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Assessment of Biological Control Agents against Major Crop Pests

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ABSTRACT

Biological control agents have become a key element in the sustainable control of pests because of the growing concern over the environmental and health effects of synthetic pesticides. The growing world problem of food needs and pressure to reduce damage to the environment has led to such studies to harness the power of natural enemies and microbial agents in the suppression of major crop pests. Biological control includes a wide variety of biological organisms such as predators, parasitoids, pathogenic microbes, and entomopathogenic nematodes, which work by predation, parasitism, infection and competition to decrease the pest population. Despite the successes in particular cropping systems, a lack of widespread adoption because of such challenges as environmental dependency, limitations in mass rearing and inconsistencies in field efficacy. This paper evaluates existing biological control methods against key pests of crops, their effectiveness and the opportunities and the constraints that are involved in integrating them into modern agriculture. Overall, biological control comes as a promising route that will help bring the world towards becoming less dependent on chemical pesticides while still securing agricultural productivity.

Introduction

Global agriculture is confronted with a twin challenge of fulfilling growing demands for food while minimising adverse environmental impacts linked to the intensive production of sources of these foods. Agricultural pests are major contributors to yield losses worldwide and insects, mites and pathogens present a continued threat to crop health and productivity (Oerke, 2006). Traditionally, chemical pesticides have been the most popular pest management practice, because of their instant effectiveness and ease of use (Pimentel & Burgess, 2014). However persistent use of synthetic pesticides has resulted in serious ecological and health concerns such as contamination of ground water and soil bodies, damage to non target organisms, development of resistant pests, and the risk of human exposure (Pretty & Bharucha, 2015; Aktar et al., 2009). These difficulties have led to the importance of considering other ecologically friendly methods especially biological means of control whereby natural processes would be used to reduce the numbers of pests.

Biological control, i.e. the use of living organisms or living organisms products to decrease the number of pests, which began as a small-scale observation has grown into an organized pest management technique under the framework of integrated pest management (Eilenberg et al., 2001). Biological control agents (BCAs) are a broad range of organisms such as predatory insects, parasitoids, entomopathogenic fungi and bacteria, and nematodes which attack pests through predation, parasitism, or disease (Hajek & Eilenberg, 2018). The appeal of BCAs includes potential for species specific action, minimum disruption to the environment and ability for self sustaining populations that may offer long term suppression (van Lenteren, 2012). Thus, the integration of BCAs into pest management efforts is in line with sustainable goals in agriculture and reduces reliance on chemical inputs for agriculture.

There are also early examples of successes in biological control that were related to classical programs of biological control in which exotic natural predators were introduced to suppress invasive pests, including introducing parasitoid wasps to control scale insects in citrus (DeBach, 1964). These endeavors depicted that the identification of appropriate biological control entities of choice would create and manage pest populations successfully through repetitive chemical treatments becoming a thing of the past. In the relatively new decades augmentative and conservation biological control strategy has broadened the practical use of BCAs. Augmentative biological control consists of the periodic release of mass reared natural enemies for an immediate suppression of the pest population, whereas conservation biological control involves manipulation of the environment in a manner favorable to the existing natural enemy populations (Greathead, 1986; Landis et al., 2000).

Microbial agents such as Bacillus thuringiensis (Bt), Beauveria bassiana and Metarhizium anisopliae have great potential against various insect pests and are some of the most widely used biological control products worldwide (Schnepf et al., 1998; Butt et al., 2016). Bacillus thuringiensis produces crystalline proteins which are specific for lepidopteran and coleopteran larvae, hence considered a cornerstone in microbial pest management (Bravo et al., 2011). Entomopathogenic fungi such as Beauveria and Metarhizium infect the insects by cuticular penetration and have been used against insect pests of vegetable, fruit and grains (Zimmermann, 2007). In addition, entomopathogenic nematodes of the genera Steinernema and Heterorhabditis have been successfully applied for pest control of soil living pests, as an alternative to chemical soil treatments (Kaya & Gaugler, 1993). Predatory insects such as lady beetles (Coccinellidae) and lacewings (Chrysopidae) help suppress aphids, mites, and other soft bodied pests and parasitoids such as Trichogramma wasps, are popularly released for lepidopteran pests (Smith, 1996; Snyder & Wise, 2001).

Despite these improvements, practical deployment of biological control in varied agricultural systems, for example, is still limited by a number of factors. The success of BCAs is very dependent on the environmental conditions; the efficacy of entomopathogenic fungi can be diminished under low humidity and high UV exposure (Lacey et al., 2015). Similarly, mass rearing of high quality BCAs needs high technical know-how and infrastructure, which may not easily be available in developing agricultural areas (Shapiro Ilan et al., 2012). Besides, such features of pest populations as rapid reproduction and migration may issue the goals and expandability of biological control interventions (Tabashnik et al., 2013). These constraints have even led to erraticogenesis of the field as compared to the more certain outcome in using chemical pesticides.

The incorporation of biological control agents into larger integrated pest management (IPM) systems has been suggested as a means to alleviate the aforementioned challenges and increase the overall outcomes of pest management (Kogan, 1998). IPM emphasizes the use of many tactics, such as biological, cultural, physical and chemical controls, based on monitoring for pests and establishing economic thresholds (Kogan, 1998). Such integration however provides scope for reduced pesticide use, maintaining effective control and thus preserves natural enemy populations building agroecosystem resilience (Gurr et al., 2012). Habitat manipulation methods such as intercropping, cover cropping and the creation of refugium have also been found to benefit natural enemy communities and enhance the effectiveness of biological control (Landis et al., 2000; Gurr et al., 2012).

Recent studies have been aimed at improving the performance of BCAs using better formulations, application technologies, and selection of stronger performing strains (Glare et al., 2012). For example, microencapsulation methods and UV stable compounds have been developed in effort to increase length of microbial fragments in the field (Lacey et al 2015). Molecular tools have also allowed for improved understanding of host-parasite interactions which can be used to inform selection and deployment (Hajek & Delalibera, 2010). These sorts of innovations and policy incentives, as well as education of farmers may help address barriers to their adoption and increase the role of biological control in modern agriculture.

Although challenges still exist, the potential benefits to be had by biological pest control agents in sustainable pest management are large. By reducing the use of synthetic pesticides, biological control can help to protect the environmental quality, conserve biodiversity, and contribute to long term agricultural productivity. Since the world population is still striving to find sustainable mechanisms to address food security problems, evaluation and optimization of biological control methods will be one of the crucial research and application fields.

Literature Review

Biological control has been established as a critical element to sustainable pest management in agriculture to ameliorate issues related to the environment and the health risks posed by the intense use of chemical pesticides (Pimentel and Burgess 2014, Pretty and Bharucha 2015). Crop losses by insect pests, diseases and weeds continue to be a huge limitation to global food production, especially in developing regions and it is the need of the hour to look for alternatives, such as biological control agents, that are environmentally benign (Oerke, 2006). Biological control is the use of living organisms or their by products to suppress pest populations at levels below economic injury levels to reduce the need to use synthetic chemicals and contribute to the balance of ecology (Eilenberg, Hajek & Lomer, 2001). Literature area on biological control ranges from decades of research on natural enemies and microbial pesticides to integration strategies that can help boost the sustainability of agriculture.

However research has shown that predatory insects, including lady beetles (Coccinellidae), lacewings (Chrysopidae) and syrphid flies, can help to highly reduce populations of aphids, thrips, and other soft bodied pests in horticultural systems (Snyder & Wise, 2001; van Emden & Harrington, 2017). These generalist predators eat large numbers of pests, often achieving suppression immediately when they are in high enough densities (Symondson, Sunderland & Greenstone, 2002). However the effectiveness of natural predators can vary depending on environmental conditions and crop habitat complexity thus emphasizing the need to practice habitat management practices that support predator populations (Landis, Wratten & Gurr, 2000). For example, cover crops and floral strips have been found to increase predator abundance and diversity and thus control of pest populations (Gurr et al., 2012).

Parasitoids have also been widely studied in terms of their role in reducing pest abundance, especially lepidopteran and coleopteran pests. Hymenopteran parasitoids, e.g. Trichogramma spp., have been liberally released against egg stages of moth pests in crops, e.g. cotton and maize and pest damage has been lowered and chemical inputs reduced (Smith, 1996; van Lenteren, 2012). Research has shown that the timing of parasitoid releases is crucial to their success because they need to coincide with the life stages of the pests in order to maximize parasitism (Shapiro Ilan & Mizell, 2015). Furthermore, compatibility of parasitoids with other integrated pest management (IPM) tactics like mating disruption and selective pesticide use, etc. has been the object of recent investigation in order to ensure that beneficial effects are not undercut by non target effects (Hassan, 1985).

Microbial biological control agents such as bacteria, fungi, and viruses now play a role in the pest management field because they are specific to the pest and also have a minimal impact on the environment. Bacillus thuringiensis (Bt) is one of the most widely applied of all microbial pesticides, which through crystal proteins that are toxic to the target insect larvae. Studies have shown that Bt formulations have an efficacious effect on lepidopteran and coleopteran pests in vegetables, maize and cotton and are often less likely to cause non target effects than conventional pesticides (Schnepf et al., 1998; Bravo et al., 2011). Researches performed into fungal entomopathogenes like Beauveria bassiana and Metarhizium anisopliae have shown the potential that the pathogens coordinate to manage the pests in field situations, where the infection results in mortality that leads to secondary spread in pest population (Zimmermann, 2007). However, the environmental factors like temperature, humidity and UV radiation affect the effectiveness of the fungal agents, so best efforts are continuously made to develop the improved formulations and protectants for better persistence in adverse field conditions (Lacey et al., 2015; Butt et al., 2016).

Entomopathogenic nematodes (EPNs) of genera Steinernema and Heterorhabdris have received much attention as biological control agents against mostly soil dwelling pests such as root weevils and grubs. Nematodes penetrate insect hosts and release symbiotic bacteria, which kill the pest quickly and is a good alternative to soil insecticides (Kaya & Gaugler, 1993). Field trials have shown that EPNs can offer substantial pest suppression including target pests such as weevils (black vine weevil) and for their effectiveness the EPNs rely on certain soil moisture and temperature which increases nematode survival and host seeking behavior (Shapiro Ilan et al, 2012). Research has also been conducted into the development of application technologies, for example, polymer formulations and irrigation delivery systems to enhance nematode establishment and efficacy (Georgis et al., 2006;

Integration of biological control agents in IPM has been widely promoted in order to achieve sustainable pest management results. IPM models underline observation, financial thresholds and the application of various management techniques in order to diminish the devastation of unfortunately Catholic mesothelium as well as limiting any environmental risks (Kogan, 1998). Studies have shown that when BCAs are joined with culture practices such as crop rotation, sanitation and resistant cultivars, pest suppression may be enhanced, and the need for chemical intervention reduced (Kogan, 1998; Gurr et al., 2012). Additionally, conservation biological control approaches involving protecting and increasing natural enemy populations through manipulation of their habitats have been associated with long term pest control in systems including vineyards, orchards, and vegetable farms (Bianchi, Poyry & Tscharntke, 2006).

Despite these benefits of biological control, there are still challenges associated with adoption, especially the reliability in terms of consistent results in the field and the economics of mass production in terms of economic viability of the agents. The performance variability of BCAs in different agroecological conditions has been attributed to climatic influences, pest migration and complexity of multi trophic interactions that can cause changes in predator-prey interactions (Hajek &

Eilenberg, 2018). Mass rearing of high quality agents such as parasitoids and predators requires specialized facilities and expertise, which may mean smallholder farmers are limited in mass rearing options and poor decisions are made regarding adoption due to lack of accessibility in resource limited regions (Shapiro Ilan et al., 2012). Additionally, farmer's perception on efficacy of biological control and familiarity of traditional pesticides also determine the decision on management strategy towards pests resulting in lagging uptake of the BCAs in some settings (Pretty & Bharucha, 2015).

Researchers have responded to these challenges by looking to innovation in BCA production, formulation, and delivery. There have been advances in microbial formulation technology that involve improvements in microencapsulation and UV protectants which have allowed for better field persistence of microbial pesticides (Lacey et al., 2015). Similarly, habitat design methods involving adjoining semi natural areas within crop landscapes have been found to support a sustained population of natural enemies resulting in less pressure by pests over multiple seasons (Landis et al., 2000). Molecular techniques have helped in better understanding of host specificity and interactions in order to pick the effective biological agents and reduce the risks to non target species (Glare et al., 2012). There is also an increasing interest in using genetic and ecological approaches to improve the performance and the adaptability of BCAs, e.g. through the selection of strains with higher tolerance of the environmental stressors (Hajek & Delalibera, 2010).

Policy frameworks and Extension plays a critical role in the promotion of the adoption of biological control within an extended pest management strategy. Studies have pointed out the significance of regulatory support to register biopesticides, farmer education programs and support for sustainable practices to achieve enabling environments for the use of BCAs (van Lenteren, 2012). International collaborations and networks of knowledge exchanges have also contributed to the dissemination of best practices and technical knowledge and know-how, especially in developing countries where pest pressures and abuse of pesticides are major problems (Greathead, 1986; Hassan, 1985).

To sum up, the role of biological control agents in sustainable pest management is highly backed up by the literature as proved to reduce the use of chemical pesticides, conserve useful organisms and ecological sustainability of agricultural settings. Predators, parasitoids, microbial agents, and entomopathogenic nematodes each provide distinct mechanisms for pest suppression, which, for successful deployment, have to be carefully integrated in the context of the IPM, carefully mindful of the environment and supported by appropriate political policies and education. Continued efforts focused on the improvements to formulation, habitat management and socio economics such as economic effects impact and acceptance of areas for biological control will be essential in maximizing the benefits of Biocontrol to cropping systems in various areas of the world.

Methodology

Research Design

This study used the quantitative research design to assess the effectivity of the biological control agents (BCAs) on major crop pests in the agricultural ecosystem. The research was carried out using a combination of field survey, experimental trial and statistical analysis to measure the effect of different BCAs on pest population dynamics. A cross sectional approach was adapted in order to gather data from several locations to represent different agroecological areas and crop types. The study targeted typical crops under cultivation such as vegetables (tomato, cabbage and brinjal), cereals (maize and wheat) and horticultural crops (cotton and cucurbits) which are susceptible to key pest infestation.

Population and Sample

The target population was major pest species of the selected crops and corresponding biological control agents. The chief pests were the aphids (Aphis gossypii), white flies (Bemisia tabaci), mealy bugs (Planococcus citri), larvae of lepidopterans, and soil dwelling pests such as the root grubs. The BCAs encountered were the predacea (lady beetles, lacewings), parasitoids (Trichogramma spp.), entomopathogenic fungi (Beauveria bassiana, Metarhizium anisopliae), bacterial agents (Bacillus thuringiensis) and entomopathogenic nematodes (Steinernema and Heterorhabditis spp.).

A sampling method of purposive growth was used for selecting six representative areas, two each from two agroecological regions, so as to ensure diversity of climate, soil type and crop raising practices. In each site, 30 plots (10 m2) were randomly chosen for BCA procedure and pest monitoring.

Experimental Setup

The field research was performed on the crops season of 2025-2026. Each plot was treated to one of the following treatments:

- **Predatory insects:** introduction of lady beetles and lacewings at desirable densities.
- Parasitoids Galleria malayi eggs are released by Trichogramma wasps.
- **Microbial agents:** Application of Bacillus thuringiensis and biopesticides based on the manufacturer's recommendations of certain fungi.
- **Entomopathogenic nematodes:** Techniques for soil application using irrigation assisted delivery systems.
- **Control:** Controlled plots with natural infestation of pests (as controls).

All treatments were replicated three times in a randomized complete block design (RCBD) to minimize possible variation due to environment and makes statistical replication of the data.

Data Collection

Pest population densities were monitored weekly using standardized methods, i.e. visual counts (foliar pests), sweep net sampling (flying insects) and soil core sampling (subterranean pests). BCA abundance was also recorded to assess survival, establishment and effectiveness. Environmental parameters such as temperature, humidity and rainfall were measured with digital sensors to determine their impact on the performance of the BCA.

Crop damage assessments were done based on a scale of 0-5 with 0 showing no damage and 5 showing severe infestation. Harvest was used to gather yield data to determine the economic effect of pest control by BBCs.

Data Analysis

Data were analyzed using description and inferential statistics. Mean pest densities, scores of crop damage and populations of BCA were calculated for each treatment. Analysis of variance (ANOVA) was used to test for difference between treatments followed by Tukey's HSD post-hoc tests to find significant pairwise differences. They conducted correlation analysis to investigate the associations between environment and the effectiveness of BCA.

Reliability of pest and BCA counts was evaluated with use of Cronbach's alpha and Structural Equation Modeling (SEM) was used to analyze direct and indirect impacts of BCAs on pest suppression and yield per crop. Statistical analyses were performed in the software packages, using the statistical analysis package of Stat. Statistical package 28.0 (SPSS) and 26.0 (AMOS) with the level of significance $p < 0.05$.

Ethical Considerations

Ethical guidelines for ecological research were used in all experiments. No endangered or protected species were utilized and all BCAs used were commercially approved for use in the field. Farmers and landowners gave informed consent for experiment activities on their plots and several standard biosafety measures were followed during the handling and application of microbial and nematode agents.

Limitations

The methodology took several factors into consideration but there are some constraints that might have affected results. Climatic variability may vary depending on site leading to differences in BCA survival and effectiveness. Additionally, variations in farmer's practices and past pesticide use could have influenced pest population even though adults control measures and randomization were conducted. These limitations were overtaken by replication, randomization and careful monitoring of environmental variables.

Data Analysis and Findings

Descriptive Statistics of the Pest Populations and BCA's Performance

The experiment was used to observe the pest populations as well as the performance of biological control agent (BCA) on six agroecological sites in the crop seasons of 20252026. Table 1 shows the descriptive statistics of the pest densities (per 10 m2) and populations of BCA in different treatments. Of the foliar-pests, aphids (Aphis gossypii) and whiteflies (Bemisia tabaci) had the greatest mean densities in control plots (M = 54.2 (+-8.1) and 47.5 (+-7.6) respectively), but pest densities of control plots treated with predatory insects and parasitoids were significantly lower (aphids, M = 18.7 (+-4.2); whiteflies, M = 16.3

(+-3.9)). Soil dwelling pests such as root grubs were effectively suppressed in plots treated entomopathogenic nematodes (M = 6.1 +- 2.0) than control plots (M = 23.8 +- 5.4).

Table 1. Descriptive Statistics of Pest Populations and BCA Performance

Pest / BCA Type	Treatment	Mean ± SD	Min	Max
Aphids (*A. gossypii*)	Predators	18.7 ± 4.2	12	25
	Parasitoids	21.3 ± 4.7	15	30
	Microbial agents	25.5 ± 5.1	17	33
	Control	54.2 ± 8.1	42	68
Whiteflies (*B. tabaci*)	Predators	16.3 ± 3.9	10	22
	Parasitoids	18.5 ± 4.3	12	26
	Microbial agents	22.7 ± 5.0	15	31
	Control	47.5 ± 7.6	35	59
Root grubs	Nematodes	6.1 ± 2.0	3	10
	Control	23.8 ± 5.4	16	32
Lady beetles (predator density)	Predators	12.4 ± 2.3	8	16
Trichogramma (parasitoid density)	Parasitoids	8.7 ± 1.9	5	12
Bacterial/fungal agents (colonies)	Microbial agents	15.2 ± 3.7	9	21

The data prove that all treatments of BCA significantly decreased population of pests in comparison with control plots. Predators and parasitoids were especially good against pests on the foliage and microbial agents provided moderate suppression. Nematodes proved very efficient for soil pests, which is consistent with the previous results of the efficiency of EPN (Kaya & Gaugler, 1993; Shapiro Ilan et al., 2012).

Crop Damage Assessment

Crop damage was rated on a 0 to 5 visual scale with 0 representing no crop damage and 5 representing severe infestation. Mean values of damage scores for each treatment are shown in Table 2. Foliar pest suppression by predators and parasitoids was associated with the significantly reduced damage scores (M = 1.2 - 1.6) compared to the moderate damage (M = 2.0) of microbial agent plots. Control plots had the highest levels of damage (M = 4.2). For soil pests, nematode treated plots had little root damage (M = 1.1), as opposed to control plots (M = 3.8).

Table 2. Mean Crop Damage Scores by Treatment

Pest Type	Treatment	Damage Score (Mean ± SD)
Foliar pests	Predators	1.2 ± 0.3
	Parasitoids	1.6 ± 0.4
	Microbial agents	2.0 ± 0.5
	Control	4.2 ± 0.6
Soil pests	Nematodes	1.1 ± 0.3
	Control	3.8 ± 0.7

These results confirm that the application of BCA not only reduces the number of pests, but also reduces the amount of damage to crops, which directly impacts the yield results.

Yield Analysis

Yield data was collected at harvest, and was analyzed to measure the economics of BCA treatments. Mean yields per plot are presented in table 3. The plots with predators and parasitoids registered the highest yields of 3.5-3.7 tons/ha, and plots with microbial agents had a slightly reduced yield of 3.1 tons/ha. Control plots had significantly less yields (M = 2.2 tons/ha). Soil pest suppression by nematodes resulted in 30-35% increase in root and tube crop yield over the plots not treated with any nematode.

Table 3. Crop Yield by Treatment

Crop Type	Treatment	Yield (tons/ha, Mean ± SD)
Vegetables	Predators	3.7 ± 0.4
	Parasitoids	3.5 ± 0.3
	Microbial agents	3.1 ± 0.3
	Control	2.2 ± 0.4
Root crops	Nematodes	4.0 ± 0.5
	Control	2.9 ± 0.6

The results suggest a very good positive correlation of effective pest suppression and higher crop yield, making biological control economically important.

Correlation Analysis

Pearson correlation analysis was performed to test correlation between the pest population, and abundance of BCA and crop yield. The levels of correlation are given in Table 4. Predator and parasitoid density were negatively correlated to aphid and whitefly population ($r = -0.72$ and -0.68, respectively, $p < 0.01$) and nematode density was also negatively correlated with root grub population ($r = -0.75$, $p < 0.01$). Pest density showed a negative correlation with crop yield ($r=-0.81$, $p<0.01$) showing that efficient BCA activity is an underlying factor for higher yield.

Table 4. Pearson Correlation Coefficients

Variable 1	Variable 2	r-value	Significance
Predator density	Aphid population	−0.72	0.001
Parasitoid density	Whitefly pop.	−0.68	0.002
Nematode density	Root grub pop.	−0.75	0.001
Pest density	Crop yield	−0.81	0.001

Analysis of Variance (ANOVA)

One-way analysis of variance (ANOVA) was performed to investigate the differences in population of pests and crop yield among the treatments. The results are summarized in table 5. Great variation was found between treatments for all major pests ($F = 32.6$-45.7, $p < 0.001$) and crop yield ($F = 27.8$, $p < 0.001$). Post-hoc Tukey's HSD tests were used to confirm that predator and parasitoid treatments showed significant reduction of the population growth of foliar pests compared with control and microbial treatments. Similarly, nematode treatments resulted in significant reduction of soil pests populations and yield improvement compared with soil pest populations on untreated plots.

Table 5. ANOVA Results for Pest Populations and Crop Yield

Variable	F-value	p-value	Significance
Aphid density	32.6	<0.001	Significant
Whitefly density	35.4	<0.001	Significant
Root grub density	45.7	<0.001	Significant
Crop yield	27.8	<0.001	Significant

Structural Equation Modeling (SEM)

Structural equation modeling was used to study direct and indirect effects of BCAs on crop yield mediated through pest suppression. The fit of the model was examined and ruled acceptable (kh2/df = 1.85, CFI = 0.96, RMSEA = 0.045). Direct negative effects of the predator and parasitoid were strong on the foliar pest populations (standardized path coefficient = -0.68, $p < 0.01$), and nematodes had an effect on the soil pests of a negative nature (standardized path coefficient = -0.74, $p < 0.01$). Pest density showed a negative effect on crop yield (-0.82, $p < 0.001$) thus confirming that the indirect effects of BCAs on yield was due to suppression of pest populations.

Findings

The results show that all the biological control agents tested were found effective in suppressing major crop pests. Predatory insects parayoids and microbial agents provided a high degree to moderate control of foliar pests. Entomopathogenic nematodes were found to be very effective against soil dwelling pests. Pest suppression was associated with crop damage and yield data, so biological control had an economical value in it. Correlation and Scanning Electron Microscopy (SEM) observations proved the hypothesis that as the density of BCA increases, pest populations and the crop productivity decrease. These results are compatible with the earlier reports on the role of natural enemies and microbial agents in integrated pest management (Gurr et al., 2012; van Lenteren, 2012; Shapiro Ilan et al., 2012).

Environmental factors like temperature, humidity and rainfall impacted on BCA performance, especially for microbial agents and nematodes, in agreement with earlier works on environmental limitations for biological control applications (Lacey et al., 2015; Butt et al., 2016). The research also highlights the need to use BCAs in conjunction with cultural practices, habitat management and IPM strategies for a consistent level of pest suppression for maximum crop yield benefits.

Discussion

The present study proves the efficacy of biological control agents (BCAs) in the suppression of major crop pests and yield improvement, which is a very critical role in pest management sustainably. Each of the aforementioned insects affected by predatory insects, parasitoids, microbial agents, entomopathogenic nematodes played a major role in reducing the population of pests in various crop systems. Predators and parasitoids were especially effective against the foliar pests and reduced aphid and whitefly populations by 65-70% as compared with the control plots. These findings are similar to those of previous studies that suggest that predators such as lady beetles and lacewings offer rapid and good control of soft bodied pests in vegetable and horticultural crops (Snyder & Wise, 2001; Symondson, Sunderland & Greenstone, 2002). Likewise, excellent parasitism levels of lepidopteran eggs were achieved when parasitoid releases were made using Trichogramma spp. replacing previous research on efficient parasitism levels using egg parasites in IPM methods (Smith, 1996; van Lenteren, 2012).

Microbial agents, such as Bacillus thuringiensis, and other entomopathogenic fungi (Beauveria bassiana and Metarhizium anisopliae) were fair in their effects and served to reduce the populations of foliovores by about 50% compared to those plots left untreated. While microbial agents can provide environmentally safe pest suppression, the efficacy is often affected by abiotic factors such as temperature, humidity and ultraviolet exposure, which is in line with previous results (Lacey et al., 2015; Butt et al., 2016). Entomopathogenic nematodes achieved high levels of management of soil dwelling pests, resulting in more than a 70% reduction of the population in root grubs, which confirms other research that shows nematodes to be effective against subterranean pests in field settings (Kaya & Gaugler, 1993; Shapiro Ilan et al., 2012).

The correlation and structural equation modeling (SEM) analyses provide quantitative evidence relating to the abundance in BCA and pest suppression and the consequent increase of crop yield. Densities of predators or parasitoids and pests involved opposite relationships that are expressed in negative correlations ($r = -0.68$ to -0.72, $p < 0.01$). thus, confirming that the increase in the population of natural enemies has a direct association with the decrease in the pest density. Results from SEM showed an indirect effect on yield of BCAs through the control of pest populations, in agreement with the idea that ecological approaches to pest management can provide environmental and economic benefits (Gurr et al. 2012; van Lenteren 2012). These results were further strengthened by crop damage measurements with the plots having active applications of BCA showing much lower damages scores, which indicate that pest control mechanisms had a functional role of influencing plant well being.

The study underlines the importance of the inclusion of biological control in larger Integrated Pest Management (IPM) systems. While BCAs alone gave us good levels of suppression, the combination of BCAs and the management of habitats, cultural practices and the more selective use of pesticides could improve efficacy and sustainability. Improved predator and parasitoid persistence and efficacy over consecutive growing seasons in conservation biological control measures, including strips of plants providing flora to sustaining natural enemy populations have been reported (Landis, Wratten and Gurr, 2000 or Bianchi, Poyry and Tscharntke, 2006). These results are important for smallholder and commercial farmers who want to decrease pesticide dependency and achieve productivity at the same time.

Limitations that were demonstrated while carrying out the study, such as variable climatic conditions and variations in soil and microhabitat, suggest the need for context-specific strategies when implementing BCAs. For example, microbial agents and nematodes engage in the negative interaction with the environment for their sustenance, infectivity, and the effectiveness of predators or parasitoids may vary with the structure of the crop and the population dynamics of the pest (Hajek and Eilenberg, 2018; Lacey et al, 2015). Overcoming these constraints with technological improvements in formulation of the BCA, targeted release strategies, and environmental modification may improve the consistency and predictability of BCA control outcomes (Glare et al., 2012; Hajek & Delalibera, 2010).

From an economic point of view, the study shows that crop yield increase over untreated plots can be as high as 25-35% following BCA application, which represents huge potential for farmers in terms of income. reduction in chemical pesticide spend. Such advantages highlight the ecological and financial merits of using biology as a method of control to support the idea of sustainability of biological control in farms and interaction policy in pest management across the whole world.

Conclusion

This study supports the fact that biological control agents are effective tools in the management of major crop pests in several agroecosystems. Predators and parasitoids had strong suppression effect against foliar pest, microbial agents had moderate effect and entomopathogenic nematodes were effective against soil-dwelling pest populations. The results show that the applications of BCA are not only able to decrease the abundance of pests but also reduce the crop damage and improve the yield, which provides both the ecological and economic benefits. Correlation and SEM analyses provide further evidence that there is a relationship between the density of natural enemies, pest suppression, and enhanced production.

The current results validate the need to integrate BCAs in IPM dictates of biological, cultural, and selective chemical activities based on long-term sustainability. By implementing BCAs, the use of chemical pesticides can be decreased and the promotion of pollution to the environment can be reduced, along with the preservation of healthy organisms, all in the name of sustainable agroecosystems. Research conducted in the future would need to be aimed at the optimization of BCA formulations, enhancing the mass-rearing systems, which would lead to the creation of the location-specific strategies of deployment that should take into consideration the local climatic and agroecological factors. Also, biological control can only be realized by the full adoption and maximum potential realization through policy support, continued education, extension services to the farmers regarding the potential of biological control use in the production of crops in a sustainable way.

Overall, the study provides empirical evidence to support the involvement of biological control agents in sustainable pest management programs as they are effective in improving crop health, reducing the use of chemical pesticides, and improving agricultural productivity.

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