applied, which can spread over a distance of a few yards to several hundred miles. As much as 80–90% of an applied pesticide can be volatilized within a few days of application (Majewski and Capel 1995). In addition to killing insects or weeds, pesticides can be toxic to a host of other organisms including birds, fish, beneficial insects, and nontarget plants.

1.3.3.4 Surface Water Contamination

Pesticides can reach surface water through runoff from treated plants and soil. Contamination of water by pesticides is widespread. The results of a comprehensive set of studies done by the US Geological Survey (1998) on major river basins across the country in the early to mid-90s yielded startling results. More than 90% of water and fish samples from all streams contained one or, more often, several pesticides (Kole et al. 2001). Pesticides were found in all samples from major rivers with mixed agricultural land use (Bortleson and Davis 1987–1995).

1.3.3.5 Groundwater Contamination

Groundwater pollution due to pesticides is a worldwide problem. Pesticides enter surface and groundwater primarily as runoff from crops and are most prevalent in agricultural areas. A decadal assessment by the National Water-Quality Assessment (NAWQA) Program of the US Geological Survey (1998) showed that pesticides are frequently present in streams and groundwater at concentrations that may have effects on aquatic life or fish-eating wildlife and human beings. According to the USGS, at least 143 different pesticides and 21 transformation products have been found in groundwater, including pesticides from every major chemical class.

1.3.3.6 Soil Contamination

Agrochemicals sprayed aerially reach the soil (by means of air currents or are washed off the plant surface due to rain) and contaminate soil. A large number of transformation products (TPs) from a wide range of pesticides have been documented (Barcelo and Hennion 1997; Roberts 1998; Roberts and Hutson 1999). Persistency and movement of these pesticides and their TPs are determined by some parameters, such as water solubility, soil-sorption constant (Koc), water partition coefficient (K_ow), and half-life in soil (DT_{50}). Pesticides and TPs could be grouped into hydrophobic, persistent, and bioaccumulable pesticides that are strongly bound to soil. Pesticides that exhibit such behavior include the organochlorine DDT, endosulfan, endrin, heptachlor, lindane, and their TPs. Polar pesticides are represented by herbicides, carbamates, fungicides, and some organophosphorus insecticides and their TPs. They can be moved to soil and thereby contaminate soil.

1.3.3.7 Pesticide Resistance in Pest Species

Problems associated with reliance on chemical control include the development of pesticide resistance in important pest species. This encourages an increase in dosage and number of pesticide applications which magnifies the adverse effects on natural enemies. Pests may also resurge because of the destruction of predators and parasitoids, breeding without restraint from natural enemies. If pesticides eliminate natural enemies, populations of pests may increase dramatically. Melander (1914) first time reported the resistance of San Jose scale (*Quadraspidiotus perniciosus* L.) insect to lime sulfur in the USA. In India Pradhan (1960) reported resistance of singhara beetle (*Galerucella birmanica* (Jacoby)) to DDT and BHC. The problem of fungicide resistance became apparent following the registration and widespread use of the systemic fungicides. Fungicide resistance is now a widespread problem in global agriculture. Fungicide resistance problems in the field have been documented for nearly 150 diseases (crop-pathogen combinations) and within about half of the known fungicide groups. Resistance is now found in more than 500 insect and mite pests, in over 100 weeds, and in about 150 plant pathogens (WRI 1994).

1.3.3.8 Effect on Beneficial Organisms

Heavy treatment of soil with pesticides can cause populations of beneficial soil microorganisms to decline. According to the soil scientist Dr. Elaine Ingham, “If we lose both bacteria and fungi, then the soil degrades. Overuse of chemical fertilizers and pesticides have effects on the soil organisms that are similar to human overuse of antibiotics. Indiscriminate use of chemicals might work for a few years, but after awhile, there aren’t enough beneficial soil organisms to hold onto the nutrients” (Savonen 1997). For example, plants depend on a variety of soil microorganisms to transform atmospheric nitrogen into nitrates, which plants can use. Glyphosate reduces the growth and activity of free-living nitrogen-fixing bacteria in soil (Santos and Flores 1995). 2,4-D reduces nitrogen fixation by the bacteria that live on the roots of bean plants (Arias and Fabra 1993; Fabra et al. 1997). 2,4-D reduces the growth and activity of nitrogen-fixing blue-green algae (Singh and Singh 1989). Mycorrhizal fungi grow with the roots of many plants and aid in nutrient uptake. These fungi can also be damaged by herbicides in the soil. One study found that oryzalin and trifluralin both inhibited the growth of certain species of mycorrhizal fungi (Kelley and South 1978). Roundup has been shown to be toxic to mycorrhizal fungi in laboratory studies (Chakravarty and Sidhu 1987; Estok et al. 1989).

1.4 Biocontrol

Biological control, the use of specific microorganisms that interfere with plant pathogens and pests, is a nature-friendly, ecological approach to overcome the problems caused by standard chemical methods of plant protection (Harman et al. 2004). Most biological control agents, including predators and parasitoids, at work in our agricultural environment are naturally occurring ones, which provide excellent regulation of many insect pests and diseases with little or no assistance from humans. The existence of naturally occurring biological control agents is one reason that many plant-feeding insects and plant pathogens do not ordinarily become economic pests. The importance of such agents often becomes quite apparent when pesticides applied to control one pest cause an outbreak of other pests because of the chemical destruction of important natural enemies. There is great potential for increasing the benefits derived from naturally occurring biological controls, through the elimination or reduction in the use of pesticides toxic to natural enemies. Biological control offers a novel approach when applied either alone or in combination with other management practices (Papavizas 1985; Mukhopadhyay 1987). Several advantages of using biological control agents have been reported by different workers.

1. Eco-friendly (Bohra et al. 2006 and Gaur et al. 2005)
2. Effective in managing diseases caused by soilborne plant pathogens which cannot be easily controlled by chemicals (Harman 2000; Howell 2003 and Manoranjitham et al. 2000)
3. Ease of multiplying antagonists with less cost of production (Gaur et al. 2005 and Das et al. 2006)
4. Growth-promoting effect (Mukhopadhyay 1987; Jang et al. 1993; Das et al. 2006; Pan and Bhagat 2007)
5. Long-lasting effective disease management (Harman 2000; Howell 2003)

1.4.1 Effect of Agrochemicals on Biocontrol Agents

Understanding the effect of agrochemicals on the beneficial activities of microorganisms is important to assess the hazards associated with agrochemicals used in agriculture. Crop productivity and economic returns will be maximized with the use of products controlling pests but preserving beneficial organisms. *Trichoderma* spp. are common soil inhabitants and have been extensively studied as biocontrol agents in the management of soilborne plant pathogens (Elad et al. 1980; Papavizas 1985; Upadhyay and Mukhopadhyay 1986; Adams 1990; Muthamilan and Jeyarajan 1992; Manoranjitham et al. 2000; Whipps 2001; Mohanan 2007 and RakeshKumar and Indra Hooda 2007). *Trichoderma* spp. offer biological control against soilborne plant pathogens by utilizing mechanisms such as antibiosis (Sivan et al. 1984; Shanmugam and Varma 1999; Hazarika et al. 2000; and Das et al. 2006), competition (Khan and Sinha 2007), and mycoparasitism (Upadhyay and Mukhopadhyay 1986 and Pandey et al. 2005). *Trichoderma* spp. are used either in seed treatment or soil application. In both the cases, the antagonist will be continuously exposed to different agrochemicals such as fungicides, insecticides, fertilizers, and herbicides applied to the field either in soil or as foliar sprays. Agrochemicals sprayed aerially reach the soil (by means of air currents or are washed off the plant surface due to rain) and influence the efficacy of native or applied biocontrol agents. Effects of agrochemicals on antagonists were reported by several workers (Pandey and Upadhyay 1998; Vijayaraghavan and Abraham 2004; Rai Ajay Kumar et al. 2005; Surajit et al. 2006 and Lal and Maharshi 2007). However, a great deal of the work done was based on arbitrary concentrations that were less than the field concentrations. Further, as variation exists between strains and species within a genus isolated from different climatic conditions, a thorough knowledge on sensitivity of applied biocontrol agent is necessary so as to exploit the full potential of the biocontrol agent. In this chapter an attempt has been made to summarize the effect of agrochemicals on biocontrol agent based on our experimentations (Ranganathswamy 2009) as well as reports of previous workers.

1.4.1.1 Effect of Fungicides

Plant pathogens cause significant loss (14.1%) in agricultural crops (Agrios 2005). Use of fungicides and bactericides is an age-old practice and has been proven effective in controlling the plant pathogens and thereby the loss caused by them. Fungicides are applied in various methods such as seed treatment and soil and foliar application. Fungicides applied by either of any methods will ultimately reach soil and interact with the biocontrol agents. These fungicides may drastically affect the growth, reproduction, and survivability of biocontrol agents in a particular cropping system and thereby on their biocontrol efficacy. Several workers (Karpagavalli 1997; Upadhyay et al. 2000; Akbari and Parakhia 2001; Vijayaraghavan and Abraham 2004; Tiwari and Singh 2004; Bhattiprolu 2007 and Madhavi et al. 2008) reported that fungicides were toxic to the biocontrol agents. We have (Ranganathswamy et al. 2013) evaluated the effect of the most commonly used 18 fungicides on assimilative (radial growth) and spore phases of the antagonist (*T. harzianum* and *T. virens*). Comparison was made between the two isolates selected, between the growth phases (assimilative and spore phase) and between different agrochemicals. Further, EC_{50} and EC_{90} values of test chemicals were calculated. Based on these observations, the chemicals were grouped into dangerous, cautious, and safe to antagonist.

1.4.1.1.1 Copper Group

Copper fungicides still form a major group of fungicides especially in the management of diseases caused by soilborne lower fungi such as *Pythium* and *Phytophthora*. Being soilborne, their management essentially deals with treating the soil through pre- or post-planting applications such as drenching. At this juncture, there is every reason to believe that the soil-inhabiting *Trichoderma* (employed through inundative or augmentative measures) is under continuous direct exposure to the applied field concentration. Several workers indicated that in general copper fungicides especially Bordeaux mixture and copper oxychloride have their impact on the growth of biocontrol agents (*Trichoderma* spp. and *Pseudomonas fluorescens*). Several reports published based on the in vitro assay indicated that copper fungicides are in general less toxic to *Trichoderma* spp. (Karpagavalli 1997; Upadhyay et al. 2000; Akbari and Parakhia 2001; Vijayaraghavan and Abraham 2004; Tiwari and Singh 2004; Bhattiprolu 2007 and Madhavi et al. 2008). However, variation existed in the type of chemical under study, i.e., Bordeaux mixture, copper oxychloride, and cuprous hydroxide.

Srinivasulu et al. (2002) reported 100% inhibition of *T. harzianum*, *T. viride*, and *T. hamatum* in Bordeaux mixture amended medium at 1% concentration. Similar report of highly incompatible nature of Bordeaux mixture with *Trichoderma* spp. was reported by Vijayaraghavan and Abraham (2004). Ranganathswamy et al. (2011) reported copper oxychloride had higher inhibitory effect on *Trichoderma* spp. compared to Bordeaux mixture on assimilative phase (mycelium), while it was reverse in the case of spore phase where Bordeaux mixture showed cent percent inhibition on spore germination.

1.4.1.1.2 Dithiocarbamates

Among the dithiocarbamates, mancozeb and thiram are the most commonly used in plant disease management – mancozeb mainly as foliar spray and thiram as seed treatment. Thiram will have a direct effect on the antagonist on the efficacy of *Trichoderma* spp. especially when applied as seed treatment in integration. Desai et al. (2002) reported that the radial growth inhibition of *T. harzianum* in mancozeb amended medium was 5.7% and 4.9% at 500ppm and 1000 ppm concentrations, respectively, which was found compatible. Moderate compatibility of mancozeb with *T. harzianum* was also reported by Vijayaraghavan and Abraham (2004), Tiwari and Singh (2004), Kumar et al. (2005), and Surajit et al. (2006). Madhavi et al. (2008) reported isolate variation in sensitivity to mancozeb when two mutants ThM_1 and TvM_1 were assessed. ThM_1 was compatible up to 0.125%, while TvM_1 was not compatible at the same concentrations.

Several reports suggested the incompatibility of thiram with *Trichoderma*. Complete inhibition of *Trichoderma* growth on thiram amended medium was reported by Sharma and Mishra (1995), Karpagavalli (1997), Pandey and Upadhyay (1998), Desai and Kulkarni (2004), and Upadhyay et al. (2004). In our study also thiram was highly toxic to *Trichoderma* spp., while mancozeb and wettable sulfur were least toxic (Ranganathswamy et al. 2011).

1.4.1.1.3 Heterocyclic Nitrogenous Compounds

Captan, a heterocyclic nitrogenous compound and another most commonly used seed dressing fungicide, was found to be less toxic with little inhibition of *Trichoderma* growth (Sharma and Mishra 1995; Gupta 2004; Desai and Kulkarni 2004 and Pandey et al. 2006). Contradictory to the above reports, a more toxic nature of captan to *Trichoderma* was reported by Vijayaraghavan and Abraham (2004), Tiwari and Singh (2004), Upadhyay et al. (2004), and Surajit et al. (2006).

1.4.1.1.4 Systemic Fungicides

Most of the systemic fungicides such as benzimidazoles, triazoles, acylalanines, strobilurins, etc. were reported toxic to biocontrol agents. Metalaxyl, an acylalanine group member highly effective against lower fungi, was reported to be less toxic to *Trichoderma* (Sharma and Mishra 1995). Indu and Mukhopadhyay (1990) reported zero inhibition at 50 ppm and 30% inhibition at 1000 ppm concentration in metalaxyl-insensitive isolate of *Trichoderma* (IMI No. 238493).

Carbendazim and benomyl, two most commonly used systemic fungicides belonging to benzimidazoles, were found to be extremely toxic to *Trichoderma* isolates in all the reports published so far. Carboxin, an oxathiin derivative highly effective against smuts and *Sclerotium rolfsii*, was reported to be toxic to *Trichoderma* spp. (Desai et al. 2002 and Tiwari and Singh 2004). Mondal et al. (1995) reported higher inhibitory effect of carboxin on *T. harzianum*. Oxycarboxin, another oxathiin derivative effective against rusts, was reported to have no effect on the growth of *T. harzianum* (Tiwari and Singh 2004).

All the triazole compounds such as tebuconazole, hexaconazole, propiconazole, tricyclazole, and epoxiconazole were reported to be highly toxic to biocontrol agents (Tiwari and Singh 2004; Pandey et al. 2006). Tridemorph, member of morpholine group, showed complete inhibition (100%) of assimilative and spore phases of both the test *Trichoderma* isolates at field concentration (Srinivasulu et al. 2002).

Ranganathswamy et al. (2011) evaluated ten systemic fungicides, viz., carbendazim, benomyl, metalaxyl, carboxin, propiconazole, hexaconazole, tricyclazole, tridemorph, fosetyl-Al, and azoxystrobin, which are commonly used to control plant pathogens in different agricultural and horticultural crops. It was reported that all the ten fungicides were toxic to biocontrol agents (*Trichoderma* spp.) affecting the vegetative (mycelium) as well as reproductive growth (spore) at their filed concentration.

1.4.1.2 Effect of Insecticides

1.4.1.2.1 Old-Generation Insecticides

Several kinds of insecticides were commonly used for the management of insect pests in agriculture crops. These insecticides were reported to affect the growth and survivability of biocontrol agents.

Endosulfan, a synthetic hydrocarbon belonging to cyclodiene compounds, constitutes a major insecticide used for the management of foliage-eating insects in vegetables. Endosulfan being a contact insecticide has retarding effect on the growth and survivability of concerned organism when comes in direct contact with particular organism. Several reports published based on in vitro assay indicated toxicity of endosulfan on *Trichoderma* spp. (Sushir and Pandey 2001; Vijayaraghavan and Abraham 2004; Tiwari et al. 2004 and Lal and Maharshi 2007). However, variation existed with respect to the concentration evaluated and isolate studied. Sushir and Pandey (2001) reported 55.5% inhibition of radial growth of *T. harzianum* at 50ppm concentration, while Vijayaraghavan and Abraham (2004) observed more than 83% inhibition at 400 ppm concentration. Tiwari et al. (2004) reported that endosulfan, in dust as well as EC formulation, was found toxic on the radial growth of *T. harzianum*.

Organophosphate (OP) compounds constitute a major group of chemicals used for the management of sucking pests. Several workers reported toxicity of OP compounds to *Trichoderma* and other biocontrol agents; however, variation was reported with respect to the concentration, isolates, and formulation of compound. Vijayaraghavan and Abraham (2004) reported toxicity of chlorpyriphos (0.02%), quinalphos (0.04%), and dimethoate (0.04%) to *Trichoderma* spp. Cent percent inhibition of radial growth of *Trichoderma* spp. at all the concentrations (500, 1000, 1500, and 2000 ppm) of chlorpyriphos tested was reported by Desai and Kulkarni (2005). However, non-inhibitory effect of chlorpyriphos on *T. harzianum* even up to 2000 ppm was reported by Sharma and Mishra (1995). Tiwari et al. (2004) reported that dust formulations of chlorpyriphos and quinalphos were nontoxic, while EC formulation showed toxic effect on *T. harzianum*. Ranganathswamy et al. (2011) reported the toxicity effect of chlorpyriphos, quinalphos, and dimethoate on *Trichoderma* spp. It may be noted here that all the OP compounds are having long residual effect in soil indicating their long-term interaction with test *Trichoderma* isolates, thereby reducing growth and survivability of test antagonists in such soil environment.

Tiwari et al. (2004) reported inhibitory effect of monocrotophos and triazophos on *T. harzianum* at 500–2000 ppm concentration. The least inhibitory effect of acephate on *Trichoderma* spp. was reported by Desai and Kulkarni (2005).

Several workers reported non-inhibitory effect of phorate and carbamate insecticides, on *Trichoderma* (Sharma and Mishra 1995; Gupta 2004; Vijayaraghavan and Abraham 2004 and Tiwari et al. 2004). However, Jayaraj and Ramabadran (1996) reported inhibitory effect of phorate, who observed almost nil growth (5 mm) of *T. harzianum* at 500 ppm concentration of phorate. Sharma and Mishra (1995) reported least toxicity of carbofuran and aldicarb on *T. harzianum*. Tiwari et al. (2004) reported inhibitory effect of carbofuran and fenobucarb on the radial growth of *Trichoderma harzianum* at all the concentrations tested (500–2000 ppm).

1.4.1.2.2 New-Generation Insecticides

New-generation insecticides, viz., indoxacarb, imidacloprid, thiamethoxam, fipronil, emamectin benzoate, and spinosad, were reported nontoxic or least toxic to biocontrol agents. Tiwari et al. (2004) reported non-inhibitory effect of indoxacarb on *T. harzianum* at all the concentrations (500, 1000, 1500, and 2000 ppm). Prasanna et al. (2002) reported the compatibility of *Trichoderma harzianum* to thiamethoxam even at 1% concentration. Lal and Maharshi (2007) reported the highly sensitive nature of *Trichoderma* spp. to imidacloprid at 500 ppm. Ranganathswamy et al. (2012a, b, c) reported the least toxicity of thiamethoxam, emamectin benzoate, and fipronil and nontoxicity of indoxacarb and spinosad. Tiwari et al. (2004) reported inhibitory effect of cartap hydrochloride on *T. harzianum* at all the concentrations tested (500–2000 ppm). Most of the synthetic pyrethroids were reported to be inhibitory on *Trichoderma*. Incompatibility of *Trichoderma* spp. to cypermethrin at 0.04% was reported by Vijayaraghavan and Abraham (2004). The toxic nature of alfamethrin, cypermethrin, and fenvalerate on *T. harzianum* at 500–2000 ppm was reported by Tiwari et al. (2004).

1.4.1.3 Effect of Fertilizers

Fertilizer is an important basic input in modern agriculture. Use of fertilizer gained momentum in the early 1960s when the use of dwarf, short-duration, and high-yielding varieties of wheat and paddy was brought into cultivation. Now, the chemical fertilizers become an integral part of agriculture in most of the developing countries. As the fertilizers were directly applied into the soil as a basal application or top dressing, they will interact with the biocontrol agents and affect their growth, reproduction, and survivability.

Several workers like Sharma and Mishra (1995); Jayaraj and Ramabadran (1998); Monga (2001); Reshmy Vijayaraghavan and Koshy Abraham (2004); Sharma and Mathur (2008); Gade et al. (2009) and Ranganathswamy et al. (2012a, b, c) reported the toxic as well as non-toxic effect of chemical fertilizers on soil beneficial microflora.

Among amide forms of nitrogenous fertilizers, urea was the most commonly used for almost all the crops. Sharma and Mishra (1995) reported the stimulatory effect of urea on growth and sporulation of *T. harzianum*; however, Vijayaraghavan and Abraham (2004) reported the compatibility of *Trichoderma* spp. to urea up to 1%, while concentration exceeding 1% resulted in toxicity. The least growth and sporulation of *T. harzianum* in urea amended medium were reported by Jayaraj and Ramabadran (1998) and Gade et al. (2009).

Most of the ammoniacal forms of nitrogenous fertilizers were reported to have no inhibitory effect on growth of *Trichoderma*. Good growth and sporulation of *T. harzianum* in ammonium sulfate and ammonium nitrate while poor growth in calcium nitrate were reported by Jayaraj and Ramabadran (1998). Among nitrate forms, sodium nitrate was found to support good growth and sporulation of *T.harzianum* (Jayaraj and Ramabadran 1998; Gade et al. 2009).

Vijayaraghavan and Abraham (2004) reported nontoxicity of phosphate fertilizer on *Trichoderma* spp. at 2% and 2.5% and even at 3% concentrations.

Potassium fertilizers irrespective of forms were reported nontoxic and compatible to *Trichoderma*. Compatible nature of *Trichoderma* spp. to muriate of potash was reported by Sharma and Mishra (1995) and Vijayaraghavan and Abraham (2004). Monga (2001) reported that potassium nitrate was proved to be the best for the growth of all the *Trichoderma* spp. Ranganathswamy et al. (2012a, b, c) reported toxicity of zinc sulfate, DAP, and urea, while nontoxicity of muriate of potash, ammonium sulfate, single superphosphate, and potassium nitrate on *Trichoderma* spp. Sharma and Mathur (2008) reported compatibility of *T. harzianum* to magnesium sulfate. Sharma and Mishra (1995) reported toxic effect of zinc sulfate on *T. harzianum* at 2%.

1.4.1.4 Effect of Weedicides (Herbicides)

Most of the herbicides, viz., pendimethalin, glyphosate, alachlor, butachlor, paraquat, atrazine, trifluralin, fluchloralin, oxadizin, 2,4-D, etc., were reported toxic on biocontrol agents. Acetamide compounds, viz., alachlor and butachlor, were reported toxic on *Trichoderma* spp. by Desai and Kulkarni (2004) and Subhalakshmi et al. (2006). Madhavi et al. (2008) reported toxicity of alachlor and butachlor even on *Trichoderma* mutants. Nil or least toxicity of 2,4-D on *Trichoderma* was reported by Jayaraj and Radhakrishnan (2000). Nitroaniline compounds, viz., fluchloralin and pendimethalin, were found toxic even on mutant isolates of *Trichoderma* spp. (Madhavi et al. 2008). Non inhibitory effect of pendimethalin, fluchloralin and oxazdiazon on *Trichoderma* spp. was reported by Parakhia and Akbari (2001). Desai and Kulkarni (2004) reported that glyphosate inhibited growth of *T. harzianum* at all the concentrations tested (500, 1000, and 2000 ppm). Triazine compound atrazine was moderately compatible with *T. harzianum* up to 2000 ppm concentration (Desai and Kulkarni 2004). Rai Ajay Kumar et al. (2005) reported high compatible nature of *Trichoderma harzianum* to isoproturon at all the concentrations tested (100–10000 ppm). Ranganathswamy et al. (2012a, b, c) evaluated the effect of four herbicides, viz., alachlor, glyphosate, pendimethalin, and 2,4-D, on *Trichoderma* spp. and reported toxicity of all the four herbicides on biocontrol agents.

Based on our experimental result (Ranganathswamy et al. 2013), all the agrochemicals were grouped as dangerous, cautious, and safe to antagonist. As the formulations of biocontrol agents are mainly based on spore preparations (with more shelf life), inhibition of spores by test agrochemicals was given higher weightage compared to mycelial inhibition while grouping into ten different categories of compatibility.

I Category: 100% inhibition of spore germination and 100 % inhibition of radial growth

II Category: 100% inhibition of spore germination and >50% inhibition of radial growth

III Category: 100% inhibition of spore germination and <50% inhibition of radial growth

IV Category: >50% inhibition of spore germination and 100% inhibition of radial growth

V Category: <50% inhibition of spore germination and 100% inhibition of radial growth

All the above five categories were placed in Group I, i.e., "dangerous" chemicals to antagonists.

VI Category: >50% inhibition of spore germination and >50% inhibition of radial growth

VII Category: >50% inhibition of spore germination and <50% inhibition of radial growth

VIII Category: <50% inhibition of spore germination and >50% inhibition of radial growth

All the above three categories were placed in Group II, i.e., "cautious" chemicals to antagonists. Further, chemicals with EC_{50} values less than field concentration but falling in cautious group are also placed in Group I, i.e., dangerous group.

IX Category: <50% inhibition of spore germination and <50% inhibition of radial growth.

X Category: No inhibition of spore germination and no inhibition of radial growth

The above two categories were placed in "safe" group.

Further, all the chemicals with EC_{50} values more than field concentration were also considered "safe."

Among 18 fungicides evaluated, 15 fungicides, viz., Bordeaux mixture, mancozeb, thiram, captan, carbendazim, benomyl, carboxin, metalaxyl, propiconazole, hexaconazole, tricyclazole, tridemorph, chlorothalonil, fosetyl-Al, and azoxystrobin, were found toxic and grouped as dangerous, and the remaining three fungicides, viz., copper oxychloride, wettable sulfur, and dinocap, were placed in "cautious group" (Table 1.1). None of the test fungicide was found safe to the test *Trichoderma* isolates.

Table 1.1 Categorization of agrochemicals into various groups based on percent inhibition of radial growth and spore germination

Sl. no.	Percent inhibition: Spore germination	Percent inhibition: Radial growth	Category	Group	Agrochemicals
1.	100	100	I	*Dangerous*	*Fungicides*: Bordeaux mixture, mancozeb, thiram, captan, carbendazim, benomyl, carboxin, metalaxyl, propiconazole, hexaconazole, tricyclazole, tridemorph, fosetyl-Al, chlorothalonil, azoxystrobin
2.	100	>50	II		***Insecticides***: chlorpyriphos, quinalphos, dimethoate
3.	100	<50	III		*Fertilizers*: zinc sulfate
4.	>50	100	IV		*Herbicides*: pendimethalin, glyphosate, alachlor
5.	<50	100	V		
6.	>50	>50	VI	*Cautious*	*Fungicides*: copper oxychloride, dinocap, wettable sulfur
7.	>50	<50	VII		*Insecticides*: endosulfan, carbofuran, thiamethoxam, emamectin benzoate, fipronil, spinosad
8.	<50	>50	VIII		*Fertilizers*: urea, DAP
					Herbicides: 2,4-D sodium salt
9.	< 50	< 50	IX	*Safe*	*Insecticides*: imidacloprid, indoxacarb
10.	0	0	X		*Fertilizers*: MOP, SSP, ammonium sulfate, potassium nitrate

Two insecticides, chlorpyriphos and quinalphos, were placed in dangerous group. Though dimethoate showed differential sensitivity on test *Trichoderma* isolates, as the EC_{50} value was less than field concentration (indicating toxic nature of the dimethoate), it was placed in dangerous group. Endosulfan, carbofuran, thiamethoxam, emamectin benzoate, fipronil, and spinosad were placed in cautious group. Only two insecticides, viz., imidacloprid and indoxacarb, were placed in safe group. Fipronil, spinosad, and carbofuran showed differential sensitivity to test *Trichoderma* isolates. Further, as the EC_{50} values of these chemicals were more than field concentrations, they were placed in safe group (Table 1.1).

Among seven fertilizers evaluated, zinc sulfate was placed in dangerous group, urea and DAP in cautious group, and muriate of potash, single superphosphate, ammonium sulfate, and potassium nitrate in safe group (Table 1.1).

Three herbicides, viz., alachlor, glyphosate, and pendimethalin, out of four evaluated herbicides were placed in dangerous group, while the fourth herbicide 2,4-D showed differential sensitivity toward test *Trichoderma* isolates with least inhibition and thereby was placed in cautious group (Table 1.1).

1.5 Measures to Overcome Negative Effect of Agrochemicals

Ideally, agricultural systems should be designed in a way that pests, diseases, and weeds do not build up to a level that they cause significant damage to the crop. Suitable agronomic practices, the use of resistant varieties, and integrated pest management are key preventive measures. Biocontrol and the use of natural substances can complement these efforts. The safe application of minimal toxic synthetic pesticides should be used as a last resort.

1.5.1 List of Strategies

- Avoid the prophylactic sprays of pesticides.
- The use of optimum dose, at the right time and on the right pest, is the key measure to reduce the indiscriminate use of pesticides and thereby development of resistant strains.
- Appropriate plant nutrition and soil fertility management based on organic matter form the basis for healthy crops that are less susceptible to pests, diseases, and weeds.
- Following crop rotation that prevents the carryover of pest, pathogen, and weed populations.
- Appropriate timing of sowing or planting and of intercultural operations reduces pest pressure.
- Precision farming like spraying of hotspots and weeding with optical detectors.
- Crops and crop varieties differ in their susceptibility to pests and diseases and in their ability to compete with weeds. The use of resistant varieties together with rotations of non-susceptible crops can substantially limit pest buildup within a field, thereby limiting the use of pesticides.
- Use of genetically modified crops. For example, Bt cotton against bollworms in cotton substantially reduced the pest incidence and thereby pesticides.
- Use of less hazardous pesticides: Phasing out the use of highly hazardous pesticides and replacing them with less hazardous ones is therefore the most obvious way to reduce the negative side effects of pesticides.
- Various plant extracts and other natural materials are used that repel pests, reduce their feeding or reproductive activities, reduce proliferation of diseases, and act as biopesticides.
- Following integrated approach for pest management.
- Policies to reduce pesticide use and risks: International codes, treaties, conventions, commissions, and advisory bodies play an important role in plant protection and pesticide management. Each country needs to follow the strict regulations to reduce the risk of pesticide effect on human health and environment.

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