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Management of root-knot nematodes (*Meloidogyne* spp.) in capsicumusing biofumigant crops under protected cultivation

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Abstract
A trial on capsicum was conducted under protected cultivation to test the efficacy of various biofumigant crops *viz*., cabbage, cauliflower, mustard, radish and broccoli, @ 25 t/ha with a view to manage the root-knot nematodes (*Meloidogyne* spp.) at Department of Nematology, B. A. College of Agriculture, Anand Agricultural University, Anand (Gujarat) during 2022-23 and 2023-24. Maximum reduction in root-knot index (RKI), number of females, egg masses, eggs, soil and final nematode population with maximum yield was obtained in the bed treated with mustard 25 t/ha followed by radish 25 t/ha.

Keywords: Biofumigation, capsicum, glucosinolates (GSLs), isothiocyanates (ITCs), root-knot nematodes

Introduction
Capsicum (*Capsicum* spp.), also called as pepper, is a main vegetable and spice crop originated in the American tropics and cultivated all over the world for fresh, dried, and processing products. Around the genus Capsicum there is an increasing interest and fascination due to the considerable variation for several traits, which makes this crop extremely versatile and suitable for innumerable uses as food and non-food products. Protected cultivation of high-value vegetable crops such as capsicum has emerged as a viable approach to enhance productivity, quality and resource-use efficiency, particularly in regions with climate variability (Singh *et al*., 2019) [12]. However, soil-borne pests, notably root-knot nematodes (*Meloidogyne* spp.), pose a serious challenge under protected cultivation, leading to significant yield losses. These obligate, sedentary endoparasites induce characteristic root galls, impair water and nutrient absorption, reduce plant vigour and predispose the host to secondary infections (Sikora *et al*., 2005; Moens *et al*., 2009) [11, 8]. The conducive warm and moist microclimate in protected environments further aggravates nematode multiplication and pathogenicity (Gaur *et al*., 2016) [4].
While synthetic nematicides have long been used to manage nematodes, their environmental toxicity, residual hazards and restrictions on use in protected cultivation necessitate the adoption of sustainable alternatives (Noling & Becker, 1994) [9]. In this regard, biofumigation, an eco-friendly cultural practice involving the use of glucosinolates rich Brassicaceae plants offers a promising solution. Upon tissue degradation, these plants release isothiocyanates and related volatile compounds with strong biocidal activity against nematodes, fungi and other soil-borne pathogens (Kirkegaard & Matthiessen, 2004; Matthiessen & Kirkegaard, 2006) [5, 6].
Several studies have demonstrated the nematode-suppressive potential of biofumigant crops such as mustard (*Brassica juncea*), radish (*Raphanus sativus*) and cabbage (*Brassica oleracea*) under open field conditions (Zasada & Ferris, 2004; Mian *et al*., 2008) [13, 7]. However, there is a paucity of data on their effectiveness under protected cultivation, where soil conditions, organic matter turnover and microbial interactions differ considerably. Furthermore, the selection of suitable biofumigant species and optimal biomass incorporation timing are crucial for maximizing isothiocyanate release and nematode suppression.
In this context, the present investigation was undertaken to evaluate the efficacy of selected biofumigant crops in managing *Meloidogyne* spp. infecting capsicum under polyhouse conditions. The study aims to contribute to the development of an integrated nematode

management strategy that is sustainable, environmentally safe and compatible with high-value vegetable production systems under protected cultivation.

Materials and Methods

Green biomass of cabbage, cauliflower, mustard, radish and broccoli were collected and chopped into small pieces. Thereafter, immediately freshly chopped green biomasses were incorporated in the beds under polyhouse. After beds were irrigated, it was covered with plastic film to conserve moisture. Thereafter, plastic was removed after 15 days, tilling of soil was done in order to allow the gases to evaporate from soil and transplanting of seedlings was carried out.

The trial comprised treatments of biofumigation with cabbage, 25 t/ha (6.075 kg/bed), cauliflower, 25 t/ha (6.075 kg/bed), mustard, 25 t/ha (6.075 kg/bed), radish, 25 t/ha (6.075 kg/bed), broccoli, 25 t/ha (6.075 kg/bed) and untreated control. Thus, six treatments were tried in Completely Randomized Design (CRD) with three repetitions. Root-knot susceptible capsicum variety *Indra* was transplanted in each bed of 0.9 x 2.7 m size and spacing 45 x 30 cm. All recommended agronomical practices were followed during the entire experimentation. Periodically picking of capsicum fruit was done and final fruit yield was recorded and same was used in statistical analysis.

Results and Discussion

To evaluate the impact of various biofumigant crops on the management of *Meloidogyne* spp. in capsicum, several biofumigant crops, including cabbage, cauliflower, mustard, radish and broccoli were tested @ 25 t/ha in a polyhouse with a mixed population of root-knot nematodes (*M. incognita* and *M. javanica*) during 2022-23 and 2023-24.

The data presented in Tables 1, 2 and 3 revealed significant variations in measured parameters, including root-knot index, final nematode population and fruit yield, due to the effects of the different treatments.

Initial nematode population

The data depicted in Table 1 regarding the initial nematode population indicated no significant differences across all treatments during both years, as well as in the pooled analysis, suggesting a uniform distribution of nematodes prior to the application of the various treatments. While the year effect was significant, the interaction between treatment and year (TxY) was not significant.

Nematode population at the time of transplanting

The data presented in Table 1 illustrated the effect of biofumigant crops on the nematode population at the time of transplanting capsicum under polyhouse conditions during the years 2022-23, 2023-24 and the pooled analysis. The results for nematode population at transplanting showed significant variations among the biofumigant crops across both years and in the pooled data.

Among the biofumigant crops, green biomass of mustard (T_3) recorded the lowest soil nematode population (35 J_2/200 cc soil) at the time of transplanting, followed by green biomass of radish (T_4) with 46 J_2/200 cc soil. The green biomass of cabbage (T_1), green biomass of cauliflower (T_2) and green biomass of broccoli (T_5) treatments were statistically at par to each other in 2022-23.

More or less same trend was observed in 2023-24 and in the pooled data, reflecting consistent and significant results of the treatments across both years.

Root-knot index

The data on the root-knot index presented in Table 2 revealed significant differences among the various biofumigant crops during both 2022-23 and 2023-24 as well as in the pooled analysis. The year effect was significant, while the treatment-by-year interaction was non-significant.

In 2022-23, among the biofumigant crops, the lowest RKI (2.66) was observed in the green biomass of mustard treatment (T_3) followed by green biomass of radish (T_4), green biomass of cabbage (T_1) and cauliflower (T_2). The highest RKI (5.00) was recorded in the control treatment (T_6).

During 2023-24 and pooled analysis, a similar trend was observed as green biomass of mustard (T_3) again proved the most effective treatment, exhibiting the lowest RKI, indicating continued nematode suppression over the year.

Root population

Number of females

The data presented in Table 2 on the number of females revealed significant variations among the biofumigant crops. The year effect was significant, while the TxY interaction was non-significant.

During 2022-23, all biofumigant treatments differed notably from one another, with the lowest number of females (122) recorded in beds treated with green biomass of mustard (T_3), which was at par with green biomass of radish [(T_4) (155)]. Subsequent treatments in effectiveness were green biomass of cabbage (T_1), cauliflower (T_2) and broccoli (T_5). The highest number of females (341) was observed in the untreated control (T_6). A similar trend was evident in 2023-24 and in the pooled analysis. Treatments with green biomass of mustard (T_3) and radish (T_4) significantly reduced the number of females in both individual years and pooled results compared to the control.

Number of egg masses and number of eggs/egg mass

The results regarding the number of egg masses and eggs followed a more or less similar pattern to the number of females observed during 2022-23 and 2023-24. In pooled results, among the treatments, the beds treated with green biomass of mustard recorded the fewest egg masses (24) followed by the green biomass of radish [(T_4) (33)]. The beds treated with green biomass of cabbage (T_1), cauliflower (T_2) and broccoli (T_5) as well as control remained at par with each other. Minimum No. of eggs recorded in T_3 and T_4 treated beds followed by green biomass of cabbage and cauliflower. The beds treated without treatment [(control) (T_6)] showed the highest number of eggs (851) and remained at par with T_5 [(724) (Table2)].

As with the number of females, the number of egg masses and eggs per 5g of root was significantly lower in all treatments compared to the control in both 2022-23, 2023-24 and the pooled analysis, highlighting the efficacy of the biofumigant crops in reducing the nematode population.

Soil nematode population (J_2/200 cc Soil)

Significant differences in soil nematode population were observed among the biofumigant crops during 2022-23, 2023-24 and the pooled results (Table 3).

In 2022-23, the application of various biofumigant crops led to a notable reduction in soil nematode population. The lowest nematode population was recorded in the plots treated with green biomass of mustard (166) followed by radish (253). The beds treated with green biomass of cabbage (370), cauliflower (322) and broccoli (580) showed relatively lower effectiveness in managing nematodes. The beds without treatment (control) had the highest soil nematode population (970). All biofumigant crops significantly reduced the soil nematode population compared to the control.

More or less similar trend was observed in 2023-24 and in the pooled data across both years.

Final nematode population

There was a significant decrease in the final nematode population due to the application of various biofumigant crops during both years of the study. In 2022-23, the lowest final nematode population was observed in the beds treated with green biomass of mustard [(616) (T_3)] followed by radish (826). Beds treated with green biomass of cabbage (T_1), cauliflower (T_2) and broccoli (T_5) were less effective than mustard and radish in reducing the nematode population. The highest final nematode population (2222) was recorded in the untreated beds (T_6).

The same trends were observed in 2023-24 and in the pooled data across both years (Table 3). The pooled data revealed that the final nematode population was recorded as follows: beds treated with green biomass of mustard (646), radish (832), cabbage (1175), cauliflower (1288) and broccoli (1862).

Fruit yield (t/ha)

The data shown in Table 3 revealed significant differences among the treatments for fruit yield in both 2022-23, 2023-24 and pooled analysis.

In terms of yield, the maximum fruit yield was recorded for the various biofumigant crops. In 2022-23, the maximum yield was observed in the plot treated with green biomass of mustard (T_3) at 59.33 t/ha, followed by green biomass of radish (T_4) with 51.48 t/ha. The next best treatment was green biomass of cauliflower (47.35) and cabbage (45.24) and it was at par with broccoli (37.45).

In 2023-24, a similar pattern was observed, with green biomass of mustard treatment again being the most effective in suppressing the nematode population. The pooled data for both years showed yield of 60.33 for green biomass of mustard, 52.48 for green biomass of radish, 46.31 for green biomass of cabbage, 48.13 for green biomass of cauliflower and 38.12 for green biomass of broccoli. The control treatment recorded the minimum yield (37.67).

These trends were consistent across the pooled data. The results indicated that, among the biofumigant crops tested, green biomass of mustard (T_3) and radish (T_4) were the most effective in enhancing plant growth, development and reducing nematode population. The maximum fruit yield (59.83) was observed in the plot treated with green biomass of mustard (T_3). There was a significant difference between the green biomass of mustard (T_3) and radish (T_4) treatments followed by cauliflower (47.74) and cabbage (45.78). The minimum fruit yield was recorded in the green biomass of broccoli (37.79) and untreated control (36.74) which was statistically similar. In our study, green biomass of mustard and radish were effective in suppressing *Meloidogyne* spp. activity.

Till date, there have been no reports on the effects of biofumigant crops for managing nematodes in capsicum under protected cultivation. However, earlier studies provide insights into the potential of biofumigation in other crops. Anita *et al.* (2011) [1] reported that gerbera crops grown in beds biofumigated with mustard exhibited a significantly lower nematode population in the soil. Similarly, Patel *et al.* (2024) [10] demonstrated the significant impact of bed treated with mustard 25t/ha followed by radish 25t/ha in reducing root-knot index, soil nematode population and the number of females. The findings of this study align with previous results reported by El-Nagdi & Youssef (2019) [3] and Anonymous (2021) [2], further confirming the efficacy of biofumigation in managing soil-borne pathogens and nematodes. These findings highlighted the potential of biofumigants as an effective strategy for nematode management.

Table 1: Effect of biofumigant crops on nematode population at the time of transplanting during 2022-23 and 2023-24

Treatments (Biofumigation with)		Nematode population in soil (J_2/200 cc soil)					
		Initial			At the time of transplanting		
		2022-23	2023-24	Pooled	2022-23	2023-24	Pooled
T_1	Cabbage, 25t/ha	2.27 (188)	2.31 (202)	2.29 (195)	1.84 (70)	1.76 (58)	1.81 (65)
T_2	Cauliflower, 25t/ha	2.30 (202)	2.29 (196)	2.30 (200)	1.79 (62)	1.73 (54)	1.76 (58)
T_3	Mustard, 25t/ha	2.29 (196)	2.33 (212)	2.31 (204)	1.54 (35)	1.44 (28)	1.49 (31)
T_4	Radish, 25t/ha	2.28 (189)	2.29 (193)	2.28 (191)	1.66 (46)	1.61 (41)	1.64 (44)
T_5	Broccoli, 25t/ha	2.29 (197)	2.30 (202)	2.29 (195)	1.91 (82)	1.87 (75)	1.90 (79)
T_6	Control	2.29 (196)	2.28 (191)	2.29 (195)	2.23 (171)	2.18 (152)	2.21 (160)
S. Em.±	T	0.01	0.01	0.01	0.03	0.03	0.02
	Y	-	-	0.01	-	-	0.01
	T x Y	-	-	0.01	-	-	0.03
CD at 5%	T	NS	NS	NS	0.08	0.07	0.05
	Y	-	-	NS	-	-	Sig.
	T x Y	-	-	NS	-	-	NS
CV (%)		0.59	1.08	0.87	2.48	2.76	2.91

Note: 1. NS= Non significant, Sig.= Significant

2. Figures in parentheses are re-transformed values of log transformation.

Table 2: Effect of biofumigant crops on root-knot index, number of females, egg masses and eggs/egg mass during 2022-23 and 2023-24

Treatments (Biofumigation with)		Root-knot index (0-5 scale) at harvest*			Nematode population/5 g roots								
					Number of females			Number of egg masses			Number of eggs/egg mass		
		2022-23	2023-24	Pooled	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled
T_1	Cabbage, 25t/ha	1.93 (3.73)	1.94 (3.77)	1.94 (3.76)	2.36 (231)	2.41 (257)	2.39 (245)	1.66 (47)	1.67 (46)	1.66 (46)	2.70 (501)	2.71 (516)	2.71 (513)
T_2	Cauliflower, 25t/ha	2.00 (4.00)	2.05 (4.20)	2.02 (4.08)	2.47 (292)	2.46 (291)	2.46 (288)	1.62 (42)	1.65 (45)	1.64 (44)	2.74 (556)	2.75 (565)	2.75 (562)
T_3	Mustard, 25t/ha	1.63 (2.66)	1.66 (2.76)	1.65 (2.72)	2.09 (122)	2.08 (119)	2.08 (120)	1.39 (24)	1.36 (23)	1.38 (24)	2.48 (302)	2.52 (335)	2.50 (316)
T_4	Radish, 25t/ha	1.91 (3.66)	2.00 (3.99)	1.96 (3.84)	2.19 (155)	2.17 (149)	2.18 (151)	1.52 (33)	1.50 (31)	1.52 (33)	2.58 (380)	2.59 (388)	2.58 (380)
T_5	Broccoli, 25t/ha	2.16 (4.66)	2.20 (4.83)	2.18 (4.75)	2.50 (316)	2.48 (302)	2.49 (309)	1.72 (53)	1.70 (51)	1.71 (51)	2.89 (769)	2.83 (684)	2.86 (724)
T_6	Control	2.24 (5.00)	2.24 (5.00)	2.24 (5.00)	2.53 (341)	2.51 (320)	2.52 (331)	1.77 (59)	1.78 (60)	1.77 (58)	2.93 (848)	2.93 (857)	2.93 (851)
S. Em. ±	T	0.03	0.04	0.03	0.03	0.03	0.02	0.03	0.03	0.02	0.04	0.04	0.03
	Y	-	-	0.02	-	-	0.01	-	-	0.01	-	-	0.02
	T x Y	-	-	0.04	-	-	0.03	-	-	0.03	-	-	0.04
CD at 5%	T	0.10	0.13	0.08	0.11	0.09	0.07	0.09	0.11	0.07	0.11	0.13	0.08
	Y	-	-	Sig.	-	-	Sig.	-	-	Sig.	-	-	Sig.
	T x Y	-	-	NS	-	-	NS	-	-	NS	-	-	NS
CV (%)		2.80	3.56	3.21	2.56	2.14	2.36	3.25	3.69	3.48	2.38	2.63	2.51

Note: 1. 0 = Free; 5 = Maximum disease intensity, NS= Non-significant, S= Significant

2. *Figures in parentheses are re-transformed values of ($\sqrt{x+0.5}$)

3. Figures in parentheses are re-transformed values of log X

Table 3: Effect of biofumigant crops on soil, final nematode population and fruit yield during 2022-23 and 2023-24

Treatments (Biofumigation with)		Soil nematode population			Final nematode population (Soil + Root)			Fruit yield (t/ha)		
		2022-23	2023-24	Pooled	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled
T_1	Cabbage, 25t/ha	2.57 (370)	2.59 (390)	2.58 (380)	3.06 (1151)	3.08 (1202)	3.07 (1175)	45.24	46.31	45.78
T_2	Cauliflower, 25t/ha	2.51 (322)	2.63 (428)	2.57 (372)	3.09 (1219)	3.13 (1349)	3.11 (1288)	47.35	48.13	47.74
T_3	Mustard, 25t/ha	2.22 (166)	2.25 (179)	2.24 (174)	2.79 (616)	2.83 (676)	2.81 (646)	59.33	60.33	59.83
T_4	Radish, 25t/ha	2.40 (253)	2.41 (257)	2.40 (255)	2.92 (826)	2.93 (851)	2.92 (832)	51.48	52.48	51.98
T_5	Broccoli, 25t/ha	2.76 (580)	2.96 (912)	2.86 (724)	3.24 (1725)	3.31 (2042)	3.27 (1862)	37.45	38.12	37.79
T_6	Control	2.99 (970)	3.00 (1011)	3.00 (1001)	3.35 (2222)	3.40 (2512)	3.37 (2344)	35.81	37.67	36.74
S. Em. ±	T	0.05	0.05	0.04	0.03	0.02	0.02	2.16	2.42	1.59
	Y	-	-	0.02	-	-	0.01	-	-	0.91
	T x Y	-	-	0.05	-	-	0.03	-	-	2.29
CD at 5%	T	0.17	0.17	0.11	0.10	0.06	0.06	6.66	7.46	4.63
	Y	-	-	Sig.	-	-	Sig.	-	-	Sig.
	T x Y	-	-	NS	-	-	NS	-	-	NS
CV (%)		3.64	3.06	3.35	1.82	1.10	1.50	8.11	8.89	8.52

Note: 1. 0 = Free; 5 = Maximum disease intensity, NS= Non-significant, S= Significant
2. Figures in parentheses are re-transformed values of log x

Conclusion

From the above result of the two years, it can be deduced that mustard and radish found as most effective biofumigant crops for management of root-knot nematodes infecting capsicum under protected cultivation.

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Conflict of Interest

All authors declared that they have no conflicts of interest.

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