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Research article

Biorational management of root-knot of brinjal (*Solanum melongena* L.) caused by *Meloidogyne javanica*

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ABSTRACT

Production of brinjal (*Solanum melongena* L.) is considerably reduced by infestations of root-knot nematodes (RKN). As chemical pesticides are increasingly being regulated globally, scientists are focusing on biorational management. An experiment was undertaken to screen resistant brinjal cultivars in Bangladesh against *Meloidogyne javanica* in a pot trial. Pot and field trials were also conducted to evaluate the efficacy and profitability of individual and combined applications of several biorational components to manage *M. javanica* on brinjal. Of twenty brinjal cultivars screened, cv. Noagram was found 'moderately resistant' and others were 'susceptible' to 'highly susceptible' against *M. javanica*. In both pot and field trials, most of the growth parameters of brinjal and reproductive parameters of *M. javanica* were significantly different than the control for both the individual and combined treatments of different biorational components which included cabbage, marigold, vermicompost, biogas digestate, *Bacillus subtilis* and *Pseudomonas fluorescens*. The yield was significantly higher for the combined treatments than the individual applications. The benefit-cost ratio (BCR) differed among the treatments. The highest yield (29.5 t/ha) and BCR (3.67) with the lowest reproductive factor (0.33) was obtained by the combined application of biogas digestate and *B. subtilis*. This is the first report on the efficiency and profitability assessment of biogas digestate in combination with a bio-agent in addressing the management of RKN, which might be very important considering the global concern of environmental pollution. The cultivar Noagram might be a potential source of resistant genes in brinjal against *M. javanica*.

1. Introduction

Brinjal *Solanum melongena* L. is one of the most popular vegetables in S. Asia, and is consumed worldwide. It is also known as eggplant or aubergine in several countries (Rangarajan et al., 2021). An edible portion of 100 gm brinjal contains 1.4 gm protein, 18 mg calcium, and 24 kcal of food energy (Hasan and Bai, 2016). Production of brinjal is affected by the infestation of several pests which include plant-parasitic nematodes (PPN). Among the PPN, root-knot nematode (RKN) is the most prominent. Globally, three species of RKN, *Meloidogyne incognita*, *M. javanica,* and *M. arenaria* have been found to be associated with the root-knot of brinjal, however, in Bangladesh *M. javanica* is the most prevalent one (Das et al., 2021c). Globally, 27%–62% yield of brinjal is lost due to the infection of RKN (Darekar and Mhase, 1988; Bari, 2001). Generally, broad-spectrum synthetic chemical pesticides are applied to control RKN. Since these broad-spectrum non-selective pesticides are designed to kill animals, they are also dangerous to human beings, and detrimental to non-target organisms in many ways (Kepenekci et al., 2017). In addition, as a consequence of the long-term use of these chemicals, resistance-breaking nematode pathotypes emerge on many important crops which are guiding policymakers to impose restrictions on various molecules used worldwide (Abu-Elgawad and Askary, 2015). Therefore, as an alternative, the efficacy of biorational components against the infection of RKN is evaluated (Huang et al., 2016).

Plant resistance is the heritable ability of plants to escape the extent of damage caused by pathogens (Stenberg and Muola, 2017). As the most effective and environmentally safe method, plant resistance is the foremost component in integrated pest management. Reasonably, finding resistance in plants against RKN is one of the quests of nematologists. The use of biocontrol agents like fungi and bacteria is of growing interest for controlling PPN non-chemically (Crawford and Clardy, 2011). Two rhizosphere bacteria *Bacillus subtilis* and *Pseudomonas fluorescens* have

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been reported to inhibit RKN reproduction, egg hatch, and juvenile survival by producing different enzymes and toxins (Siddiqui and Mahmood, 1999; Das et al., 2021a). As bio-nematicides are formulated based on living systems, there has always been a gap between laboratory and field performance of those (Abu-Elgawad and Askary, 2015).

Bio-fumigation is another non-chemical approach. Here, various plant species are incorporated into the soil to liberate volatiles which suppresses soil-borne pests (Berbegal et al., 2008). For example, marigold and cabbage are important sources of nematicidal compounds (Zasada and Ferris, 2004; Abo-Elyousr et al., 2010; Taye et al., 2012; Youssef and Lashein, 2013). It is already reported that the life cycle and pathogenicity of RKN are adversely affected by marigold (*Tagetes* spp.) (Abo-Elyousr et al., 2010; Tibugari et al., 2012; Taye et al., 2012). However, its effect on the population of RKN varies depending on the cultivar of marigold and the species of RKN (Karssen and Moens, 2006). It is hypothesized that marigold might exert an antagonistic effect on RKN populations whereby the second-stage juvenile (J_2) fails to initiate giant cells in the roots (Karssen and Moens, 2006). On the other hand, cabbage (*Brassica* spp.) releases glucosinolates (GSL) which on hydrolysis produce isothiocyanate (ITC) that has a toxic effect on certain nematode species (Zasada and Ferris, 2004). However, incorporation of the appropriate amounts of glucosinolate-containing biomass and sensitivity of the target PPN species to ITC are important determinants of the successful outcome (Zasada and Ferris, 2004).

As an alternative to chemical pesticides, several organic amendments are being investigated to determine their efficacy in controlling PPN, although, results have been inconsistent (Akhtar and Malik, 2000). Vermicompost, composted in the presence of earthworm, is an important organic amendment that increases crop production. Vermicompost results in high porosity, aeration, drainage, water-holding capacities, and low C: N ratios (Edwards, 1998). Vermicompost was reported to decrease RKN-induced galls, and to increase the concentration of root defense metabolites in plants (Xiao et al., 2016). Biogas digestate (BD), produced as a byproduct of a biogas facility, is an organic amendment that improves soil fertility, crop quality, and plant immunity to biotic and abiotic agents (Koszel and Lorencowicz, 2015). To reduce the negative impact of burning fossil fuels, environmentalists and policymakers are considering biodegradable organic waste as an alternative energy source (Koszel and Lorencowicz, 2015). In a biogas facility, organic wastes are anaerobically decomposed in an environment-friendly way to produce biogas (Koszel and Lorencowicz, 2015). It has been reported that BD has some potential to reduce PPN infestation (Min et al., 2007).

Various concentrations of culture filtrates of *B. subtilis* and *P. fluorescens* have been reported to strongly influence mortality and hatching of *M. javanica* (Das et al., 2021a). In an *in vitro* experiment, the effect of vermicompost, BD, and botanical extracts of marigold and cabbage was evaluated on the hatching and mortality of *M. javanica* (Das et al., 2021b). Results showed that mortality and inhibition of hatching of *M. javanica* were higher in botanical extracts than those of organic amendments. However, the soil is a complex ecosystem where results are affected under several physical, chemical, and biological stressors. Moreover, the biocontrol of RKN does not rely on any single measure, but rather an integrated approach (El-Ashry et al., 2021). To be sustainable, control measures need to be economically feasible for the farmers. There are few publications that link effective control measures with an economic return. As *M. javanica* is the most prevalent RKN of brinjal in Bangladesh, the objectives of this experiment were 1) to screen brinjal cultivars against *M. javanica* in a pot trial and 2) to evaluate the individual and combined applications of biorational components to manage *M. javanica* of brinjal under field condition with an assessment of the economic benefit.

2. Materials and methods

2.1. Nematode inoculum

Egg masses of a pure culture of *M. javanica* (NCBI accession no. MN196542) were used in this experiment (Das et al., 2021b).

2.2. Screening of brinjal cultivars for resistance

Twenty brinjal germplasms were considered for screening for resistance. Eight cvs. (BARI begun 1, 4, 5, 6, 7, 8, 9, 10) were improved varieties of Bangladesh Agricultural Research Institute (BARI) and twelve cvs. (Borkha, Black long, Noagram, Shyla, Mental Red, Jhumka, Hari, Hajari begun, Tilokpur, shingnath, Narsingdi, Manikganj) were collected from local farmers of Bangladesh. Seeds were sown into pots at the net house of Seed Pathology Center (SPC), Bangladesh Agricultural University (BAU), Mymensingh under 25–30 °C temperature with 12–13 h of daily daylight. Pots (16 cm × 25 cm each) were filled with 0.1% formalin-sterilized soil. Each pot received a single seedling of each cultivar with four replications. At thirty days, each seedling was inoculated with two hundred eggs of *M. javanica*. Sixty days after inoculation, growth parameters of the plant and reproductive parameters of the nematodes were recorded (Begum et al., 2014). Egg masses were stained with acid fuchsin to aid in counting (Bybd et al., 1983). A root-knot index scale was used to resistance, where 1 = no egg mass = highly resistant; 2 = 1–10 egg mass = resistant; 3 = 11–30 egg mass = moderately Susceptible; 4 = 31–100 egg mass = Susceptible; 5 = > 100 egg mass = highly susceptible (Gaur et al., 2001). Plants were arranged in a completely randomized design (CRD).

2.3. Preparation and application of treatments

2.3.1. Cabbage and marigold leaves

Cabbage (*B. oleracea*) and marigold (*Tagetes* spp.) leaves were collected from cultivated fields and chopped into 1–2 cm pieces. Chopped cabbage/Marigold leaves were incorporated immediately into the soil @ 20 g/pot (pot trial) and @ 200 g/plot (field trial) of soil 10 days before transplanting of the seedlings (Youssef and Lashein, 2013). Until transplanting, the treated soil was covered with a plastic sheet to retain the volatiles in the soil.

2.3.2. Vermicompost and biogas digestate (BD)

Animal dung and agro/kitchen waste were used to produce vermicompost and biogas (Nath and Singh, 2011). Earthworms (*Eisenia fetida*) were used as a composter @ 2kg/vermibed (3 m × 1 m × 9m). Solid BD was collected from a household biogas facility at Mymensingh, Bangladesh. For the vermicompost-soil mixture and BD-soil mixture treatments, vermicompost and BD were mixed with soil @ 500 g/pot (pot trial) and @ 5 kg/plot (field trial) 10 days before transplanting (Serfoji et al., 2010).

2.3.3. Preparation of B. subtilis and P. fluorescens suspension

Two bacterial strains *B. subtilis* (MN252542.1) and *P. fluorescens* (MN256394.1) were isolated from the rhizosphere soil of Meherpur (24°N, 89°E) and Mymensingh (25°N, 90°E) of Bangladesh, and stored at -80 °C at the Department of Plant Pathology, BAU maintaining proper condition (Schaad, 1980; Krieg and Holt, 1984; Zihad et al., 2021). For bacterial inoculum, *B. subtilis* was grown on nutrient agar and *P. fluorescens* was grown on King's medium B for 24 h at 28 °C (Mahesha et al., 2017). The bacteria were then transferred to nutrient broth in a 250 ml conical flask and incubated for 48 h at 200 rpm at 32 °C (Sela et al., 1998). Bacterial suspensions @ 40 ml/plant (10^9 CFU/ml) were applied twice, immediately after inoculation (in pot trial)/transplanting (in field trial) and 15 days after the 1st application, in both pot and field trials (Abo-Elyousr et al., 2010).

2.3.4. Chemical pesticide

For a positive control, the organophosphate nematicide, Cadusafos @ 1g/pot (pot trial) and @ 10g/plot (field trial) was mixed into the soil 10 days before transplanting (Abo-Elyousr et al., 2010). Pots or plots with brinjal seedlings receiving no treatments served as a negative control.

Table 1. Treatments of biocomponents applied in the pot and field experiment.

T_0 = Control	T_6 = Bacterial suspension of *Pseudomonas fluorescens*
T_1 = Marigold leaf	T_7 = Rugby 10G (Positive Control)
T_2 = Cabbage leaf	$T_8 = T_3 + T_5$
T_3 = Vermicompost	$T_9 = T_3 + T_6$
T_4 = Biogas Digestate	$T_{10} = T_4 + T_5$
T_5 = Bacterial suspension of *Bacillus subtilis*	$T_{11} = T_4 + T_6$

$T_8 = T_3$ (Vermicompost @ 500g/pot or 5kg/plot) + T_5 (Bacterial suspension of *Bacillus subtilis* @ 40 ml/plant).
$T_9 = T_3$ (Vermicompost @ 500g/pot or 5kg/plot) + T_6 (Bacterial suspension of *Pseudomonas fluorescens* @ 40 ml/plant).
$T_{10} = T_4$ (Biogas Digestate @ 500g/pot or 5kg/plot) + T_5 (Bacterial suspension of *Bacillus subtilis* @ 40 ml/plant).
$T_{11} = T_4$ (Biogas Digestate @ 500g/pot or 5kg/plot) + T_6 (Bacterial suspension of *Pseudomonas fluorescens* @ 40 ml/plant).

2.4. Evaluation of different biorational components against RKN (pot trial)

Pots were prepared the same as for resistance screening. The susceptible cv. BARI begun 4 (Begum et al., 2014) was used for evaluating the biorational components. Each pot received a single seedling with 4 replications per treatment (Table 1). After thirty days, each seedling was inoculated with two hundred eggs of *M. javanica*. Data on growth parameters of plants and reproductive parameters of nematodes were recorded 45 days after inoculation (DAI) and 90 DAI (Akhter and Khan, 2018). Eggs were extracted from egg masses following the sugar floatation method with 40% sucrose solution (Hussey and Barker, 1973), and J_2 from soil was extracted by a modified centrifugal-flotation technique (Jenkins, 1964). Egg masses on the infected roots were counted by staining with acid fuchsin (Bybd et al., 1983). Plants were arranged in a CRD.

2.5. Evaluation of different biorational components against RKN (field trial)

The field experiment was conducted at a farmer's field naturally infested with *M. javanica* (Das et al., 2021c). The field was located at Madhupur (24.61°N, 90.03°E) of the Tangail district where brinjal is cultivated year-round (Das et al., 2021c). To assess the level of infestation, 10 soil samples were collected 15 cm deep in each of the plots. The plots were 3.5 square meters. The number of nematodes was expressed as the number of J_2/100g soil. The field plots had sandy loam soil with a pH of 6.4. A humid tropical climate prevailed with an average temperature of 25–34 °C during the experiment period. The plots were prepared by standard agronomic practices. In each plot, six thirty-day-old cv. BARI begun 4 were transplanted with a spacing of 75 × 50 cm and standard levels of fertilizers (SRDI, 2021), irrigation, and pesticides (when necessary) were provided. Each plot was applied with any one of the treatments and was replicated three times. Plots were arranged in an RCBD. Data on plant growth and yield and reproductive parameters of *M. javanica* were recorded 90 days after transplanting (DAT). Data from each of the six plants per plot were averaged. Staining of egg masses, and the extraction of J_2 and eggs from soil and egg masses, respectively, were conducted as for the pot trial. The cost of cultivation of brinjal was estimated by the method of Hasan and Bai (2016). The benefit-cost ratio (BCR) was calculated using the formula:

$$BCR = (A \times C) \div B \text{ (Reddy and Reddy, 1992)} \quad \ldots\ldots(1)$$

Where, A = Yield (kg/ha), B = Cost of cultivation of the crop (Tk/ha), C = Price of the product (Tk/kg), Tk = Bangladeshi Taka/Currency.

2.6. Statistical analysis

Data were subjected to an analysis of variance (ANOVA) using Statistix 10 (© 1985–2013 Analytical Software, Miller Landing Rd, Tallahassee, FL 32312) and significant means were separated using Tukey's HSD test at 5% level of probability. For resistance screening, a pairwise T-

Table 2. Growth responses and resistance (root-knot index) of brinjal cultivars infected by *Meloidogyne javanica*.

Cultivar	Shoot length (cm)		Root length (cm)		Shoot weight (g)		Root weight (g)		Leaf number		Branch number		Root-knot Index	
	C	I	C	I	C	I	C	I	C	I	C	I	C	I
BARI begun 1	77.5	71.5*	11.5	14.25*	75.5	56.5*	23.25	18.25*	20.5	17.5	4	3	0	5
BARI begun 4	57	50*	21.75	18.75*	79.5	58.5*	25.5	17.5*	20.75	18.75	4.25	3.5	0	5
BARI begun 5	62.5	50*	17	12.25*	65.25	41.75*	18.75	12.5*	16	14.75	4	3.5	0	4
BARI begun 6	76.75	66.5*	25.25	18.5*	86.75	67.25*	23	17.75*	18.5	16	4.5	3.75	0	5
BARI begun 7	64.75	53.5*	25	21.5*	87.5	71*	25.5	16.75*	14.5	12	3	3.5	0	5
BARI begun 8	75.75	61.25*	20.75	14.5*	82	55.25*	23	12.75*	16.5	13.75	3.75	2.75	0	5
BARI begun 9	68.5	50.25*	23.75	18.25*	58.75	46*	21	11.5*	14.25	12.75	3.75	3	0	5
BARI begun 10	74	59.75*	20.75	13.5*	90	33.5*	22	16*	11.75	16	3.25	2.5	0	5
Borkha	65.25	51.75*	28.25	21.25*	46.75	29.25*	25.25	17.5*	14.25	13.5	2.75	2.5	0	5
Noagram	54.75	52.25	56.25	53.5	67.75	65.25	16.5	14.25	14.5	12.75	2.5	2.5	0	3
Black long (Black long)	61.75	52.5*	38.0	29.25*	51.75	41.75*	14.5	10.75*	14	12.5	2	2	0	4
Shyla	64.25	53*	58.25	44.25*	69	58.25*	28.5	22.75*	15	13.75	2.75	2.5	0	5
Mental Red	60.75	49.25*	44.75	34.75*	46.75	38.75*	15.25	12*	17.25	16	3	2.25	0	5
Jhumka	65	55*	26.75	21.25*	48.5	38.5*	20.25	12.75*	26	22.75	5.25	4.5	0	4
Hari	57.5	48.25*	28	21.25*	48	40.5*	15	10.5*	14.75	12.75	3	2.5	0	5
Hajari begun	64	54.75*	43.75	33*	61.25	49*	21.75	14.5*	19.5	17	3	2.5	0	4
Tilokpur	63.5	52*	29.5	23*	48.5	40.75*	17.5	11.25*	16	12.75	2.75	2.25	0	5
Shingnath	59.75	49.75*	29.75	22.25*	62.5	55*	16.75	12.5*	14.25	12.25	2.5	2	0	4
Narsingdi	65	53.75*	27.75	21.75*	59.75	41*	20.25	13*	13	12	2.25	2	0	5
Manikganj shingnath	59.5	48.5*	31	23.5*	46.5	35*	24.75	15.25*	11.25	10	2	2	0	5

Means are the average of four replications; C = Control; I = inoculated; * = Significantly different in pairwise T test; Root-knot Index = 1 = no egg mass = highly resistant; 2 = 1–10 egg mass = resistant; 3 = 11–30 egg mass = moderately resistant; 4 = 31–100 egg mass = Susceptible; 5 = > 100 egg mass = highly susceptible (Gaur et al., 2001).

Table 3. Effects of biocomponents on the reproductive parameters of *Meloidogyne javanica* at 45 DAI in a susceptible brinjal cultivar (BARI begun 4) in pots.

Treatment	Root (3g)			J_2/100g soil
	Gall	Egg mass	Egg	
T_0	25 ± 1.78a	19 ± 1.41a	285 ± 21.21a	200 ± 14.85a
T_1	5.5 ± 1.04def	0 ± 0e	0 ± 0e	0 ± 0e
T_2	10.25 ± 1.11cd	5.5 ± 0.65cd	66 ± 4.33cd	36.25 ± 4.33cd
T_3	15.75 ± 0.95b	11 ± 0.71b	165 ± 10.61b	99 ± 6.36b
T_4	13 ± 1.29bc	7.75 ± 0.85c	100.75 ± 11.1c	57.25 ± 6.37c
T_5	4 ± 0.91f	0 ± 0e	0 ± 0e	0 ± 0e
T_6	4.5 ± 0.87ef	0 ± 0e	0 ± 0e	0 ± 0e
T_7	3.25 ± 0.25f	0 ± 0e	0 ± 0e	0 ± 0e
T_8	9.25 ± 0.48cde	4.75 ± 0.25d	57 ± 3d	25.75 ± 1.25de
T_9	9.75 ± 1.11cd	5.25 ± 0.48cd	63 ± 5.74cd	28.25 ± 2.39d
T_{10}	8 ± 0.41def	3.75 ± 0.25d	45 ± 3d	20.5 ± 1.5de
T_{11}	9.25 ± 0.85cde	4.25 ± 0.48d	51 ± 5.74d	23 ± 2.61de
CV (%)	20.46	23.26	23.96	25.94
F-value	36.59	88.2	101.25	119.23
df	11			
Level of significance *				

Values are the mean ± Standard Error of four replicates; Treatment means were compared by one-way ANOVA; Same letter in a column do not differ significantly according to Tukey's test at 5% probability; DAI = Days after incubation *1% level of probability; T_0 = Control, T_1 = Marigold leaf, T_2 = Cabbage leaf, T_3 = Vermicompost, T_4 = Biogas Digestate,T_5 = Bacterial suspension of *Bacillus subtilis*, T_6 = Bacterial suspension of *Pseudomonas fluorescens*, T_7 = Rugby 10G (Positive Control), $T_8 = T_3 + T_5$, $T_9 = T_3 + T_6$, $T_{10} = T_4 + T_5$, $T_{11} = T_4 + T_6$.

test was performed using MS Excel to differentiate the parameters between control and inoculated plants.

3. Results

3.1. Screening of brinjal cultivars for resistance to RKN

All of the BARI varieties were 'susceptible' to 'highly susceptible' to RKN, with a root-knot index of 4–5 (Table 2). All of the local cultivars except 'Noagram', had a root-knot index 4 to 5. The cultivar 'Noagram' had a root-knot index of 3. Growth parameters of the germplasms were also studied. The number of branches and leaves was not significantly different between the control and inoculated plants in any of the cultivars. The rest of the growth parameters (shoot length, root length, shoot weight, root weight) were found significantly different than that of the control in the pairwise T-test for all cultivars except 'Noagram'. There was no significant difference between the control and the inoculated plants in any growth parameters for the cultivar 'Noagram', suggesting that this cultivar has moderate resistance against the infestation of *M. javanica*.

3.2. Evaluation of biorational components against RKN (pot trial)

All of the reproductive parameters of *M. javanica* differed significantly at 45 and 90 DAI (Tables 3 and 4). AT 45 DAI, the lowest number of galls were found in the treatment T_5 and T_7, while no egg masses, eggs, and J_2 were observed for the treatment T_1, T_5, T_6, and T_7. At 45 DAI, the second-highest number of galls, egg masses, eggs, and J_2 were observed for the treatment T_3. At 90 DAI, the lowest number of galls were recorded in the treatment T_7, however, a statistically similar number of galls were found in some other treatments (T_1, T_5, T_6, T_8). Similarly, the lowest number of egg masses were found in the treatment T_7, and some other treatments (T_1, T_2, T_5, T_8) had statistically similar counts for the same variable. The number of eggs was the lowest for the treatment T_1 and T_5, and the number of extracted J_2 from soil was the lowest in T_1, T_5, T_6, and T_7 at 90 DAI. All of the reproductive parameters had the highest count in T_0 at both 45 and 90 DAI.

In the pot experiment, all the growth parameters of plants, except branch numbers, differed significantly at both 45 and 90 DAI (Tables 5 and 6). Root length was the highest in T_5 and T_7, while the maximum leaf number was observed in T_5 at 45 DAI. At 90 DAI, shoot length, root length, shoot weight, and root weight was the highest in the treatment T_{10}. At both 45 and 90 DAI, all of the growth parameters of plants were the lowest in T_0.

3.3. Evaluation of biorational components against RKN (field trial)

All of the growth parameters of plants, *viz.* shoot length (F-value = 24.73, df = 11), root length (F-value = 11.44, df = 11), shoot weight

Table 4. Effects of biocomponents on the reproductive parameters of *Meloidogyne javanica* at 90 DAI in a susceptible brinjal cultivar (BARI begun 4) in pots.

Treatment	Root (3g)			J_2/100g soil
	Gall	Egg mass	Egg	
T_0	140 ± 5.96a	82.75 ± 1.93a	1820.5 ± 42.48a	1459 ± 33.65a
T_1	17 ± 1.87cd	13 ± 1.68cde	125 ± 11.52f	75 ± 6.98e
T_2	30.5 ± 2.1c	22.5 ± 2.18cde	337.5 ± 32.69d	239 ± 21.52d
T_3	89 ± 4.55b	49.5 ± 3.77b	891 ± 67.95b	705.5 ± 54.36b
T_4	82 ± 5b	43.75 ± 3.04b	656.25 ± 45.57c	457.75 ± 29.6c
T_5	16.75 ± 1.75cd	12.75 ± 2.38de	123.75 ± 10.13f	74.5 ± 6.22e
T_6	17.5 ± 1.76cd	14 ± 1.68cde	136.75 ± 5.88ef	82 ± 3.49e
T_7	13.75 ± 1.11d	11.5 ± 1.19e	128 ± 6.86f	76.75 ± 4.17e
T_8	26.25 ± 1.89cd	20.5 ± 2.99cde	307.5 ± 44.79de	215.25 ± 31.35d
T_9	30.5 ± 2.22c	24 ± 2.08c	360 ± 31.22d	254.25 ± 22.48d
T_{10}	29 ± 0.91c	23.5 ± 1.71cd	352.5 ± 25.62d	230.5 ± 16.3d
T_{11}	29.5 ± 1.94c	23.75 ± 2.06cd	356.25 ± 30.85d	244 ± 21.89d
CV (%)	13.90	15.89	14.90	14.85
F-value	168.19	84.88	194.87	242.72
df	11			
Level of significance *				

Values are the mean ± Standard Error of four replicates; Treatment means were compared by one-way ANOVA; Same letter in a column do not differ significantly according to Tukey's test at 5% probability; DAI = Days after incubation *1% level of probability; T_0 = Control, T_1 = Marigold leaf, T_2 = Cabbage leaf, T_3 = Vermicompost, T_4 = Biogas Digestate,T_5 = Bacterial suspension of *Bacillus subtilis*, T_6 = Bacterial suspension of *Pseudomonas fluorescens*, T_7 = Rugby 10G (Positive Control), $T_8 = T_3 + T_5$, $T_9 = T_3 + T_6$, $T_{10} = T_4 + T_5$, $T_{11} = T_4 + T_6$.

Table 5. Effects of biocomponents on the growth parameters of a susceptible brinjal cultivar (BARI begun 4) in response to inoculation with *Meloidogyne javanica* at 45 DAI in pots.

Treatment	Shoot length (cm)	Root length (cm)	Shoot weight (g)	Root weight (g)	Branch number	Leaf number
T_0	34.5 ± 2.39b	16.75 ± 1.03b	21.75 ± 2.69b	11.25 ± 0.85b	1.5 ± 0.29	8.5 ± 0.65b
T_1	51 ± 1.35a	26 ± 1.29ab	42 ± 2.12a	21 ± 0.91a	1.75 ± 0.25	11.25 ± 0.63ab
T_2	52.75 ± 4.59a	25.75 ± 2.5ab	43.25 ± 3.42a	20.5 ± 1.19a	1.5 ± 0.29	11 ± 0.71ab
T_3	53.75 ± 2.06a	25.75 ± 2.39ab	44.5 ± 1.85a	20.25 ± 1.11a	1.25 ± 0.25	10.5 ± 0.87ab
T_4	51 ± 0.71a	25 ± 2.68ab	42.75 ± 2.5a	19 ± 1.08a	1.5 ± 0.29	11.25 ± 0.48ab
T_5	51.25 ± 2.56a	27 ± 2.12a	46.5 ± 2.53a	21.25 ± 1.25a	1.75 ± 0.25	12 ± 0.41a
T_6	50.75 ± 1.44a	23.5 ± 2.22ab	44.75 ± 2.28a	19 ± 1.41a	1.75 ± 0.25	11 ± 0.41ab
T_7	50.75 ± 1.43a	27.5 ± 1.04a	44.5 ± 2.25a	19.75 ± 0.85a	1.5 ± 0.29	11.75 ± 0.75ab
T_8	55.5 ± 5.24a	26 ± 1.58ab	43 ± 2.04a	22 ± 1.22a	2 ± 0	11 ± 0.41ab
T_9	56.25 ± 3.5a	26.25 ± 2.75ab	43.5 ± 3.5a	19.75 ± 0.85a	1.75 ± 0.25	11.5 ± 1.19ab
T_{10}	57.25 ± 2.78a	25.75 ± 0.75ab	46 ± 1.87a	21.5 ± 1.55a	2 ± 0	12.25 ± 0.75b
T_{11}	53.5 ± 3.61a	24.5 ± 1.94ab	44 ± 3.03a	21.25 ± 1.88a	1.5 ± 0.29	10.25 ± 0.48ab
CV (%)	11.46	15.8	12.15	12.39	29.95	12.36
F-value	3.89	2.01	6.57	5.39	-	2.07
df	11					
Level of significance *						

Values are the mean ± Standard Error of four replicates; Treatment means were compared by one-way ANOVA; Same letter in a column do not differ significantly according to Tukey's test at 5% probability; DAI = Days after incubation *1% level of probability; T_0 = Control, T_1 = Marigold leaf, T_2 = Cabbage leaf, T_3 = Vermicompost, T_4 = Biogas Digestate,T_5 = Bacterial suspension of *Bacillus subtilis*, T_6 = Bacterial suspension of *Pseudomonas fluorescens*, T_7 = Rugby 10G (Positive Control), T_8 = $T_3 + T_5$, T_9 = $T_3 + T_6$, T_{10} = $T_4 + T_5$, T_{11} = $T_4 + T_6$.

(F-value = 31.58, df = 11), root weight (F-value = 10.85, df = 11), branch number (F-value = 4.13, df = 11), leaf number (F-value = 10.07, df = 11) and yield (F-value = 96.26, df = 11) differed significantly (Table 7). In the field trial, shoot length was the highest in T_7 and T_{10}. However, for other growth parameters, the treatment T_{10} was superior. The highest and statistically similar yield of brinjal was recorded in all of the combined treatments, i.e., T_8, T_9, T_{10}, and T_{11}. R_f was the lowest (0.33) in T_{10}. On the other hand, significantly the lowest growth parameters of plants and yield were recorded in T_0, while the R_f was the highest (2.68) in this treatment. The efficacy of all of the treatments was also analyzed in the light of BCR (see Eq. (1)) to determine their economic feasibility (Table 8). As higher yield was obtained in the combined treatments, higher revenues were also obtained from those treatments (T_8, T_9, T_{10}, and T_{11}). The highest BCR (3.67) was recorded for the treatment T_{10} which was followed by T_{11} (3.4). Although total revenue was almost similar to T_{10} and T_{11}, the BCR was much lower (2.59) in the treatment T_8 and T_9. On the contrary, BCR for the treatment T_5 (3.23), T_6 (3.23), and T_7 (3.26) were much closer to the highest one despite having much lower revenue than that of T_{10} and T_{11}.

Table 6. Effects of biocomponents on the growth parameters of a susceptible brinjal cultivar (BARI begun 4) in response to inoculation with *Meloidogyne javanica* at 90 DAI in pots.

Treatment	Shoot length (cm)	Root length (cm)	Shoot weight (g)	Root weight (g)	Branch number	Leaf number
T_0	38.5 ± 1.94e	18.75 ± 1.31e	22.75 ± 1.1d	15.75 ± 1.5c	1.75 ± 0.25	11.75 ± 0.85b
T_1	53.25 ± 2.17cd	26.75 ± 0.75cd	46 ± 1.08abc	22.75 ± 1.44ab	2.25 ± 0.25	14.25 ± 1.11ab
T_2	53 ± 3.03cd	26.25 ± 1.31d	44.5 ± 1.85bc	22 ± 1.08bc	2.25 ± 0.25	14 ± 0.71b
T_3	54.25 ± 1.89 (a-d)	26 ± 1.58d	45 ± 2.04bc	21.5 ± 1.04bc	2.5 ± 0.29	16 ± 1.08ab
T_4	52 ± 2.12d	25.75 ± 1.31d	43 ± 1.59c	22.5 ± 1.32ab	2.25 ± 0.25	14.25 ± 1.18ab
T_5	53.5 ± 2.25bcd	27.5 ± 1.19bcd	47.25 ± 2.78abc	23.5 ± 1.25ab	2.75 ± 0.25	15.75 ± 1.49ab
T_6	51.5 ± 1.55d	26 ± 1.47d	45.5 ± 1.32bc	23.25 ± 1.25ab	2.25 ± 0.25	15 ± 0.82ab
T_7	51.25 ± 1.31d	28.5 ± 0.65 (a-d)	45.75 ± 0.85bc	24 ± 1.22ab	3 ± 0.41	14.5 ± 1.55ab
T_8	62.25 ± 0.48ab	32.25 ± 0.63ab	51.5 ± 1.71ab	27.25 ± 1.65ab	3 ± 0	16.5 ± 0.65ab
T_9	61.75 ± 1.18abc	32 ± 0.91abc	51.25 ± 1.8ab	27 ± 1.22ab	3 ± 0.41	15 ± 1.47ab
T_{10}	62.5 ± 0.86a	33.25 ± 0.63a	53.75 ± 1.03a	29 ± 1.83a	3.25 ± 0.48	19.5 ± 0.65a
T_{11}	61 ± 0.82abc	32.25 ± 0.85ab	51.75 ± 0.95ab	28 ± 1.47ab	3 ± 0.41	15.5 ± 1.04ab
CV (%)	6.52	7.9	7.02	11.21	24.16	14.45
F-value	14.52	13.7	24.95	7.27	-	2.79
df	11					
Level of significance *						

Values are the mean ± Standard Error of four replicates; Treatment means were compared by one-way ANOVA; Same letter in a column do not differ significantly according to Tukey's test at 5% probability; DAI = Days after incubation *1% level of probability; T_0 = Control, T_1 = Marigold leaf, T_2 = Cabbage leaf, T_3 = Vermicompost, T_4 = Biogas Digestate,T_5 = Bacterial suspension of *Bacillus subtilis*, T_6 = Bacterial suspension of *Pseudomonas fluorescens*, T_7 = Rugby 10G (Positive Control), T_8 = $T_3 + T_5$, T_9 = $T_3 + T_6$, T_{10} = $T_4 + T_5$, T_{11} = $T_4 + T_6$.

Table 7. Effects of biocomponents on the growth parameters and yield of a susceptible brinjal brinjal cultivar (BARI begun 4), and reproductive factor (R_f) of *Meloidogyne javanica* at 90 DAT in a farmer's field.

Treatment	Shoot length (cm)	Root length (cm)	Shoot weight (g)	Root weight (g)	Branch number	leaf number	Yield (ton/ha)	Pi	Pf	R_f
								J_2/100g soil		
T_0	87 ± 4.62e	18.33 ± 1.76f	609 ± 32.33e	40.33 ± 3.84e	6.67 ± 0.33c	77.33 ± 4.33d	15.81 ± 0.13c	240	642	2.68
T_1	104 ± 4.58de	26.33 ± 0.88 (b-e)	761 ± 14.64cd	58 ± 2.08bcd	11.33 ± 0.88abc	147.33 ± 11.46bc	17.71 ± 0.33bc	240	168.33	0.7
T_2	106.67 ± 3.92cde	25 ± 0.58de	746.67 ± 27.51cd	55 ± 1.15cd	9.33 ± 0.88bc	121.33 ± 11.46cd	17.52 ± 0.25bc	240	365	1.52
T_3	94 ± 3.79de	24.67 ± 1.2ef	658 ± 26.5de	54.67 ± 2.73de	11.67 ± 0.88abc	163.33 ± 12.34abc	17.9 ± 0.415bc	240	516.67	2.15
T_4	105.33 ± 2.6cde	25.33 ± 1.76cde	737.33 ± 18.22cd	55.67 ± 4.09cd	10 ± 1.52bc	140 ± 21.38bc	18.76 ± 0.41b	240	516.67	2.15
T_5	111.67 ± 4.05bcd	28.33 ± 1.2 (a-e)	781.67 ± 28.38c	62.33 ± 2.73 (a-d)	10.33 ± 1.2abc	134.33 ± 15.62bcd	18.29 ± 0.66bc	240	136.33	0.57
T_6	108 ± 3.78cde	26.33 ± 2.02 (b-e)	756 ± 26.5cd	58 ± 4.35bcd	9.67 ± 0.33bc	122 ± 6.08cd	18.29 ± 0.43bc	240	173.33	0.72
T_7	151.33 ± 4.09a	28.67 ± 0.88 (a-e)	847.33 ± 15.8bc	63 ± 2.08 (a-d)	11.67 ± 1.86abc	150.67 ± 10.36bc	18.57 ± 0.19b	240	160	0.67
T_8	132.67 ± 6.74ab	31.67 ± 0.33abc	932.67 ± 12.77ab	69.33 ± 0.88abc	11.33 ± 0.88abc	180.33 ± 3.53ab	27 ± 0.76a	240	108.33	0.45
T_9	126.33 ± 3.52bc	31.33 ± 0.88 (a-d)	937 ± 17.78ab	69 ± 2.08 (a-d)	12 ± 1.53abc	184.33 ± 8.41ab	27 ± 0.76a	240	113.33	0.47
T_{10}	153.33 ± 3.18a	33.33 ± 0.88a	1049.33 ± 18.66a	73.33 ± 2.02a	16 ± 0.57a	210.33 ± 6.64a	29.5 ± 0.58a	240	80	0.33
T_{11}	131.67 ± 4.05ab	32.33 ± 1.2ab	937.67 ± 21.68ab	71.33 ± 2.73ab	13 ± 0.58ab	177.33 ± 6.06abc	27.33 ± 0.44a	240	115	0.48
CV (%)	6.31	7.84	4.92	8.02	17.33	12.87	4.13			
Level of significance *										

Values are the mean ± Standard Error of three replicates; Treatment means were compared by one-way ANOVA; Same letter in a column do not differ significantly according to Tukey's test at 5% probability; DAT = Days after transplantation *1% level of probability; T_0 = Control, T_1 = Marigold leaf, T_2 = Cabbage leaf, T_3 = Vermicompost, T_4 = Biogas Digestate, T_5 = Bacterial suspension of *Bacillus subtilis*, T_6 = Bacterial suspension of *Pseudomonas fluorescens*, T_7 = Rugby 10G (Positive Control), $T_8 = T_3 + T_5$, $T_9 = T_3 + T_6$, $T_{10} = T_4 + T_5$, $T_{11} = T_4 + T_6$; Pi = Initial population; Pf = Final population; Rf = Reproductive factor (Pf/Pi), ha = hectare, J_2 = Juveniles.

4. Discussion

Brinjal is susceptible to the infection of several species of RKN (Anwar and Mckenry, 2010). Cultivation of resistant cultivars is one of the most desirable components of integrated pest management (Barzman et al., 2015). In this experiment, twenty brinjal cultivars were evaluated for their responses to infection by *M. javanica*. Of the twenty cultivars, only 'Noagram' was found to be 'moderately resistant', and the responses of the rest of the cultivars were 'susceptible' to 'highly susceptible'. These findings are supported by two similar screening experiments conducted in Bangladesh and India, where very few brinjal cultivars were found to have significant resistance to RKN (Begum et al., 2014; Akhter and Khan, 2018). In most screening trials, RKN is considered a generalized pest, although the combination of crop and pest species plays an important role in the outcome of resistance or susceptibility. In a moderately resistant plant, nematodes fail to produce enough functional feeding sites in the host leading to the failure of developing reproducing females (Williamson and Kumar, 2006). For decades, *Solanum peruvianum* derived *Mi* gene has been the only source for conferring resistance to *M. incognita*, *M. javanica,* and *M. arenaria* in all commercial tomato cultivars (Seid et al., 2015). Some other resistance genes have also been identified in other crops that are effective against RKN e.g., *Me* and *N* genes from pepper, and *Mj* gene in carrot (Ali et al., 2014). However, there have been no reports of a resistance gene in brinjal. Therefore, the findings of this experiment should be useful for further research on resistance screening against *M. javanica* in brinjal plants as well as other solanaceous crops.

In the pot trial, the effect of the individual applications of crushed marigold leaves (T_1) on egg masses, eggs, and J_2's in soil was statistically similar to the positive control (T_7). Similarly, the R_f of the nematode population (0.7) for this treatment was close to the positive control (0.67) in the field trial. Ploeg (2000) also had similar findings as the application of marigold cultivars gave statistically similar results with methyl iodide fumigation for controlling RKN. Marigold releases alpha-terthienyl, an oxidative stress-inducing chemical, which has nematicidal, insecticidal, antiviral, and cytotoxic properties (Hamaguchi et al., 2019). Although no egg masses, eggs, and J_2's were observed for this treatment (T_1) at 45 DAI in the pot trial, they were present at 90 DAI. It is assumed that over the course of time the influence of chopped marigold leaves on the reproduction of nematodes was reduced as the treatment was applied ten days before transplanting. It was reported that stem extracts were less efficacious than whole *T. erecta* plant extracts and alpha-terthienyl is only released by active, living marigold roots and becomes inactivated on exposure to near-UV light (Ploeg, 2000; Natarajan et al., 2006). Moreover, not all marigold cultivars control all types of nematodes (Krueger et al., 2019). The findings of this experiment showed that the studied growth parameters and yield were not much influenced by the marigold treatment in comparison to the control. Likewise, comparatively lower BCR (2.99) also would rule out marigold as a profitable management option against the RKN infection. In terms of the studied growth, yield, and reproductive parameters, the individual application of crushed cabbage leaves (T_2) produced significantly better results than the control but inferior to some other treatments (T_1, T_5, T_6, T_7) in both pot and field trials. The reason for less efficacy may be explained by the fact that GSL profiles vary among plant species and cultivars, and their ITC derivatives differ in toxicity to nematodes (Zasada and Ferris, 2004). Moreover, the effect of cabbage on PPN could be inconsistent because the enzymatic conversion of GSL to ITC is temperature-dependent (Lazzeri et al., 2009). In a similar experiment, Youssef and Lashein (2013) did not find an increase in plant growth parameters due to the immediate phytotoxicity exerted by the brassica. They suggested that quick decomposition, rapid evaporation and partial loss of volatile compounds after removing the plastic sheet during the transplanting process and before nematode inoculation could limit the efficacy of *Brassica* crops in controlling PPN. In the field trial, comparatively lower BCR (2.96) was estimated for this treatment (T_2) which

Table 8. Benefit-Cost Ratio (BCR) of brinjal cultivation with the application of biocomponents to manage *Meloidogyne javanica* in a farmer's field.

Treatment	Seed cost (Tk/ha)	Plowing Cost (Tk/ha)	Labour Cost (Tk/ha)	Fertilizer Cost (Tk/ha)	Irrigation Cost (Tk/ha)	Treatment Cost (Tk/ha)	Total Cost (Tk/ha)	%Yield increase Over control	Total Revenue (Tk/ha)	*BCR
T_0	18,000	24,000	1,00,000	10,000	14,000	-	1,66,000	-	4,74,300	2.85
T_1	18,000	24,000	1,00,000	10,000	14,000	11,428	1,77,428	12	5,31,300	2.99
T_2	18,000	24,000	1,00,000	10,000	14,000	11,428	1,77,428	10.81	5,25,600	2.96
T_3	18,000	24,000	1,00,000	10,000	14,000	1.42,850	3,08,850	13.2	5,37,000	1.73
T_4	18,000	24,000	1,00,000	10,000	14,000	71,425	2,37,425	18.65	5,62,800	2.37
T_5	18,000	24,000	1,00,000	10,000	14,000	3,500	1,69,500	15.62	5,48,700	3.23
T_6	18,000	24,000	1,00,000	10,000	14,000	3,500	1,69,500	15.62	5,48,700	3.23
T_7	18,000	24,000	1,00,000	10,000	14,000	4,500	1,70,500	17	5,57,100	3.26
T_8	18,000	24,000	1,00,000	10,000	14,000	1,46,350	3,12,350	70	8,10,000	2.59
T_9	18,000	24,000	1,00,000	10,000	14,000	1,46,350	3,12,350	70	8,10,000	2.59
T_{10}	18,000	24,000	1,00,000	10,000	14,000	74,925	2,40,925	86.59	8,85,000	3.67
T_{11}	18,000	24,000	1,00,000	10,000	14,000	74,925	2,40,925	72.86	8,19,900	3.4

T_0 = Control, T_1 = Marigold leaf, T_2 = Cabbage leaf, T_3 = Vermicompost, T_4 = Biogas Digestate, T_5 = Bacterial suspension of *Bacillus subtilis*, T_6 = Bacterial suspension of *Pseudomonas fluorescens*, T_7 = Rugby 10G (Positive Control), $T_8 = T_3 + T_5$, $T_9 = T_3 + T_6$, $T_{10} = T_4 + T_5$, $T_{11} = T_4 + T_6$; Tk = Bangladeshi Taka/currency; ha = hectare.
* BCR was calculated on a variable cost basis.

suggested that application of cabbage leaves to control *M. javanica* is not a feasible option.

Vermicompost minimizes the use of chemical fertilizers and improves soil quality. Vermicomposts have abundant humic acid substances and hormones such as indole acetic acid (IAA), cytokinins, and gibberellins which could suppress nematode infestation (Oka, 2010). In this experiment, the individual application of vermicompost (T_3) did not have much impact on the reproductive parameters of *M. javanica* in both pot and field trials, although those were significantly lower than control (T_0). Similarly, Mondal et al. (2021) observed that vermicompost exudate did not directly kill nematodes or alter the infectivity of J_2 in rice. There are published results that report a significant reduction in the numbers of nematode-induced galls with the application of vermicompost (Kumar et al., 2011; Xiao et al., 2016). According to Akhtar and Alam (1993), the effect of vermicompost on PPN depends on many factors, e.g., the type and ingredient of organic amendments, the dose, soil structure, nematode species, etc. Although reproductive parameters were largely unaffected by the individual application of vermicompost, growth parameters of the brinjal plants were found significantly higher than the control and some other treatments in this experiment. Kumar et al. (2011) found that a vermicompost fortification treatment resulted in increased growth characteristics with increases in sugar, protein, and lipid content. However, due to the requirement of a high amount of vermicompost to cultivate a unit area of land, production cost was higher for this treatment (T_3) leading to a lower BCR (1.73). Hence, the individual application of vermicompost might not be considered profitable for the control of RKN. Similarly, the results of this experiment do not support the application of BD to mitigate the infection by RKN, as this treatment (T_4) resulted in mixed results. It was found in this experiment that most of the reproductive parameters of RKN were significantly lower than the control (T_0) and vermicompost (T_3), but higher than the positive control (T_7) in both the pot and field trial, and yield and BCR (2.37) were higher than vermicompost (T_3) for the individual application of BD (T_4). Ammonium and acetic acid ingredients of BD were proposed as the possible mechanisms of reducing PPN (Min et al., 2007) which is partly in agreement with the results of this experiment. However, the lower purchasing cost of BD contributed to the higher BCR than for vermicompost in this study.

In this experiment, two rhizosphere bacteria *B. subtilis* and *P. fluorescens* were applied individually (T_5 and T_6) and in combination with vermicompost and BD (T_8, T_9, T_{10}, and T_{11}) in both pot and field trials. In several preliminary *in vitro* experiments, it was found that *B. subtilis* and *P. fluorescens* strongly influenced the mortality and hatching of *M. javanica*, however, the pattern of influence of two organic amendments (vermicompost and BD) on the nematode was inconsistent (Das et al., 2021a; 2021b). On the basis of these findings, organic amendments were integrated with the two bacteria in these trials. Different reproductive parameters (gall number, egg mass number, egg number, no. of J_2's) were the lowest among all treatments and statistically similar to the positive control (T_7) for the individual application of both of the bacterial treatments in the pot trials. Similarly, Morgado et al. (2015) also observed that the nematicidal potential of *B. subtilis* was equivalent to that of the carbofuran treatments against *M. incognita*, *M. javanica,* and *P. zeae* in sugarcane. Borrajo et al. (2021) studied the biocontrol of the nematode *M. javanica* using several strains of *P. fluorescens* and *Bacillus* sp. and found that most of the tested strains reduced egg hatching and juvenile survival, however, juvenile mortality was higher when *M. javanica* was exposed to *Bacillus* spp. than to *Pseudomonas* spp. Berlitz et al. (2014) reported that *B. subtilis* reduced the number of eggs and J_2's of *M. javanica* by producing antibiotics and hydrolytic enzymes which acted on the fecundity and fertility of the nematode. On the other hand, *Pseudomonas* spp. produce iron-chelating siderophores, antibiotics, and/or hydrogen cyanides that limit deleterious and pathogenic rhizosphere microorganisms (Dejene, 2014). In the pot trial, there were no egg masses, eggs, and J_2's at 45 DAI, but they did occur at 90 DAI in the individual bacterial treatments (T_5 and T_6). This may have happened as some species of RKN undergo diapause under stressful conditions and resume activity when favorable conditions return (Wright and Perry, 2006). However, in the combined treatments (T_8, T_9, T_{10}, and T_{11}) reproductive parameters were higher than the individual application of bacterial suspension in pot trials, whereas, R_f was lower in the field. The microenvironment of a pot is different than the field and the mixing of two components might not have worked synergistically in that limited space. Both in the pot and field trials, growth parameters were statistically similar for the individual and combined treatments of bacterial suspension, whereas, the yield was significantly higher in the combined treatments compared to the individual bacterial treatments. Nath and Singh (2011) reported increased production of cauliflower after applying organic amendments with biopesticides which is in agreement with the findings of this study. Serfoji et al. (2010) tested the effectiveness of organic amendments and rhizotrophic rhizosphere microorganisms for the management of *M. incognita* on tomatoes. It was found that organic amendments in combination with *Bacillus coagulans* significantly increased the growth, biomass, and nutrients of tomatoes and decreased the RKN population and root-knot index. The use of organic amendments with biopesticides is helpful to compensate for the deficiency of nutrients in the soil as well as to

control PPN (Nath and Singh, 2011). Among the combined treatments, the combination of BD and *B. subtilis* (T_{10}) had the highest yield and BCR (3.67) with the lowest R_f. Among the plant growth-promoting rhizobacteria, *Bacillus* spp. has several benefits compared to other rhizobacteria. For example, *Bacillus* is omnipresent within the rhizosphere, endospore-forming, and highly resistant to heat, desiccation, and chemical destruction (Abu-Elgawad and Askary, 2018). In addition, BD contains considerable amounts of mineral elements (nitrogen, phosphorus, potassium) and organic matter that serves as a bio-fertilizer to stimulate crop yields (Koszel and Lorencowicz, 2015). Arshad et al. (2021) reported that the combined application of biochar and *B. subtilis* effectively managed RKN, enhanced overall plant biomass, and triggered defense-related genes in tomato plants. This finding supports the superior performance of the combined application of BD and *B. subtilis* obtained in this experiment, as both biochar and BD are produced by anaerobic digestion (Koszel and Lorencowicz, 2015).

In this work, several biorational components either individually or in combination were evaluated against infection of *M. javanica* of brinjal with regards to their efficacy and economic benefit. Results revealed that the combined treatments were better than the individual applications in terms of efficacy and profitability. The highest yield and BCR of brinjal were obtained by the combined application of biogas digestate and *B. subtilis* with the lowest R_f of *M. javanica*. To the best of our knowledge, this is the first report on a profitability assessment of BD in combination with a bio-agent in addressing the management of RKN which is important in the backdrop of the global concern for environmental pollution. However, further research on the ingredients of BD would be helpful to develop a more effective product. Brinjal cv. Noagram was found to be 'moderately resistant' and this could be a potential source of resistant genes against RKN.

Declarations

Author contribution statement

Sukalpa DAS: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Md. Abdul WADUD; Shila CHAKRABORTY: Performed the experiments; Contributed reagents, materials, analysis tools or data.

Md. Atiqur Rahman KHOKON: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

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Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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