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Evaluation of augmentative biological control strategy against major borer insect pests of sugarcane—a large-scale field appraisal

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Abstract

Background: Biological alternatives to pesticides in agriculture do not harm non-targets organisms including natural enemies of insect pests. Experiments were conducted at sugarcane fields during 2015 to 2019 to assess large scale biocontrol practices, involving inundative releases of trichogrammatids against lepidopteran borers in comparison to conventional chemical-based farmers' practice.

Main body: Eight releases each of *Trichogramma chilonis* Ishii and *Trichogramma japonicum* Ashmead were made at 50,000 ha⁻¹ at 10 days interval for the management of sugarcane stem borer, *Chilo infuscatellus* Snellen and the sugarcane top borer, *Scirpophaga excerptalis* (Fabricius) (Lepidoptera: Crambidae), respectively. Likewise, 10–12 releases of *T. chilonis* were made at 50,000 ha⁻¹ at 10 days interval for the management of sugarcane stalk borer, *Chilo auricilius* Dudgeon (Lepidoptera: Crambidae). The biocontrol intervention was compared with farmer's practice (chemical control) in managing these borers. The results showed that farmers' practices and biocontrol treated fields resulted in a lower incidence of *C. infuscatellus* (1.1, 2.9%) and *S. excerptalis* (1.7, 3.9%) than the untreated control fields, wherein the mean per cent incidence of these borers (6.8, 8.5%) was significantly higher. The incidence of *C. auricilius* was also lower in augmented fields (2.8%) than untreated fields (7.3%). The yield data indicated that farmers adopting biocontrol practices were able to get comparable yield and benefit: cost ratio than farmers' practice, both being better than untreated control. Moreover, in biocontrol fields, parasitism rate on the factitious host, *Corcyra cephalonica* Stainton cards was estimated.

Conclusion: Thus, the study highlights the significance of adoption of biocontrol-based technology over a long run to provide sustainable system of sugarcane insect pest management and economic benefits to the stakeholders.

Keywords: Sugarcane, Lepidopteran borers, Augmentative biological control, B: C analysis

Background

Sugarcane (*Saccharum officinarum*) is the most important cash crop, being grown in diverse agro-climatic conditions throughout the world between latitude 36.7° North and 31.0° South of equator from tropical to subtropical zones. It is cultivated in more than 100 countries across Africa, Asia, Australia, North and South

America (Food and Agriculture Organization Corporate Statistical Database (FAOSTAT) 2020). The crop covers approximately 26.2 million ha in the world, with Brazil as the top country with 10.0 million ha (Knoema 2020). India ranks second among the world's sugarcane producing countries with an area of about 4.73 million ha and cane production of 376.9 million tonnes. However, productivity in India (79.68 t ha⁻¹) is far less than other sugarcane producing countries like Peru (121.83 t ha⁻¹), Guatemala (118.46 t ha⁻¹), Egypt (111.33 t ha⁻¹),

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Columbia (88.76 t ha⁻¹), and USA (86.07 t ha⁻¹) (Food and Agriculture Organization Corporate Statistical Database (FAOSTAT) 2020). The sugar recovery (10.23%) is lower than many cane-producing countries as well. One of the major reasons for the low productivity and sugar recovery is the damage caused by the insect pests and diseases. Sugarcane being the long duration crop is attacked by many sucking pests, borers and subterranean pests during different growth stages (Srikanth 2019). Lepidopteran borers are the most damaging pests in sugarcane production. The more serious among them are early shoot borer, *Chilo infuscatellus* Snellen, top borer, *Scirpophaga excerptalis* (Fabricius), and stalk borer, *Chilo auricilius* Dudgeon (Lepidoptera: Crambidae). Chemical control measures are used for the management of *C. infuscatellus* and *S. excerptalis*. However, chemical control drastically disrupts natural pest control and is associated with determining direct effects on the natural enemies (Crowder et al. 2010). Biological control, as a component of integrated pest management (IPM), is considered a preferred and sustainable alternative for the pest control (Barratt et al. 2018). The past three decades have witnessed a very fast development in mass production of natural enemies in the form of number and spectrum of species produced through evolved mass multiplication methods (van Lenteren 2012).

Globally, many agro-ecosystems employ parasitoids for the biological control of economically important insect pests. The genus *Trichogramma* (Hymenoptera: Trichogrammatidae), having several characteristics like long adult longevity in the field and their ability to parasitize eggs of multiple pest species, make them good egg parasitoids for biocontrol programs (Zucchi et al. 2010). In India, 151 species of trichogrammatids from 31 genera wherein, 32 species of genus *Trichogramma* have been recognized (Begum and Anis 2014). These species of *Trichogramma* have been utilized commercially in various biological control programs against lepidopteran pests of field and horticultural crops (Shera et al. 2017; Navik and Varshney 2018). Success of IPM strategies involving inundative releases of egg parasitoids *Trichogramma chilonis* Ishii and *T. japonicum* Ashmead (Hymenoptera: Trichogrammatidae) against sugarcane tissue borers has been well documented (Nadeem and Hamed 2011; Muzammil et al. 2016; Srikanth et al. 2016). However, it is important to study their effectiveness and economic benefit in linkage with farmers, as means of promoting the technology adoption.

Therefore, the objective of this study was to validate and promote the biocontrol technology for the management of sugarcane borers on large scale through farmers' participatory approach to quantify the economic benefits to the sugarcane farmers by comparing biocontrol practices to conventional management practices.

Materials and methods

Mass production of *Trichogramma* spp.

The egg parasitoid species, *Trichogramma chilonis* (Ishii) (Accession no. NBAIL-GN-TRI-49) and *T. japonicum* (Ash.) (Accession no. NBAIL-MP-TRI-65) were mass-reared on the laboratory host, the rice meal moth, *Corcyra cephalonica* Stainton. Bold grains of white sorghum, *Sorghum bicolor* (L.) Moench, meant for human consumption were procured. The required quantity of sorghum was milled to 3–4 pieces of each grain and heat sterilized in oven at 100 °C for 30 min (Narang Scientific Works Pvt. Ltd, India). To prevent bacterial infestation, streptomycin sulphate was added to the crushed sorghum at the rate of 0.2 g kg⁻¹ and mixed thoroughly. *C. cephalonica* rearing boxes (43 × 23 × 12 cm) each containing 2.5 kg of milled sorghum were charged with *C. cephalonica* eggs at 0.20 cc/box (Sharma et al. 2016). The boxes were kept on open racks (90 cm × 45 cm × 180 cm) in rearing laboratory at 27 ± 2 °C and 70 ± 5% RH. On 40th day, moths started emerging, collected daily, and transferred to specially designed oviposition cages. The fresh eggs of *C. cephalonica* were collected and deep frozen for 12–14 h to prevent hatching. These eggs were glued to cards of 15 × 10 cm and were exposed to adult female *Trichogramma* in the ratio of 8:1 for 24 h at 27 ± 1 °C and 65 ± 5% RH. The 6-day-old parasitized cards containing about 20,000 parasitized eggs were used as 'Tricho-cards' for field releases.

Experiment plan

Large-scale validation of standardized biocontrol technology on dose, timing, and frequency of release of trichogrammatids was carried out at farmers' fields, over a period of 5 years from 2015 to 2019. The demonstrations were conducted in different sugarcane growing districts of Indian Punjab, namely Amritsar, Fazilka, Ferozepur, Fathgarh Sahib, Gurdaspur, Hoshiarpur, Jalandhar, Kapurthala, Ludhiana, Moga, Nawanshahr, Patiala, and Sangrur, covering different agro-climate zones of the state. The details of the area covered for different sugarcane borers year wise are presented in Table 1. The released fields were compared with farmers' practice (chemical control) and untreated control in case of *C. infuscatellus* and *S. excerptalis*. Under Indian Punjab conditions, no insecticide has been recommended for the management of *C. auricilius*. Chemical control has been attempted for the management of stalk borer, but proved ineffective because of concealed habit of the larvae. Further, height and stage of the sugarcane crop at the time of its attack hinders spraying operations, thus practically not feasible. Therefore, the use of *Trichogramma* was the only option available against this pest and the biocontrol plots were compared with untreated control only. Each pest species, i.e., *C. infuscatellus*, *S.*

Table 1 Area covered against various sugarcane borers at farmers' fields during different years

| Year | Treatments | Area covered (ha) against | | | Total |
|-------|----------------------------------|---------------------------|-----------------------|----------------------|--------|
| | | <i>C. infuscatellus</i> | <i>S. excerptalis</i> | <i>C. auricilius</i> | |
| 2015 | Biocontrol practice ^a | 88.4 | 76.0 | 122.0 | 286.4 |
| | Farmers' practice | 11.0 | 9.7 | 17.6 | 48.3 |
| | Untreated control | 4.3 | 3.8 | 6.8 | 14.9 |
| 2016 | Biocontrol practice ^a | 146.0 | 78.0 | 182.4 | 406.4 |
| | Farmers' practice | 21.1 | 10.9 | 25.8 | 57.8 |
| | Untreated control | 7.9 | 4.6 | 11.1 | 23.6 |
| 2017 | Biocontrol practice ^a | 160.8 | 88.8 | 251.2 | 500.8 |
| | Farmers' practice | 24.8 | 14.3 | 37.5 | 76.6 |
| | Untreated control | 9.4 | 5.9 | 15.4 | 30.7 |
| 2018 | Biocontrol practice ^a | 217.6 | 208.0 | 482.0 | 907.6 |
| | Farmers' practice | 28.5 | 27.8 | 75.2 | 131.5 |
| | Untreated control | 13.2 | 12.6 | 28.8 | 54.6 |
| 2019 | Biocontrol practice ^a | 215.2 | 204.0 | 323.2 | 742.4 |
| | Farmers' practice | 31.0 | 29.1 | 48.4 | 108.5 |
| | Untreated control | 31.0 | 29.1 | 48.4 | 108.5 |
| Total | Biocontrol practice ^a | 828.0 | 654.8 | 1360.8 | 2843.6 |
| | Farmers' practice | 116.4 | 101.8 | 204.5 | 422.7 |
| | Untreated control | 46.3 | 40.0 | 82.7 | 169.0 |

^a8 releases against *C. infuscatellus* and *S. excerptalis* during April to June; 10–12 releases against *C. auricilius* during July to October

excerptalis, and *C. auricilius* and their respective parasitoid species were dealt with separately in the study. An isolation distance of about 50 m was maintained between released and un-released fields to eliminate any risk of contamination between treatments. In biocontrol treatment, 8 releases each of *T. chilonis* and *T. japonicum* at 50,000 ha⁻¹ were made at 10 days interval from mid-April to end-June for the management of *C. infuscatellus* and *S. excerptalis*, respectively. Against *C. auricilius*, 10–12 releases of *T. chilonis* at 50,000 ha⁻¹ were made at 10 days interval from July to October. Tricho-cards each having approximately 500 parasitized eggs were cut into 100 strips and were stapled uniformly at 100 spots per hectare to the underside of the leaves during evening hours. In farmers' practice, fipronil 0.3 G at 25 kg ha⁻¹ was used against *C. infuscatellus* during 2015. During 2016–2019, chlorantraniliprole 18.5 SC at 375 ml ha⁻¹ was applied against this pest. For the management of *S. excerptalis*, chlorantraniliprole 0.4 GR at 25 kg ha⁻¹ was used during all the cropping seasons (2015–2019).

Data collection

Pest incidence

The biocontrol, farmers' practice, and untreated control fields were divided into 6 equal blocks, each representing one replication. The blocks representing treatments both in biocontrol as well as in farmer's practice were 1000 m² each, and the block size in untreated control was 250

m². From each block, 5 plants were selected for recording the incidence of *C. infuscatellus* and *S. excerptalis*. The presence of characteristic "dead-heart" was recorded to calculate per cent *C. infuscatellus* infestation. For *S. excerptalis*, the percent incidence was calculated on the basis of red streak on the leaf, shot holes and presence of "bunchy tops." The *C. auricilius* incidence was recorded, selecting 5 canes from 10 locations per field to serve as replications. The percent incidence was worked out on the basis of exit holes in these canes.

Field parasitism

Sentinel cards having eggs of *C. cephalonica* were used for recording per cent parasitism by *Trichogramma* spp. in the released fields, farmers practice and untreated control. Small sentinel card strips (4 × 3 cm) having approximately 50 *C. cephalonica* eggs were stapled on the lower surface of the leaves uniformly at 50 spots ha⁻¹, 1 day after the release of the parasitoids. The strips were removed after 24 h from the fields and brought to the laboratory. They were kept separately in glass vials for adult emergence and were used to estimate per cent parasitism. The per cent parasitism in the released fields was compared by that of farmers' practice and untreated control to record natural prevalence or dispersal of the trichogrammatids.

Crop yield and benefit:cost analysis

The cane yield was recorded at harvest from each block. The total cost of cultivation including costs for various agronomic practices, plant protection interventions, and labor costs therefore each treatment, i.e., biocontrol practice, farmer practice and untreated control was calculated and its cost analysis (BCA) was carried out on the basis of gross economic returns over total cost of cultivation.

Statistical analyses

The data on *C. infuscatellus* and *S. excerptalis* incidence, field parasitism of *C. cephalonica* eggs were subjected to analysis of variance (ANOVA), using randomized block design (RBD) to compare the treatments in the respective fields. Data on incidence and parasitism were subjected to arcsine transformations prior to analysis. The different treatment means were separated by least significant difference test (LSD) at $P = 0.05$ (Gomez and Gomez 1984). The data pertaining to *C. auricilius* damage and field parasitism were subjected to paired-t test to compare mean incidence in biocontrol and untreated control fields. The pooled analysis of the 5 seasons (2015 to 2019) was also carried out to evaluate the impact of biocontrol and farmers' practiced treatments on the incidence of sugarcane borers.

Results and discussion

Augmentation of *T. chilonis* against *C. infuscatellus*

Pests incidence

The overall incidence of the *C. infuscatellus* was significantly lower in biocontrol and farmers' practice than in untreated control. The incidence of *C. infuscatellus* varied from 2.1 to 4.7%, 0.8 to 2.0 and 4.9 to 11.5% in biocontrol, farmers' practice and untreated control, respectively, during 2015–2019 (Table 2). The pooled analysis of the 5 years revealed that the percent incidence of *C. infuscatellus* in biocontrol (2.9%) and farmers' practice (1.1%) was significantly lower than untreated control (6.8%) (Fig. 1). The respective reduction in incidence over control was 57.4 and 83.8% (Fig. 2).

Field parasitism of *C. cephalonica*

The parasitism of *C. cephalonica* eggs wherein *T. chilonis* was released against *C. infuscatellus* varied from 42.0 to 48.8% during 2015–2019. It was significantly higher than that of farmers' practice and untreated control, where the parasitism varied from 4.0 to 5.2% and 6.1 to 7.3%, respectively. The pooled data of 5 years also revealed that the parasitism rate was significantly higher in biocontrol plots (45.1%) than at the farmers' practice (4.3%) and untreated control (6.9%) (Fig. 3).

Crop yield and benefit:cost analysis

The observations on the cane yield revealed that higher yield was recorded in farmers' practice and in bioagent

Table 2 Effect of different management practices on the incidence of sugarcane borers

| Year | Treatments | Per cent incidence | | |
|------|----------------------------------|-------------------------|-----------------------|----------------------|
| | | <i>C. infuscatellus</i> | <i>S. excerptalis</i> | <i>C. auricilius</i> |
| 2015 | Biocontrol practice [#] | 4.7 ^b | 5.1 ^b | 2.5 ^a |
| | Farmers' practice* | 2.0 ^a | 2.2 ^a | - |
| | Untreated control | 11.5 ^c | 11.0 ^c | 6.3 ^b |
| 2016 | Biocontrol practice [#] | 2.2 ^b | 3.1 ^b | 3.1 ^a |
| | Farmers' practice* | 0.7 ^a | 1.5 ^a | - |
| | Untreated control | 5.2 ^c | 7.0 ^c | 7.7 ^b |
| 2017 | Biocontrol practice [#] | 2.8 ^b | 4.7 ^b | 3.3 ^a |
| | Farmers' practice* | 1.0 ^a | 2.0 ^a | - |
| | Untreated control | 6.3 ^c | 10.2 ^c | 8.1 ^b |
| 2018 | Biocontrol practice [#] | 2.6 ^b | 3.8 ^b | 3.1 ^a |
| | Farmers' practice* | 0.8 ^a | 1.4 ^a | - |
| | Untreated control | 5.9 ^c | 7.8 ^c | 7.9 ^b |
| 2019 | Biocontrol practice [#] | 2.1 ^b | 3.0 ^b | 2.5 ^a |
| | Farmers' practice* | 1.0 ^a | 1.3 ^a | - |
| | Untreated control | 4.9 ^c | 6.4 ^c | 6.6 ^b |

Values followed by different letters in the columns are significantly different at $P = 0.05$

[#]8 releases of *T. chilonis* and *T. japonicum* at 50,000 ha⁻¹ against *C. infuscatellus* and *S. excerptalis*, respectively during April to June; 10–12 releases of *T. chilonis* at 50,000 ha⁻¹ against *C. auricilius* during July to October

*Fipronil 0.3 G at 25 kg ha⁻¹ (2015) and Chlorantraniliprole 18.5 SC at 375 ml ha⁻¹ (2016–2019) for the management of *C. infuscatellus*; Chlorantraniliprole 0.4 GR at 25 kg ha⁻¹ (2015–2019) for the management of *S. excerptalis*

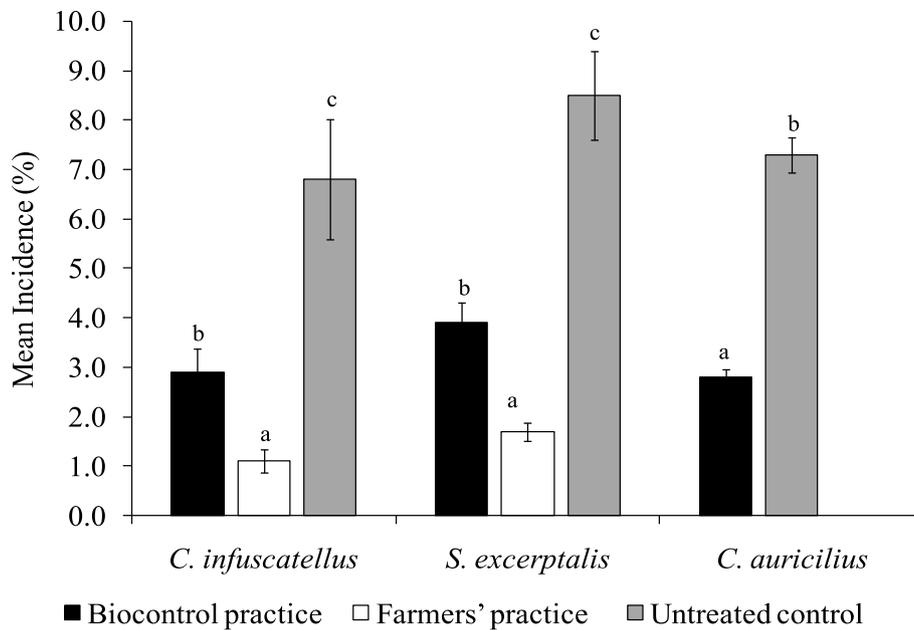


Fig. 1 Mean incidence of sugarcane borers in different management practices (pooled mean of 5 years); values followed by different letters in the columns for respective borers are significantly different at $P = 0.05$

released plots than the untreated control (Table 3). Higher cane yield of 79.10, 84.25, 82.37, 83.88, and 84.02 t/ha⁻¹ was recorded in farmers' practice than in bioagent released plots (71.66, 72.00, 70.62, 71.15, and 70.18 t/ha⁻¹), which were in turn higher than untreated control (65.22, 65.60, 63.95, 56.50, and 64.00t/ha⁻¹) during 2015, 2016, 2017, 2018, and 2019, respectively. The pooled analysis of benefit: cost ratio for the 5 seasons showed

higher B: C ratio in farmers' practice (1.90) and biocontrol treated plots (1.68) than at the untreated control (1.50).

Augmentation of *T. japonicum* against *S. excerptalis* Pest incidence

The incidence of *S. excerptalis* varied from 3.0 to 5.1%, 1.3 to 2.2%, and 6.4 to 11.0% in biocontrol

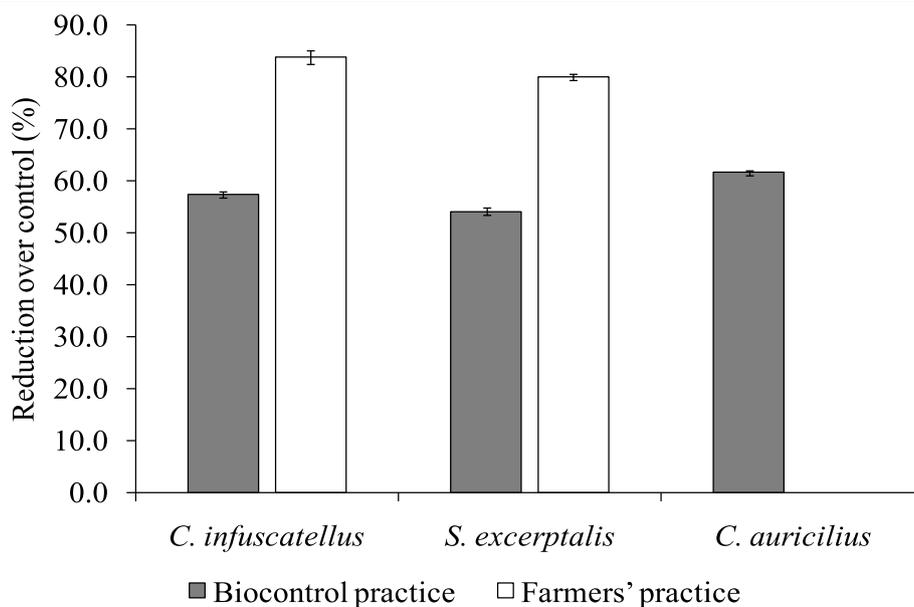


Fig. 2 Percent reduction in the incidence of sugarcane borers over untreated control (pooled mean of 5 years)

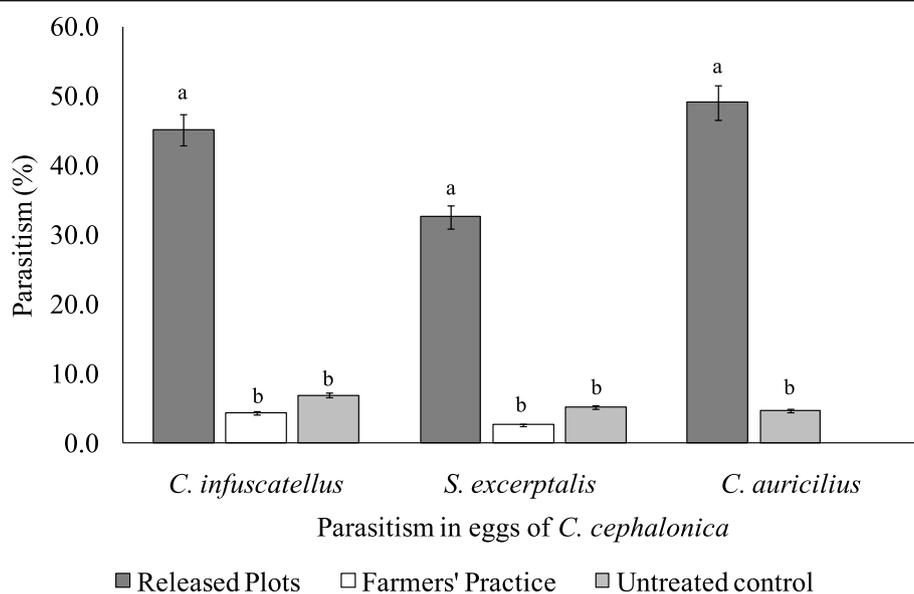


Fig. 3 Parasitism of *C. cephalonica* eggs in released fields wherein trichogrammatids were released against sugarcane borers (pooled mean of 5 years); values followed by different letters in the columns are significantly different at $P = 0.05$

Table 3 Cost of cultivation and economics returns from various treatments in the management of *C. infuscatellus*

| Year | Treatments | Yield (t ha ⁻¹) | Cost of cultivation ^b (USD ha ⁻¹) | Gross returns (USD ha ⁻¹) | Benefit:cost ratio |
|-------------|----------------------------------|-----------------------------|--|---------------------------------------|--------------------|
| 2015 | Biocontrol practice ^a | 71.66 | 1803.08 | 3140.61 | 1.74 |
| | Farmers' practice | 79.10 | 1828.70 | 3466.68 | 1.90 |
| | Untreated control | 65.22 | 1793.56 | 2858.36 | 1.59 |
| 2016 | Biocontrol practice ^a | 72.00 | 1816.09 | 3129.97 | 1.72 |
| | Farmers' practice | 84.25 | 1878.72 | 3662.51 | 1.95 |
| | Untreated control | 65.60 | 1801.36 | 2851.75 | 1.58 |
| 2017 | Biocontrol practice ^a | 70.62 | 1996.24 | 3316.53 | 1.66 |
| | Farmers' practice | 82.37 | 2064.73 | 3868.35 | 1.87 |
| | Untreated control | 63.95 | 1980.59 | 3003.29 | 1.52 |
| 2018 | Biocontrol practice ^a | 71.15 | 1891.93 | 3161.32 | 1.67 |
| | Farmers' practice | 83.88 | 1958.22 | 3726.93 | 1.90 |
| | Untreated control | 56.50 | 1877.60 | 2510.39 | 1.34 |
| 2019 | Biocontrol practice ^a | 70.18 | 1895.14 | 3047.88 | 1.61 |
| | Farmers' practice | 84.02 | 1959.93 | 3648.95 | 1.86 |
| | Untreated control | 64.00 | 1881.13 | 2779.49 | 1.48 |
| Pooled mean | Biocontrol practice ^a | 71.12 | 1879.80 | 3156.45 | 1.68 |
| | Farmers' practice | 82.72 | 1937.52 | 3673.57 | 1.90 |
| | Untreated control | 63.05 | 1866.14 | 2796.22 | 1.50 |

^a8 releases of *T. chilonis* at 50,000 per ha at 10 days interval during April to June; Price of sugarcane: USD 43.83, 43.47, 46.96, 44.43, and 43.43 tonne⁻¹ during 2015, 2016, 2017, 2018, and 2019, respectively

^bIncludes trichocard/insecticide + labor cost

treated, farmers' practice, and untreated control, respectively (Table 2). The pooled analysis (2015–2019) revealed a lower incidence in released plots (3.9%) and farmers' practice (1.7%), which were significantly lower than the control (8.5%) (Fig. 1). The percent reduction over control in the incidence of *S. excerptalis* was 54.1 and 80.0% in released fields and farmers' practice, respectively (Fig. 2).

Field parasitism of *C. cephalonica*

The parasitism in *C. cephalonica* eggs in *T. japonicum* released fields varied from 28.4 to 35.0% and was significantly better than farmers' practice (2.0–3.6%) and untreated control (4.0–6.7%). The pooled data also revealed significantly higher parasitism in biocontrol plots (32.6%) than at the farmers' practice (2.6%) and untreated control (5.2%) (Fig. 3).

Crop yield and benefit:cost analysis

Higher cane yield was recorded in farmers' practice (82.54, 83.00, 81.13, 82.50 & 84.80 t/ha⁻¹) and in biocontrol fields (71.25, 71.60, 68.75, 71.08, and 72.00t/ha⁻¹) than untreated control (64.10, 65.00, 61.90, 64.80, and 66.00 t/ha⁻¹) in the respective years of 2015, 2016, 2017, 2018, and 2019 (Table 4). The benefit: cost ratio in farmers' practice and biocontrol treated plots was also higher than untreated control. The pooled analysis

(2015–2019) revealed higher B: C ratio was recorded farmers' practice (1.90) and biocontrol practiced plot (1.67) than at the untreated control (1.53).

Augmentation of *T. chilonis* against *C. auricilius*

Pest incidence

The incidence of *C. auricilius* varied from 2.5 to 3.3% in biocontrol plots and was significantly lower than untreated control, wherein, it varied from 6.3 to 8.1% (Table 2). The pooled data across the years revealed significantly lower damage in biocontrol plots (2.8%) in comparison to untreated control (7.3%) (Fig. 1) and the reduction in incidence over control was 61.6% (Fig. 2).

Field parasitism of *C. cephalonica*

Higher percentage of *C. cephalonica* eggs was parasitized in fields, wherein *T. chilonis* was augmented (46.2–52.2%) against *C. auricilius* than in no-release control plots (4.0–6.0%). The pooled data of 5 years also revealed significantly higher parasitism in release fields (49.1%) than in untreated control (4.7%) (Fig. 3).

Crop yield and benefit:cost analysis

In fields wherein, *T. chilonis* was released against *C. auricilius*, higher cane yield was recorded in biocontrol plots (72.03, 72.86, 70.35, 72.46, and 73.64t/ha⁻¹) than untreated control (63.44, 62.28, 62.65, 63.36, and 62.81t/

Table 4 Cost of cultivation and economics returns from various treatments in the management of *S. excerptalis*

| Year | Treatments | Yield (t ha ⁻¹) | Cost of cultivation ^b (USD ha ⁻¹) | Gross returns (USD ha ⁻¹) | Benefit:cost ratio |
|-------------|----------------------------------|-----------------------------|--|---------------------------------------|--------------------|
| 2015 | Biocontrol practice ^a | 71.25 | 1804.67 | 3122.64 | 1.73 |
| | Farmers' practice | 82.54 | 1862.70 | 3617.44 | 1.94 |
| | Untreated control | 64.10 | 1793.56 | 2809.28 | 1.57 |
| 2016 | Biocontrol practice ^a | 71.60 | 1816.09 | 3112.58 | 1.71 |
| | Farmers' practice | 83.00 | 1868.77 | 3608.16 | 1.93 |
| | Untreated control | 65.00 | 1801.36 | 2825.67 | 1.57 |
| 2017 | Biocontrol practice ^a | 68.75 | 1996.24 | 3228.71 | 1.62 |
| | Farmers' practice | 81.13 | 2055.65 | 3810.11 | 1.85 |
| | Untreated control | 61.90 | 1980.59 | 2907.01 | 1.47 |
| 2018 | Biocontrol practice ^a | 71.08 | 1891.93 | 3158.21 | 1.67 |
| | Farmers' practice | 82.50 | 1943.89 | 3665.62 | 1.89 |
| | Untreated control | 64.80 | 1877.60 | 2879.17 | 1.53 |
| 2019 | Biocontrol practice ^a | 72.00 | 1895.14 | 3126.93 | 1.65 |
| | Farmers' practice | 84.80 | 1948.73 | 3682.82 | 1.89 |
| | Untreated control | 66.00 | 1881.13 | 2866.35 | 1.52 |
| Pooled mean | Biocontrol practice ^a | 70.94 | 1880.11 | 3148.93 | 1.67 |
| | Farmers' practice | 82.79 | 1935.14 | 3675.67 | 1.90 |
| | Untreated control | 64.36 | 1866.14 | 2857.45 | 1.53 |

^a8 releases of *T. japonicum* at 50,000 per ha at 10 days interval during April to June; price of sugarcane: USD 43.83, 43.47, 46.96, 44.43, and 43.43 tonne⁻¹ during 2015, 2016, 2017, 2018, and 2019, respectively

^bIncludes trichocard/insecticide + labor cost

ha⁻¹) during 2015, 2016, 2017, 2018, and 2019, respectively (Table 5). The benefit: cost ratio in biocontrol-treated plots was also higher than untreated control. Likewise, pooled analysis for the five years recorded higher B:C ratio in biocontrol practiced plot (1.70) as compared to untreated control (1.50).

Augmentative biological control, involving mass production and release of large quantities of bioagents, provides a solution for reducing or sometimes eliminating the use of pesticides (Eilenberg et al. 2001). The trichogrammatids have widely been used as egg parasitoids against Lepidopteran insect pests. *Trichogramma* releases have been carried out on about 32.0 million ha area annually in more than 50 countries including India (van Lenteren et al. 2017). The biocontrol based IPM strategy for the management of sugarcane borers needs to be adopted and validated at farmers' fields. In spite of encouraging results, it could not be explored/adopted on large scale among the Punjab cane growers due to certain gaps in dissemination of the technology owing to limited resources and lack of participation of cane growers. The present study showed that multiple releases of mass reared *T. chilonis* and *T. japonicum* were effective on large scale in reducing the incidence of sugarcane borers, though not as low as that of farmers' practice (chemical control). The large-scale evaluation and feasibility of these bioagents, thus warrants for large-scale yet cost-effective production of host insects and egg parasitoids under laboratory conditions and their utilization on farmers' fields. Therefore, there is a need to validate the adoption of biological control strategy as a major component of IPM for reducing the pesticide load in sugarcane ecosystem. This will help in reducing the expenses and increase their cane yield. The

present findings are also in agreement with earlier studies by Thirumurugan et al. (2006), Geetha et al. (2009), and Sattar et al. (2016) who have reported successful management of sugarcane borers through augmentative releases of trichogrammatids.

Effectiveness of egg parasitoids could be noticed in the field as parasitized eggs in sentinel cards, indicating that sufficient population of *T. chilonis* and *T. japonicum* prevailed in the augmented plots. The findings corroborate with the studies conducted by Souza et al. (2016) who studied the natural parasitism of lepidopteran eggs by *Trichogramma* species reported very high natural parasitism of the egg masses of *D. saccharalis* on sugarcane. The present study, supported by Singh et al. (2008) who reported field recovery of *T. chilonis* from the *C. cephalonica* eggs, when the temperature tolerant strain of the parasitoid was released at 50,000 ha⁻¹ for the management of *C. auricilius* in sugarcane. Similar results have also been reported by Rachappa and Naik (2000) while conducting dispersion studies on *T. chilonis* in sugarcane ecosystem, wherein a recovery (27.5%) of the egg parasitoid was recorded on the un-parasitized *Corcyra* egg cards eggs. They further reported that the mean recovery of *T. chilonis* was negatively correlated with the distance from the release point. Geetha and Balakrishnan (2010) studied the ability of laboratory-reared egg parasitoid, *T. chilonis* to disperse and locate *Corcyra* sentinel egg cards in the sugarcane field. They recorded a clear proportional impact on dispersal probability of the parasitoid that was influenced by the distance from release points. The parasitism in the sentinel cards varied from 66.48% at 1 m to 1.86% at 30 m from release points. In the present studies also, *Trichogramma* spp. were released uniformly in the sugarcane field to augment their

Table 5 Cost of cultivation and economics returns from various treatments in the management of *C. auricilius*

| Year | Treatments | Yield (t ha ⁻¹) | Cost of cultivation ^b (USD ha ⁻¹) | Gross returns (USD ha ⁻¹) | Benefit:cost ratio |
|-------------|----------------------------------|-----------------------------|--|---------------------------------------|--------------------|
| 2015 | Biocontrol practice ^a | 72.03 | 1807.16 | 3156.82 | 1.75 |
| | Untreated control | 63.44 | 1793.56 | 2780.35 | 1.55 |
| 2016 | Biocontrol practice ^a | 72.86 | 1823.46 | 3167.36 | 1.74 |
| | Untreated control | 62.28 | 1801.36 | 2707.43 | 1.50 |
| 2017 | Biocontrol practice ^a | 70.35 | 2004.07 | 3303.85 | 1.65 |
| | Untreated control | 62.65 | 1980.59 | 2942.24 | 1.49 |
| 2018 | Biocontrol practice ^a | 72.46 | 1899.10 | 3219.52 | 1.70 |
| | Untreated control | 63.36 | 1877.60 | 2815.19 | 1.50 |
| 2019 | Biocontrol practice ^a | 73.64 | 1902.14 | 3198.15 | 1.68 |
| | Untreated control | 62.81 | 1881.13 | 2727.81 | 1.45 |
| Pooled mean | Biocontrol practice ^a | 72.27 | 1886.49 | 3208.33 | 1.70 |
| | Untreated control | 62.91 | 1866.14 | 2792.45 | 1.50 |

^a12 releases of *T. chilonis* at 50,000 per ha at 10 days interval during July to October, price of sugarcane: USD 43.83, 43.47, 46.96, 44.43, and 43.43 tonne⁻¹ during 2015, 2016, 2017, 2018, and 2019, respectively

^bIncludes trichocard + labor cost

dispersal and propensity to search for the pest species, which in turn, influenced the parasitism rates recorded in the mass release.

Yield data indicated that though the cane yield was lower in biocontrol plots than at the farmers' practice, the former resulted in comparable economic benefits to farmers' practice, indicating higher adaptability and sustainability. The input cost for the chemical control in case of farmer's practice increased over the period of 5 years. In contrast, the cost of biocontrol treatment did not increase in these years. Present study also indicated that combination of lower input costs might offset yield differences and made biocontrol-based sugarcane production system profitable. This was evident by higher benefit: cost ratio in biocontrol plots, where the management of *C. auricilius* was carried out through *Trichogramma* releases only than untreated control. Obtained results are supported by findings in Saljoqi et al. (2015) who studied the efficacy of inundative releases of *Trichogramma* against *C. infuscatellus* in sugarcane and recorded reduction in the pest infestation and yield increase in the released fields. Virk et al. (2011) validated the on-farm benefits of *T. japonicum* releases for *S. excerptalis* management and recorded significantly higher cane yield in released plots and insecticide treated plots than the untreated control plots. Further, the benefit:cost ratio for biocontrol treatment was even better than chemical control.

Conclusions

Large-scale inundative releases of trichogrammatids against sugarcane borers revealed lower incidence of *C. infuscatellus*, *S. excerptalis*, and *C. auricilius* than at the untreated control fields, wherein the incidence of these borers was significantly higher. Higher yield and better benefit:cost ratio was obtained in biocontrol and farmers' practices than at the untreated control. The findings provide the evidence that biocontrol based technologies involving inundative releases of egg parasitoids may be considered as a better option for sustainable system of insect pest management against sugarcane borers.

Abbreviations

BCA: Benefit cost analysis; USD: United States Dollar

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Authors' contributions

SS and PSS conceptualized the project, carried out field experiments, data analyses, and original manuscript draft preparation. RK maintained the insect culture. KSS was involved in conceptualization, supervision, final

interpretation of data, and editing of the manuscript. All authors have read and approved the manuscript.

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