Biopesticides Research: Current Status and Future Trends in Sri Lanka

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Abstract

Sri Lanka is a tropical country equally having rich diversity of arthropods including natural enemies, economic pests, and indigenous plants majority with unique chemical properties. Because of the substantial losses due to pests and diseases, plant protection remains an essential issue in agriculture production in the country. There is increasing concern over synthetic pesticide usage due to their adverse long-term effects on human health, environment, and natural pest management systems. As an eco-friendly alternate, the importance of biopesticides in raising agricultural productivity is well recognized in Sri Lanka. Biopesticides are quiet popular among farming community due to their unique features, viz., safety, limited host range or target specificity, the absence of toxic residues, eco-friendly nature, and ease of application. Biopesticides have diverse modes of action and hence resistance development in pests is slower/negligible. Currently, plant powders, nonvolatile and volatile oils, and plant crude extracts are commercially available for management of insect pests and nematodes. Further, several bacterial and fungal biopesticides have shown promising results for the efficient management of plant pathogens in Sri Lanka.

Keywords

Biopesticides • Biocontrol agents • Organic farming • Agriculturally important microorganisms

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H.B. Singh et al. (eds.), *Agriculturally Important Microorganisms*,
DOI 10.1007/978-981-10-2576-1_13

13.1 Introduction

Sri Lanka has been known as an agricultural country since ancient times. Approximately 30 % of the 6.5 million ha of land area in Sri Lanka are under cultivation. Due to the substantial crop losses caused by pests and diseases, plant protection remains an essential issue for improving agriculture production in the country. The present annual synthetic pesticide consumption is estimated at 1700 t of active ingredients amounting to approximately Rs 4.6 billion. There is an increasing concern over synthetic pesticide usage due to their adverse long-term effects on human health, environment, and natural pest management systems. As an alternate, the importance of biopesticides in raising agricultural productivity is well recognized in Sri Lanka.

The term biopesticides refer to those pesticides obtained from biological sources such as microbes (fungi, bacteria, viruses, protozoa, and nematodes), semiochemicals (insect sex pheromones), biochemicals (substances from biological sources especially botanicals such as essential oils, nonvolatile oils, and extracts), and commercially produced natural enemies (predators and parasitoids). Biopesticides are distinguished from synthetic pesticides by their unique features: safety, limited host range or target specificity (very low risk to nontarget organisms), the absence of toxic residues on fruit and vegetables (easily degradable in nature), environment-friendly, and easily applied using conventional spray equipment. Biopesticides offer diverse modes of actions; hence, resistance development in pests is slower. Therefore, there is immense scope in identifying and developing biopesticides as alternative pest management strategies. The importance of novel and alternative biopesticides and the necessity for research and development of novel, cost-effective, environmentally friendly pesticide is well recognized in Sri Lanka.

Limitations and challengers of commercializing biopesticides are slow action and low persistence when exposed to solar UV, high cost of production, and lack of awareness among Sri Lankan farmers. The major constraints to biopesticide development are poor awareness of decision-makers about opportunities offered by biopesticides, lack of multidisciplinary expertise in the crucial later stages of development, difficulty in conducting toxicological tests, and the long testing period of bioactive compounds before registration and commercialization.

13.2 Classification of Biopesticides

Biopesticides are broadly categorized into two groups, biochemical pest control agents and microbial pest control agents.

Biochemical pest control agents: these chemicals are not directly toxic to target organisms like nerve poisons and exhibit different mode of action like mating disruption, molt inhibition, and growth regulation. They are naturally occurring substances; if synthesized, they must be identical to the natural chemical. There are four classes of compounds that fall into biochemical pest control agents:

1. Semiochemicals: pheromones, allomones, and kairomones
2. Hormones: molt hormones (ecdysteroids) and juvenile hormones (IGR)
3. Natural plant regulators: auxins, gibberellins, cytokinins, and inhibitors
4. Enzymes

Microbial pest control agents: these include formulations that occur in nature or organisms effective as pest management agents. Microbial pest control agents include:

1. Bacteria: *Bacillus thuringiensis* (Bt)
2. Fungi: *Verticillium*, *Metharizium*, and *Hirsutella*
3. Virus: *Nuclear polyhedrosis virus* (NPV)
4. Nematodes: *Steinernema* sp.

13.3 Biopesticides Used in Agriculture in Sri Lanka

Nearly 30 % of the 6.5 million ha of lands in Sri Lanka are cultivated to agricultural crops. Of this, the food crop sector dominated by rice (730,000 ha), vegetables (90,000 ha), root and tuber crops (100,000 ha), fruits, other field crops, and export agricultural crops (200,000 ha) occupies around 12 million ha. The plantation crops and other perennials occupy around 700,000 ha. Sri Lanka has a very rich natural enemy complex of crop pests as compared to tropical Asian countries giving more opportunities for the utilization of natural biocontrol. For instance, the egg parasitism of brown plant hopper found to reach as high as 80 % in fields kept free of pesticides during the early vegetative stage. Furthermore, rice land spiders fauna were found very effective in managing hopper pests and also less affected by diamondback moth damage when the wrapper leaves are kept free of insecticides to allow the multiplication of parasitoids like *Cotesia plutellae*, *Diadegma* sp. The leaf miner, *Liriomyza* sp., damage found to be low when the affected crops are sprayed only with neem extracts as compared to other insecticides. These evidences suggest the vast potential available for the application of biological pest control agents for crop pest management in Sri Lanka (Table 13.3).

However, at present, only a few pesticides that qualify as biological pesticides are marketed in Sri Lanka (Tables 13.1 and 13.2). Furthermore, farmer acceptance and applicability of these products at field level are found to be very low. This could be due to the inherent features of the biopesticides that require careful planning in the treatment schedules than the conventional pesticides and the low profile given for promotional activities including education of farmers and extension staff.

Table 13.1 Commercially available biopesticides and other related compounds in Sri Lanka

Common name	Origin	Trade name/mode of action	Toxicity	Remarks
Bacillus thuringiensis Bt	*Bacillus thuringiensis* subsp. *kurstaki*	Bt 85 % WG	Stomach poison. The endotoxin crystals are solubilized, and the epithelial cells of the gut are damaged, insects stop feeding, and eventually starve to death	Acute oral LD50 for rats > 2.67 g/kg, 1 × $10^{11 spores/kg}$
Abamectin	Isolated from fermentation of *Streptomyces avermitilis*. Avermectin (Vertimec)	Acts by stimulating the release of r-aminobutyric acid, an inhibitory neurotransmitter, thus causing paralysis		Acute oral LD50 for rats 10s
Azadirachtin/neem seed water extract	Principal insecticidal ingredient of neem seed extract – contains limonoids	Neemasal and Neemgrow	Ecdysone antagonist. Disrupts insect molting. Fungicidal and miticidal, antifeedant and repellent	Acute oral LD50 for rats >5000 mg/kg

13.4 Regulatory Frameworks and Research and Training in Pest Management

13.4.1 Botanical Products

Many plant species with pest control properties were identified and used at village level in small scale, and Sri Lankan farmers have sound knowledge about the indigenous practices of utilization of plant products for pest management. Neem products are highly utilized in pest management, and many researches have been conducted to estimate their possible effects with fulfilled results. A number of neem-based commercial products are available in Sri Lankan market for agricultural uses in different trade names, and it is recommended to use for the control of

Table 13.2 Commercially available insect growth regulators, chitin synthesis inhibitors, molt-accelerating compounds in Sri Lanka

Common name	Origin	Trade name	Mode of action	Toxicity	Remarks
Tebufenozide	Molt-accelerating compound	Mimic	Ecdysone agonist, binds to the receptor sites of molting hormone, ecdysone, lethal molting	Acute oral LD50 – rats 5000 mg/Kg	Recommended for the control of leaffolder of rice and leaf-eating caterpillar on vegetables
Methoxyfenozide	Molt-accelerating compound	Runner	Accelerate molting	Acute oral LD50 – rats >5000 mg/Kg	Recommended for the control of leaffolder of rice and leaf-eating caterpillar on vegetables
Chlorfluazuron	Chitin synthesis inhibitor	Atabron	Anti-molting agent	Acute oral LD50 – rats 5000 mg/Kg	Recommended for the control of leaffolder of rice and leaf-eating caterpillar on vegetables
Cyromazine	Inhibits molting and pupation	Trigard	IGR with contact action interferes with molting and pupation systemic in plants	Acute oral LD50 – rats 3387 mg/Kg	Effective against leaf miners
Buprofezin	Chitin synthesis inhibits	Applaud	Chitin synthesis and prostaglandin inhibition	Acute oral LD50 – rats 2000 mg/Kg	Recommended against BPH and whiteflies
Novaluron	Chitin synthesis inhibits	Rimon	Affect molting, abnormal endocuticular deposition, and abortive molting	Acute oral LD50 – rats 5000 mg/Kg	Recommended against BPH, fruit borer, and leafhopper

leaf-eating caterpillars in vegetables, diamondback moth in cabbage, rice leaffolder, sesame leaf webber, leaf miners in vegetables, and mites in vegetables. In addition, neem-based pesticides have a considerable potential for controlling *Callosobruchus* spp. (Rajapakse 1990) and *Sitophilus oryzae* (Mannakkara 2002) under storage conditions. The other popular botanical products for pest management are *Allium*

Table 13.3 Biopesticides with potential use in Sri Lanka for crop pest management

Common name	Origin	Trade name	Mode of action	Toxicity	Remarks
Spinosad (spinosyn C and D)	Actinomycetes *Saccharopolyspora spinosa*	Success	Nicotinic acetylcholine receptor, different from nicotine or imidacloprid leads to paralysis	Acute oral LD50 – rats 5000 mg/kg	No residues, rapidly degraded, for leaf miner control
Metarhizium anisopliae local cultures	Entomopathogenic fungus	–	–	LC50 for rats > 4850 mg/m^3	BPH control in rice
Predatory mites	–	–	–	–	For the control of coconut mites
Spodoptera exigua NPV	Baculoviridae: Nucleopolyhedrovirus	“Spod-X” Ness A WA, LC	Active by ingestion. Caterpillars cease feeding after 4 days and die after 5–10 days	–	For vegetable caterpillar control
Essential oils of plants like-*Cinnamomum zeylanicum*, *Cymbopogon nardus*, *C. citratus*, etc.	Bioactive compounds	–	Act as a repellents, growth inhibitors	–	Stored grain pests of rice, cereals, legumes, and potatoes

sativum, *Capsicum frutescens*, *Gliricidia sepium*, *Adathoda vesica*, *Pleurostylia opposita*, *Acronychia pedunculata*, *Alseodaphne semecarpifolia*, etc.

13.4.2 Plant-Derived Biochemicals Used in Postharvest Storage

The postharvest losses and quality deterioration caused by storage pests are major problems throughout the world and more vulnerable in tropical countries like Sri Lanka. Traditional methods of pest control in grains by mixing them with neem, citrus and maduruthala leaves, plant oils, and powdered plant materials have been utilized by farmers for many years.

Continuous research has been performed systematically to evaluate plant-derived biochemicals using various indigenous plant species in different forms such as crude ethanol (CE) extracts, vegetable oils, dry powders, and combinations of plant materials with insecticides against *Callosobruchus* spp. in laboratory conditions (Rajapakse et al. 1998, 2002; Rajapakse and Ratnasekera 2009; Ratnasekera and Rajapakse 2012).

13.4.3 Crude Extracts

Extracting plant materials with an appropriate solvent generally results in concentration of active ingredients. Such extracts are therefore often more effective against storage beetles than powders of fresh plants. Usually the extracts are mixed with the seeds as a liquid, and the solvent evaporates before the seeds are stored. Many local plant species have been tested for bioactive compounds, and various degrees of bioactivities were recorded. According to Rajapakse and Ratnasekera (2008), the highest bioactivity (90–100 % mortality) was manifested by the crude ethanol extracts of *Azadirachta indica* (neem), *Annona reticulata* (anona), and *Ocimum sanctum* (maduruthala/sacred basil) among the 20 plant crude ethanol extracts tested. Extracts of *Myristica fragrans*, *Gliricidia sepium*, *Ricinus communis*, *Cajanus cajan*, *Mangifera indica*, *Eupatorium odorantum*, *Dioscorea polygonoides*, and *Hibiscus rosa-sinensis* showed no toxicity, while those of *Citrus reticulata*, *Artocarpus heterophyllus*, and *Cassia occidentalis* had little toxicity. *Capsicum annuum* and *Dillenia retusa* plant extracts were slightly toxic. *C. frutescens* and *Piper nigrum* were moderately toxic, while those of *Eugenia caryophyllata* caused fairly high-toxic plants to the beetle mortality (Table 13.1). Plant extracts of*Allium sativum*, *Piper guineense*, and *Capsicum annuum* from different solvents such as petroleum ether and ethanol effective on stored beetle adults are either acting as repellent, toxicant, or combination of these two actions (Rajapakse 2000).

The disadvantages of using crude extracts are mostly difficulty to prepare and laborious to make low yields and hence need large quantities of plant materials, and farmers have no facilities to extract plants in village level (Table 13.4).

13.4.4 Nonvolatile Oils

Mixing plant oils with stored seeds is common among farmer communities. Nonvolatile oil is used as a coating for seeds and effectively protects seeds against insect pests during stage. The film of oil prevents the attachment of the egg to the seed coat. Most of the oils are very effective and retain their effectiveness over a long period. The non-bitter taste of plant oil used is an added advantage over neem oil, which is known for its bitter taste. The relatively small amounts of oils required their effectiveness, and the simple technology of extraction will make these plant oils a better candidate for seed dressing purposes for cowpea storage. Nonvolatile oils can have negative effects on adult beetles through contact toxicity or through deterrence. With increase of prevailing prices of insecticides, the application of plant oils would be an inexpensive control method against *C. maculatus* and *C.*

Table 13.4 Toxicity of the ethanol extracts of the leaves of 20 plants to *C. maculatus* and *C. chinensis*

Plant species	Corrected mortality					
	Day-1		Day-2		Day-3	
	C.c.	*C.m.*	*C.c.*	*C.m.*	*C.c.*	*C.m.*
Capsicum frutescens	35 ± 1.0	40 ± 2.6	45 ± 1.2	48 ± 3.1	60 ± 6.6	60 ± 6.7
Myristica fragrans	00	00	00	00	00	00
Piper nigrum	35 ± 1.2	40 ± 1.8	48 ± 2.1	50 ± 2.7	55 ± 2.1	60 ± 6.5
Citrus reticulata	10 ± 0.8	12 ± 1.0	10 ± 1.0	08 ± 0.7	12 ± 1.1	14 ± 1.0
Cymbopogon citratus	50 ± 3.5	60 ± 5.2	50 ± 4.6	60 ± 4.3	65 ± 3.7	67 ± 4.9
Artocarpus heterophyllus	05 ± 0.5	08 ± 0.7	12 ± 1.0	11 ± 1.0	15 ± 1.1	17 ± 1.1
Gliricidia sepium	00	00	00	00	00	00
Eugenia caryophyllata	50 ± 4.8	60 ± 5.1	60 ± 4.8	60 ± 4.0	71 ± 5.6	70 ± 6.2
Ricinus communis	00	00	00	00	00	00
Dillenia retusa	40 ± 2.8	44 ± 3.0	50 ± 3.7	56 ± 3.8	50 ± 4.2	58 ± 4.7
Azadirachta indica	50 ± 3.5	60 ± 4.2	60 ± 4.0	65 ± 4.6	80±	6.7
Cajanus cajan	00	00	00	00	00	00
Cassia occidentalis	06 ± 0.4	09 ± 0.6	12 ± 0.8	13 ± 1.1	15 ± 1.3	18 ± 1.5
Annona reticulata	80 ± 5.7	80 ± 5.6	80 ± 6.3	90 ± 6.0	90 ± 6.8	91 ± 7.1
Mangifera indica	00	00	00	00	00	00
Eupatorium odoratum	00	00	00	00	00	00
Ocimum sanctum	80 ± 5.7	80 ± 5.6	80 ± 6.3	90 ± 6.0	90 ± 6.8	91 ± 7.1
Capsicum annuum	30 ± 1.8	35 ± 2.1	43 ± 3.8	50 ± 4.6	48 ± 3.9	45 ± 3.2
Dioscorea polygonoides wild	00	00	00	00	00	00
Hibiscus rosainensis	00	00	00	00	00	00

Source: Rajapakse and Ratnasekera (2008)

chinensis. Oils of *O. sanctum* at 1.5 μL and *A. reticulata* at 3.0 μL completely inhibited oviposition and adult emergence of *C. maculatus* and *C. chinensis* inferring their potential utilization (Ratnasekera and Rajapakse 2012). Oviposition could be influenced by treatment of the stored product with nonvolatile oil. Rajapakse and Vanemden (1997) reported that the four oils; corn, groundnut, sunflower, and sesame reduced oviposition of all three bruchid species tested. Further, groundnut, coconut, and soybean oils reported to be reduced adult mortality significantly compared to standard chemical control by pirimiphos-methyl. However, direct mixing oils might reduce consumer demand (Table 13.5).

13.4.5 Volatile Oils

Volatile oils can be extracted mostly by aromatic plants. The yield volatile oil is usually low, but due to repellence or toxicity, even small amounts of the concentrated essential extract can be very effective in airtight or hermetic storage

Table 13.5 The effect of standard chemical control, pirimiphos-methyl, and nonvolatile vegetable oil against *C. maculatus* adults

Treatments	Dosage	Mean (1 DAT)	% mortality (7 DAT)
Control		0.00[g]	2.700[g]
Pirimiphos-methyl	Full dose	100.00[a]	100.000[a]
	¾ dose	90.367[c]	95.300[b]
	½ dose	73.267[e]	85.700[e]
	¼ dose	65.000[f]	81.000[f]
Groundnut oil	10 ml/kg	95.000[b]	85.700[e]
Coconut oil	10 ml/kg	91.000[c]	92.000[c]
Soybean oil	10 ml/kg	85.000[d]	87.700[d]

Source: Rajapakse 2002

structures. Nayanathara and Ratnasekera (2010) reported that volatile fumes of cinnamon and citronella oil could effectively repel stored pests in bulk storages. According to their findings, no losses on viability and no off-flavors are detected. Hence, volatile oils have broad consumer preference in seed storage both for consumption and store as planting material as oils are not mix with seeds.

Further, the repellent effects of ten oils, Domba (*Calophyllum inophyllum* L.), Batu (*Solanum indicum* L.), leaf oil and bark oil of cinnamon (*Cinnamomum verum* Presl.), mustard oil (*Brassica juncea* Cross.), neem oil (*Azadirachta indica* A. Juss.), mee oil (*Madhuca longifolia* Koenig.), castor oil (*Ricinus communis* L.), citronella oil (*Cymbopogon nardus* L.), and sesame oil (*Sesamum indicum* L.) were tested for pulse beetle (*Callosobruchus maculatus* L.) in the laboratory conditions, and they reported that citronella oil, neem oil, cinnamon leaf oil, and cinnamon bark oil vapors showed significantly control in pulse beetles after infestation indicating the highest repellent action and toxic effects (Rajapakse and Ratnasekera 2009).

13.4.6 Plant Powders

Mixing plant materials as powder form is a simple technique that can be easily adopted among farmers. Many plants have been tested in the laboratory as powders to evaluate their possible effects. Clove powder was the most effective among the four powders tested for adult mortality followed by root dust of papaya. Among the plant powders tested, maduruthala (*O. sanctum*) was the most effective for suppressing oviposition significantly followed by geta thumba (*Leucas zeylanica*). Same study reported that enhanced toxicity and mortality to *Callosobruchus* spp. persistence of the insecticide in causing significant reduction when combined with vegetable oils. Further, these results revealed the potential applicability of some indigenous plant materials as stored grain protectants. The modes of action of these substances are not yet known, and further studies must be carried out especially to clarify how it is involved in the physiology of reproduction.

13.5 Microbial Pest Control Agents

Currently, many scientists are focusing research on utilization of microorganisms as a biofertilizer, and several studies have been done to identify the advantages of utilizing *Rhizobia*, *Azotobacter*, *Azospirillum*, blue-green algae, *Azolla*, and phosphate solubilizers (several bacteria and fungi) in local conditions, and it showed good results.

The soil is the natural habitat of N-fixing bacteria, but due to the degradation of agricultural soil, often our soil do not have either the proper kind of nodule-forming bacteria or enough quantity of certain bacteria to enhance the good legume growth. *Rhizobium* is the most well-known species for symbiotic nitrogen fixation, and many research works have been done to the collection, isolation, and subsequent selection of effective rhizobial strains, and its uses in agriculture have yielded fruitful results. And also, use of *Rhizobia* as biofertilizers in mushroom cultivation also seems to be a promising result in experimental basis (Senevirathna et al. 2009).

Utilization of *Azolla* spp. for nitrogen fixation in paddy land results strong support to the potential use as a biofertilizer for rice in Sri Lanka. Seventy-three strains of nitrogen-fixing blue-green algae, belonging to 21 genera, were isolated in rice soils in Central Sri Lanka (Kulasooriya and de Silva 1981).

The basic research on P-solubilizing biofertilizers was successfully established resent past. Biosolubilization of rock phosphate using fungal solubilization such as a *Penicillium* spp., an *Aspergillus* spp., *Pleurotus ostreatus*, *Bradyrhizobium elkanii*, and P-solubilizing bacteria was investigated and identified an effective method of fungal-rhizobial biofilm-mediated solubilization of Eppawala rock phosphate deposit in Sri Lanka (Jayasinghearachchi and Seneviratne 2006).

Plantation sector of Sri Lanka faces massive problem on soil degradation due to mismanagement of soil resources and monoculture cropping system adopted in plantation sector. To minimize this target, usage of inorganic and organic manures and biofertilizer will have a major and important role to play. Basic research has been implementing studies on biofertilizers based on microbial biofilms and their effects on soil carbon accumulation. In a nursery tea soil, a liquid formulation of biofilmed biofertilizers together with 50 % of recommended chemical fertilizers for tea increased soil organic carbon by 30 %, compared to the application of 100 % of the recommended fertilizers alone (Jayasekara et al. 2008). Many basic researches have been done to utilization of mycorrhizal inoculants to improved crop productivity and showed that inoculation of tea cuttings with VAM significantly enhanced the growth of tea seedlings.

13.5.1 Bacteria

A number of bacteria have been reported as entomopathogenic, and formulation of *Bacillus thuringiensis* is registered as a biopesticide in Sri Lanka since the 1990s. However, their potential has not been fully exploited by Sri Lankan farmers due to high cost and rapid breakdown of these bacteria under conditions.

13.5.2 Fungi

Mortality of insects due to fungal attack is considerably reported in the natural conditions but did not utilized one of them as a biopesticide in commercial level up to now. Recently, the Tea Research Institute of Sri Lanka focusing research on utilization of locally isolated *Beauveria bassiana* against shot hole borer, and it shows promising results under laboratory conditions (Pavithrani et al. 2009). *Metarhizium anisopliae* has a potential use to manage coconut black beetle, *Oryctes rhinoceros* (Fernando et al 1995), and the Coconut Research Institute of Sri Lanka has recommended it to manage this beetle in local conditions. *Metarhizium anisopliae* and entomopathogenic nematodes (Nematoda: Heterorhabditidae) were bioassayed against Kalotermitidae termites of tea by the Tea Research Institute of Sri Lanka, and promising strains are identified and further experiments are continuing yet.

A fungus *Trichoderma viride* normally colonizes near the rhizosphere and parasitize on pathogenic fungi such as *Phythium*, *Rhizoctonia*, and *Fusarium*. Commercial formulations of *T. viride* are available in the local market, and it provides resistance to rot and wilt diseases of many crops.

13.5.3 Insect Viruses

Insect viruses have long been considered as advantageous agents for management of insect pests of agricultural important crops, and among them, baculoviruses pay a vital role in pest management in the world. The scientist in the Coconut Research Institute at Sri Lanka did several attempts to use baculoviruses against the coconut black beetle, *Oryctes rhinoceros*, and it is recommended to use *Oryctes rhinoceros* virus (Orv) for control of coconut black beetle. Commercial formulation of *Spodoptera exigua* NPV is available in the local market and is recommended for management of caterpillars on vegetables.

13.6 Prospects of Biopesticides and Plant Disease in Sri Lanka

The economy of Sri Lanka is mainly agriculture-based. It has two sectors, namely, domestic and plantation sector. The domestic sector, which forms the dominant part of agriculture, accounts for 1.7 million farming families in a population of around 19 million. Both sectors jointly contribute 20 % to gross domestic product (GDP) and 34 % to employment (Central Bank of Sri Lanka Report 2002). In management of pests, the plantation sector approaches in a more organized manner, whereas in the domestic sector, it is more complicated due to large number of farmers, crops, and the pests involved. Pest management in Sri Lanka is mostly synthetic pesticide-dependent, and the annual imports of pesticides cost around 0.1 % of the gross domestic production in 2012. Apart from pests and weeds, plant diseases caused by various groups of plant pathogens are often a big challenge in agriculture in

Sri Lanka. Currently, protection of plants from diseases has also been largely based on the use of synthetic chemical pesticides. Applications of pesticides can have drastic negative effects on the environment, consumer, applicant, and appearance of pesticide resistance strains of the target organisms. Therefore, reduction or elimination of chemical pesticides in agriculture is highly important. One of the most desirable means to achieve this goal is by the use of new tools based on biological control agents (BCAs) and natural antimicrobial chemicals for disease control. Many studies have been devoted in Sri Lanka to the identification of microorganisms and antimicrobial botanicals that can be able to reduce activity and/or kill plant pathogens during the past two decades. When a particular country is concerned, it is important to develop its own BCAs as many quarantine procedures are imposed in almost all countries. On the other hand, BCAs are very specific in action, and many factors are involved in their mode of actions. Therefore, BCA developed for a particular plant-pathogen interaction in a country may not be suitable or not effective in another country. However, most experiences were on laboratory scale, and disease control trials were confined to experimental greenhouses or small field plots. Thus, large-scale mass production, formulations, and storage of biopesticides must be initiated, and research leading for these aspects should be given more priorities.

Up to now, BCAs against several important soilborne pathogens, foliar pathogens, and postharvest pathogens in different crops have been tested in different laboratories in Sri Lanka. For soilborne pathogens, *Trichoderma*, *Bacillus*, and *Pseudomonas* spp. have been identified for *Rhizoctonia*, *Sclerotium*, and *Fusarium* spp. on rice, chili, bean, cucumber, and banana. Soe and Costa (2012) reported that *Bacillus megaterium*, *Bacillus subtilis*, and *Aspergillus niger* isolated from the rice sheath were antagonistic to *Rhizoctonia solani*, the causal agent of sheath blight disease of rice. The talc-based formulations of these antagonists were effective as biopesticides on sheath blight pathogen. Abeysinghe (2009a) showed that *Bacillus subtilis* was effective on *Sclerotium rolfsii* on chili *and Pseudomonas* spp. introduced to the root system of bean was able to induced systemic resistance to bean rust caused by *Uromyces appendiculatus* has also reported (Abeysinghe 2009b). *Trichoderma harzianum* has also been identified as a biocontrol agent against bean rust, and induced systemic resistance (ISR) was identified as a possible mode of action (Abeysinghe 2009c). In the case of postharvest diseases Wijesinghe et al. (2011) has shown that *Trichoderma asperellum* was effective against black rot pathogen, *Thielaviopsis paradoxa* on pineapple. Jayasuriya and Thennakoon (2007) reported that one of the important soilborne fungal pathogens of rubber, *Rigidoporus microporus*, could be controlled by *Trichoderma* spp. Sivakumar et al. (2000) reported that *Trichoderma harzianum* was effective on *Nephelium lappaceum* against *Botryodiplodia*, *Colletotrichum*, *and Gliocephalotrichum*. Adikaram et al. (2002) reported that *Aureobasidium pullulans* is effective against *Botrytis cinerea* of strawberry fruits, and ISR has been identified as the mode of action. Gunasinghe et al. (2009) reported that *Flavobacterium* spp. and *Pantoea agglomerans* have been identified for *controlling Colletotrichum musae* and *Lasiodiplodia theobromae,* the postharvest pathogens of banana.

Apart from these microorganisms, some botanical extracts have also been tested against nematodes and fungal pathogens. Root nematodes in tomato have been successfully controlled by leaf extract of *Piper betle* (Premachandra et al. 2014). Field trials conducted by using *Trichoderma* bioformulation against Panama wilt pathogen *Fusarium oxysporum* f.sp. *cubense* have been successful in initial trials, and further testing is in progress (Abeysinghe et al. unpublished). Moreover, biofilm formation is one of the important aspects of root-colonizing bacteria, and efficacy of such biofilms formation is known as an important factor for success of biocontrol agents (Seneviratne et al. 2008). Therefore, numbers of research topics are currently being focused into these aspects in Sri Lanka.

As mentioned above, biological control research toward screening, formulation, and testing them under greenhouse as well as in field conditions are being conducted. However, very limited biocontrol agents are evaluated to make a successful transition from the laboratory to field. A good formulation is the key to the commercial success of biocontrol agents. Understanding the biocontrol agent can lead to innovative ways of improving the efficacy of the biocontrol product because many physical and biological parameters could be influenced to the efficacy of the product.

However, more efficient and effective ways of growing and formulating BCAs are needed in many cases in order to make biocontrol economically viable. Research on safety and environmental fate of BCAs is lacking at present. Therefore, regulatory criteria that are essential for safety have to be worked out. Additional funding is needed for biocontrol research to be progressed in Sri Lanka. In this context, importance of private/public partnerships with academia should be highlighted.

13.7 Policy Issues

The Sri Lanka National Agricultural Policy clearly mentions the importance of promoting production and utilization of organic and biofertilizer and gradually reduces the use of chemical fertilizers through integrated plant nutrition system.

In 2002, the National Engineering Research and Development Center (NERD) established the "Biogas and Biofertilizer Project at Muthurajawela in Sri Lanka," and this project was due to misunderstanding between the NERD and local authorities.

Sarvodaya Economic Enterprise Development Service (Guarantee) Limited has established effective microorganisms unit in 1996, and presently, this is the only one producer with sole agent right to produce and market effective microorganism products in Sri Lanka. They marketed several EM products for crop production.

The search of new innovative crop management programs to reduce the health risk and environmental pollution should have focused in the future research and biofertilizer, and biological pesticides will ensure these criteria in food safety and sustainability of agriculture in Sri Lanka. But there are several technological and policy gaps to promote biofertilizer and biopesticide in Sri Lanka. The major problems are lack of funds for research and fewer facilities in research laboratories with no novel equipment for research. It is necessary to train the research scientists with no novel equipment for research, and also, it is necessary to develop international linkages of local scientist with other scientists worldwide to easily exchange their knowledge. The Sri Lanka National Agricultural Policy clearly mentions the importance of promoting production and utilization of organic and biofertilizer and gradually reduces the use of chemical fertilizers through integrated plant nutation system. But fertilizer subsidy is one of the major benefits enjoyed by farmers especially small holders and rice farmers. Rice is the staple food crop grown in Sri Lanka and very difficult to cut down the fertilizer subsidy without proper low-cost alternatives because of the political influence of the country. Fertilizer subsidy is one of the barriers to promote biofertilizer, and meanwhile more research is required to develop low-cost technology for utilization of biofertilizer as an alternative to inorganic fertilizer. More field of research on biofertilizer is still in its infancy; therefore, both laboratory and field experiments are required to fully explore potential use of biofertilizer for crop production in the future.

13.8 Current Status

Sri Lanka's agriculture have been practicing organic farming over centuries and use of biofertilizer and biopesticides has been a traditional practice followed by many rural farmers to increase the soil fertility, soil aggregate stability, water infiltration, and soil water-holding capacity. Commercial formulation of biochemical pest control agents such as semiochemicals, hormones like ecdysteroids and juvenile hormones, natural plant regulators, and enzymes is available in the pesticide market of Sri Lanka today. As well, effective microorganisms such as bacteria, fungi, viruses, nematodes, or genetically modified microorganisms effective as pest and pathogen management agents are also available in the pesticide market.

13.9 Commercialization of Biocontrol

Some of the important strategies for commercialization of biopesticides are to strengthen the commercial microbial pesticide and natural enemy industry; promote research and education on the use of biocontrol agents; exploit the export market; develop quality certification programs for biocontrol agents, requirements for commercialization research teams vs. individual isolated studies, and financial support for R&D Practical technology; improve rearing and release methods and field tests to determine efficacy, quality control, effectivity against pest, high benefit/cost, and safety for the environment. Customer services such as companies to provide detailed information on how to use their products and companies to deliver excellent customer service for site-specific biological control need to be developed. The marketplace ultimately determines the usefulness of commercial natural enemies and the viability of the industry.

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