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Field evaluation of the entomopathogenic fungus Metarhizium anisopliae (Metschnikoff) Sorokin delivered through organic soil amendments against the subterranean termites Odontotermes obesus (Rambur) and Microtermes obesi Holmgren (Blattodea: Termitidae) in wheat

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Field evaluation of the entomopathogenic fungus *Metarhizium anisopliae* (Metschnikoff) Sorokin delivered through organic soil amendments against the subterranean termites *Odontotermes obesus* (Rambur) and *Microtermes obesi* Holmgren (Blattodea: Termitidae) in wheat

Abstract

Background: Subterranean termites, mainly *Odontotermes obesus* (Rambur) and *Microtermes obesi* Holmgren, attack the roots and underground stem of wheat on the light soils of north Gujarat, India and are usually controlled with soil-applied insecticides. This study examined whether the entomopathogenic fungus *Metarhizium anisopliae* (1×10^8 CFU/g, 2 kg/ha) gives better control when it is delivered through an organic soil amendment. Seven amendments (farmyard manure, vermicompost, mustard cake, castor cake, tobacco dust, neem cake and poultry manure) were each mixed with the fungus and applied at land preparation. They were compared with the fungus on sand, as an inert carrier and an untreated control. The trial ran for two *rabi* seasons (2024–25 and 2025–26) in a randomized block design with three replications and means were compared by Tukey's HSD test.

Results: No treatment affected germination. Pooled plant damage was lowest with neem cake + *M. anisopliae* (3.94%) and vermicompost + *M. anisopliae* (5.15%), which were statistically at par, against 18.45% in the control. Neem cake + *M. anisopliae* also had the fewest termites on bait sticks (7.06 against 42.93 per stick). The fungus on sand reduced damage only to 15.35%. Grain yield was highest with neem cake (4295 kg/ha) and vermicompost (4250 kg/ha), against 2745 kg/ha in the control and yield fell by about 104 kg/ha for every 1% increase in plant damage ($r = -0.97$, $P < 0.001$). Poultry manure + *M. anisopliae* (ICBR 1:7.9) and vermicompost + *M. anisopliae* (1:6.7) gave the best return on cost.

Conclusions: *Metarhizium anisopliae* controlled termites in wheat much better when it was applied with an organic carrier than with sand. Vermicompost and poultry manure combined good protection with low cost and neem cake gave the strongest protection at a higher price. Because the amendments were not tested without the fungus, the contribution of each component needs to be separated in further trials.

Keywords: Biological control, Entomopathogenic fungi, *Metarhizium anisopliae*, Neem cake, Organic amendments, Subterranean termites, Vermicompost, Wheat

Background

Wheat (*Triticum aestivum* L.) supplies about a fifth of the calories and protein eaten worldwide (Shiferaw et al. 2013) and in north Gujarat it is the main *rabi* cereal, grown largely under irrigation on loamy sand. On these light soils with little organic matter, termites are among the most persistent soil pests of the crop. Fungus-growing termites of the genera *Odontotermes* and *Microtermes* are the main termite pests of field crops in dry tropical regions (Rouland-Lefèvre 2011) and in north-western India *O. obesus* (Rambur) and *M. obesi* Holmgren are the species most often found in cereal fields (Rajagopal 2002). Workers tunnel into the roots and the underground part of the stem. Attacked plants wilt and dry, come out of the soil easily and are lost in patches that widen as the crop matures. Because the damage happens below ground, it is usually noticed only after the plants are already lost.

Farmers still rely mainly on insecticides applied to the seed or the soil to protect wheat from termites (Rouland-Lefèvre 2011). These treatments work, but concerns about residues in soil and water, about harm to non-target soil fauna and about the withdrawal of persistent termiticides have kept interest in alternatives alive. These alternatives include botanical products, entomopathogens and cultural measures (Verma et al. 2009).

Metarhizium anisopliae (Metschnikoff) Sorokin is the entomopathogenic fungus most often tested against termites. Its conidia attach to the cuticle, germinate and penetrate the body and the host dies of mycosis (Lacey et al. 2015). Isolates highly virulent to termites have been selected in several countries (Milner et al. 1998; Wright et al. 2005) and their use has been reviewed repeatedly (Rath 2000; Hassan et al. 2024). The field record, however, is much weaker than the laboratory record. Termites groom conidia off one another (Yanagawa et al. 2009), isolate or bury infected nestmates and avoid treated soil (Culliney and Grace 2000).

Conidia also lose viability quickly in hot, dry soil (Jaronski 2010). After five decades of attempts, Chouvenc et al. (2011) concluded that applying the fungus directly against termite colonies had rarely given dependable control.

One way to improve field performance is to change how the fungus reaches the soil. An organic amendment may give the conidia a food base and a moister microhabitat in sandy soil. Some amendments, such as neem cake, also act on termites directly because of their repellent and antifeedant compounds (Isman 2006; Verma et al. 2009). At the same location, Patel et al. (2022) found that *M. anisopliae* applied with vermicompost, castor cake or neem cake clearly reduced white grub damage in groundnut. To our knowledge, a similar comparison has not been made for termites in wheat. This study therefore compared seven organic amendments and sand as an inert carrier, as vehicles for *M. anisopliae* against termites in wheat over two seasons. We measured their effects on crop establishment, plant damage, termite activity, yield and economic return.

Methods

Experimental site

Crop and experimental design

Wheat cv. GW 513 was sown during the *rabi* seasons of 2024–25 and 2025–26 at a seed rate of 120 kg/ha, with 22.5 cm between rows and 10 cm between plants. Fertilizer was applied at 90:60:00 kg N:P_2O_5:K_2O/ha. The trial was laid out in a randomized block design with nine treatments and three replications. Gross plots measured 4.50 m × 3.60 m and net plots 4.05 m × 3.20 m. All recommended agronomic practices were followed and no insecticide was applied to any plot.

Treatments and application

The nine treatments are listed in Table 1. A commercial formulation of *M. anisopliae* containing 1×10^8 CFU/g was used at 2 kg/ha in every treatment except the control. The fungus was mixed with the respective amendment 7 days before sowing and the mixture was applied to the soil at final land preparation. All amendments were applied at 1 t/ha, except farmyard manure (FYM), which was applied at the usual field rate of 10 t/ha. Sand (100 kg/ha) was used as an inert carrier, so that the fungus applied without organic matter could be compared with the fungus delivered through an amendment.

Observations

Germination. Emerged seedlings were counted in 1 m of row in each plot 7 days after sowing and expressed as a percentage of the seeds sown in that length of row.

Tillers. The number of tillers was recorded on ten randomly selected plants in each plot.

Plant damage. Healthy plants and plants damaged by termites were counted in 1 m of row in each plot at weekly intervals from the 5th to the 14th week after sowing. Plant damage (%) was calculated as the number of damaged plants divided by the total number of plants observed, multiplied by 100.

Termite activity. Twenty-five wooden eucalyptus sticks were buried 15 cm deep after sowing and examined weekly from the 1st to the 14th week after sowing. The termites on each stick were counted and sticks that had been eaten were replaced. Termite activity is expressed as the number of termites per stick.

Yield. Grain and straw were harvested from the net plot and converted to kg/ha. The increase in yield over the control was calculated as $(Y_t - Y_c)/Y_c \times 100$. The avoidable loss was calculated as $(Y_{max} - Y_t)/Y_{max} \times 100$, where Y_t is the yield of the treatment, Y_c the yield of the control and Y_{max} the highest yield among the treatments.

Economics. Gross return was calculated from pooled grain and straw yields at ₹ 25/kg grain and ₹ 8/kg straw. Net return was the gross return minus the cost of treatment (Table 1).

Net gain was the net return of a treatment minus the gross return of the control. The incremental cost–benefit ratio (ICBR) was the net gain divided by the cost of treatment, expressed as 1:x.

Statistical analysis

Percentage data were arcsine-transformed and termite counts were transformed to $\sqrt{(x + 0.5)}$ before analysis. Data from each observation were analysed by analysis of variance for a randomized block design. Data pooled over observation periods and over the two seasons were analysed as a factorial randomized block design (Gomez and Gomez 1984). Treatment means were separated by Tukey's honestly significant difference (HSD) test at $P \leq 0.05$ (Tukey 1949), using the error mean square of the respective analysis. The relationships of pooled plant damage with grain yield and with termite numbers were examined by linear regression on treatment means ($n = 9$).

Results

Germination and tillering

Germination did not differ significantly among treatments in either season. It ranged from 84.00 to 88.33% in 2024–25 and from 83.67 to 87.33% in 2025–26 (Table 2), so applying the amendments and the fungus at land preparation did not harm crop establishment. Tillering did respond to the treatments. Neem cake + *M. anisopliae* had the most tillers in both seasons (3.83 and 4.07 per plant), at par with FYM, castor cake and mustard cake with the fungus. The control had the fewest tillers (2.40 and 2.17 per plant) and sand + *M. anisopliae* did not differ from it in either season.

Plant damage

Termite damage built up steadily through both seasons, but its pattern differed between years (Fig. 1). In 2024–25, damage in the control increased almost linearly from 2.32% in the 5th week to 38.10% in the 14th. In 2025–26, damage stayed low until about the 9th week and

then rose sharply, reaching 29.62% by the 11th week. Neem cake + *M. anisopliae* kept damage below 10% until the 13th week in both seasons. In 2025–26, damage in this treatment was still under 3% in the 10th week, when the control already had 22.92% (Additional file 1: Tables S1, S2).

The treatments ranked in nearly the same order in both seasons (Table 3). Neem cake + *M. anisopliae* had the least damage each year (4.70% and 3.25%) and it was statistically at par with vermicompost + *M. anisopliae* (6.25% and 4.14%). Pooled over both seasons, damage was 3.94% with neem cake, 5.15% with vermicompost, 6.47% with castor cake and 8.91% with poultry manure, against 18.45% in the control (Fig. 2a). These four treatments reduced damage by 52–79% compared with the control. Mustard cake and tobacco dust gave the weakest protection among the organic carriers (12.10% and 12.60%). Sand + *M. anisopliae* reduced damage by only 17% (15.35%). This reduction was significant over the two seasons, but in 2024–25 alone sand did not differ from the control.

Termite activity on bait sticks

Termite numbers on the sticks rose through each season in every treatment. In the control, they increased from 8.50 per stick in the 1st week to 92.00 in the 14th week in 2024–25 and from 7.50 to 87.97 in 2025–26 (Additional file 1: Tables S3, S4). Pooled over both seasons, neem cake + *M. anisopliae* had significantly fewer termites than any other treatment (7.06 per stick, an 84% reduction), followed by poultry manure (11.40) and tobacco dust (13.41), which were at par (Table 4; Fig. 2b). FYM + *M. anisopliae* (28.02) and sand + *M. anisopliae* (29.42) were at par and had about two-thirds of the termites recorded in the control (42.93).

The stick counts did not rank the treatments in the same order as plant damage. Tobacco dust had the third-lowest termite count but among the highest damage of the organic carriers. Vermicompost and castor cake, by contrast, protected plants well despite intermediate counts (17.06 and 20.29 per stick). Across treatments, plant damage increased with termite numbers

($r = 0.77$, $P = 0.016$), but termite numbers explained only 59% of the variation in damage (Fig. 4b).

Grain and straw yield

In the pooled analysis, the neem cake, vermicompost, poultry manure, castor cake and mustard cake carriers raised grain yield significantly above the control (2745 kg/ha), whereas FYM, tobacco dust and sand did not (Table 5; Fig. 3a). Neem cake + *M. anisopliae* (4295 kg/ha) and vermicompost + *M. anisopliae* (4250 kg/ha) gave the highest yields, 56.5% and 54.8% more than the control. Poultry manure, castor cake, mustard cake and FYM carriers (3500–3950 kg/ha) did not differ significantly from them. Within each season, only the neem cake and vermicompost treatments differed significantly from the control (Additional file 1: Table S5). Straw yield followed the same order, from 5250 kg/ha with neem cake to 3245 kg/ha in the control. The avoidable loss due to termites was 36.1% of grain yield in the untreated plots and 29.1% in plots that received the fungus on sand.

Grain yield was closely and negatively related to plant damage (Fig. 4a). The regression (yield = 4718 − 104.5 × damage; $r = -0.97$, $R^2 = 0.93$, $P < 0.001$) indicates a loss of about 104 kg/ha of grain for every 1% of plants damaged. This is about 2.4% of the highest yield obtained in the trial.

Economics

The return from each treatment depended as much on the price of the amendment as on the yield gained (Table 6; Fig. 3b). Poultry manure + *M. anisopliae* was the cheapest organic treatment (₹ 4,839/ha) and gave the highest ICBR (1:7.9), followed by vermicompost + *M. anisopliae* (1:6.7). Neem cake + *M. anisopliae* gave the highest gross return (₹ 1,49,375/ha), but because neem cake is expensive its ICBR was only 1:3.0, the same as castor cake. Sand + *M. anisopliae* ranked third (1:4.8), but only because it cost very little; its yield gain was not

significant. Mustard cake (1:0.9) and FYM at 10 t/ha (1:1.3) with the fungus were the least economical.

Discussion

The main finding of this trial is that the carrier mattered more than the fungus alone. The same dose of *M. anisopliae* applied with sand reduced pooled damage by 17% and did not raise yield significantly. Applied with neem cake or vermicompost, it reduced damage by more than 70% and increased grain yield by more than half. Patel et al. (2022) saw a similar pattern against white grub in groundnut on the same farm, where *M. anisopliae* on vermicompost, castor cake or neem cake clearly outperformed the other combinations. The pests and crops were different, but the two studies agree: on these sandy soils, how the fungus is delivered largely decides whether it works.

The weak effect of the fungus on sand matches what is known about *Metarhizium* against termites in the field. Termite colonies groom conidia off nestmates (Yanagawa et al. 2009), remove infected individuals and avoid contaminated soil, which limits the spread of infection (Culliney and Grace 2000; Chouvenc et al. 2011). Conidia applied to soil also lose viability under high temperature, low moisture and solar radiation (Jaronski 2010). Loamy sand during the *rabi* season dries quickly between irrigations and sand gives the fungus nothing to grow on. An organic carrier may let conidia survive longer and possibly multiply, near the roots where termites forage. We did not count the fungus in the soil, so this remains a hypothesis. Counting colony-forming units in the rhizosphere at intervals after application would test it directly.

Neem cake gave the most consistent protection, but not all of its effect can be credited to the fungus. Neem seed products contain limonoids, chiefly azadirachtin, that repel insects and deter feeding (Isman 2006) and neem materials are used on their own against termites (Verma et al. 2009). The low numbers of termites at the sticks in neem cake plots are consistent with

repellence. Since the amendments were not tested without the fungus, the neem cake and fungus effects cannot be separated in this treatment. Vermicompost is more informative in this respect. It has no known strong activity against termites, yet it was statistically as effective as neem cake, which suggests that it improved the survival or activity of the fungus. Mustard cake points the other way. Brassicaceous materials release isothiocyanates that can reduce the survival and infectivity of entomopathogenic fungi (Klingen et al. 2002) and this may explain why mustard cake was one of the weakest carriers despite being the most expensive.

Plant damage, not the stick count, was what determined yield. Grain yield fell almost linearly with damage and damage alone explained 93% of the differences in yield among treatments. Termite numbers at the sticks explained a much smaller share of the damage. A buried stick shows how many workers forage at a piece of wood, not how much they feed on wheat roots. Some amendments, tobacco dust in particular, may have changed where termites foraged without reducing their feeding on the crop. Stick counts were useful for following termite activity through the season, but plant damage and yield are the better grounds for choosing a treatment.

The extra tillers in the best treatments probably reflect better survival of young plants during the early weeks of attack, together with the nutrients supplied by the amendments. *Metarhizium* can also live in plant tissues as an endophyte, transfer insect-derived nitrogen to its host plant (Behie et al. 2012) and influence the growth of wheat (González-Guzmán et al. 2022). We did not test for endophytic colonization, so its contribution here is unknown.

For farmers, the most protective treatment was not the most profitable. Neem cake gave the highest yield, but at ₹ 12,000/t its ICBR (1:3.0) was far below that of poultry manure (1:7.9) and vermicompost (1:6.7). Poultry manure is cheap and widely available in Banaskantha and with the fungus it kept damage below 9% and gave a yield statistically at par with the best treatment. Vermicompost matched neem cake in both damage and yield at about half the cost.

Amendment prices vary between places and years, so the ICBR ranking should be read as a guide rather than a fixed order.

The study has three limitations. Amendment-only treatments were not included, so the effect of each amendment and its interaction with the fungus cannot be estimated. The two termite species were not recorded separately. The trial was done at one site, although over two seasons with different damage patterns. A factorial trial (amendment × with or without fungus) that also counts fungal colony-forming units in the soil and identifies termites to species would answer these questions.

Conclusions

Applying *M. anisopliae* with an organic amendment at land preparation reduced termite damage in wheat on loamy sand far more than applying the fungus with sand. Neem cake and vermicompost carriers gave the lowest damage and the highest yields and were statistically at par. Vermicompost and poultry manure gave the best economic return. Where these materials are available, vermicompost or poultry manure carrying *M. anisopliae* can be suggested for termite management in wheat. Neem cake is an option where cost is less important. Further trials should separate the effects of the fungus and the amendments.

Abbreviations

CFU: Colony-forming units; CV: Coefficient of variation; FYM: Farmyard manure; HSD: Honestly significant difference; ICBR: Incremental cost–benefit ratio; Ma: *Metarhizium anisopliae*; SEm: Standard error of mean

Availability of data and materials

All data generated or analysed during this study are included in this article and its supplementary information file.

Declarations

Consent for publication Not applicable.

Competing interests The authors declare that they have no competing interests.

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Table 1 Treatments and their cost

Tr. no.	Treatment	Dose/ha (amendment + *M. anisopliae*)	Cost of amendment (₹/t)	Total treatment cost[a] (₹/ha)
T1	FYM + *M. anisopliae*	10 t + 2 kg	1,000	11,839
T2	Vermicompost + *M. anisopliae*	1 t + 2 kg	5,000	6,839
T3	Mustard cake + *M. anisopliae*	1 t + 2 kg	15,000	16,839
T4	Castor cake + *M. anisopliae*	1 t + 2 kg	8,000	9,839
T5	Tobacco dust + *M. anisopliae*	1 t + 2 kg	5,000	6,839
T6	Neem cake + *M. anisopliae*	1 t + 2 kg	12,000	13,839
T7	Poultry manure + *M. anisopliae*	1 t + 2 kg	3,000	4,839
T8	Sand + *M. anisopliae*	100 kg + 2 kg	–	1,839
T9	Untreated control	–	–	0

[a]Includes *M. anisopliae* (1×10^8 CFU/g; ₹ 720/kg × 2 kg = ₹ 1,440/ha) and one labour-day for application (₹ 399/ha)

311 **Table 2** Effect of organic amendments with *M. anisopliae* on germination and tillering of wheat

Tr. no.	Treatment	Germination (%)		Tillers per plant	
		2024–25	2025–26	2024–25	2025–26
T1	FYM + *M. anisopliae*	84.00	85.00	3.57ab	3.87ab
T2	Vermicompost + *M. anisopliae*	87.00	86.00	3.27ab	3.23bc
T3	Mustard cake + *M. anisopliae*	86.00	87.00	3.30ab	3.60ab
T4	Castor cake + *M. anisopliae*	84.00	84.67	3.47ab	3.63ab
T5	Tobacco dust + *M. anisopliae*	87.00	86.33	3.17abc	3.13bc
T6	Neem cake + *M. anisopliae*	86.33	86.67	3.83a	4.07a
T7	Poultry manure + *M. anisopliae*	85.00	83.67	3.20abc	3.17bc
T8	Sand + *M. anisopliae*	84.00	85.00	2.83bc	2.63cd
T9	Untreated control	88.33	87.33	2.40c	2.17d
	SEm ±	5.90	5.71	0.16	0.15
	HSD ($P = 0.05$)	NS	NS	0.81	0.76
	CV (%)	11.92	11.55	8.76	8.18

312 Means followed by a common letter do not differ significantly by Tukey's HSD test at $P = 0.05$; NS, non-significant
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Table 3 Effect of organic amendments with *M. anisopliae* on termite damage in wheat (mean of weekly observations, 5–14 weeks after sowing)

Tr. no.	Treatment	Termite-damaged plants (%)		
		2024–25	**2025–26**	**Pooled**
T1	FYM + *M. anisopliae*	19.66cd (11.32)	17.45cd (8.99)	18.56de (10.13)
T2	Vermicompost + *M. anisopliae*	14.48ef (6.25)	11.74fg (4.14)	13.11fg (5.15)
T3	Mustard cake + *M. anisopliae*	21.52bc (13.46)	19.20bc (10.82)	20.36cd (12.10)
T4	Castor cake + *M. anisopliae*	15.81e (7.42)	13.65ef (5.57)	14.73f (6.47)
T5	Tobacco dust + *M. anisopliae*	21.85b (13.85)	19.73bc (11.40)	20.79c (12.60)
T6	Neem cake + *M. anisopliae*	12.52f (4.70)	10.38g (3.25)	11.45g (3.94)
T7	Poultry manure + *M. anisopliae*	18.67d (10.25)	16.07de (7.66)	17.37e (8.91)
T8	Sand + *M. anisopliae*	24.07a (16.63)	22.06b (14.11)	23.07b (15.35)
T9	Untreated control	25.49a (18.52)	25.38a (18.37)	25.43a (18.45)
	SEm ±	0.49	0.65	0.41
	HSD (P = 0.05)	2.17	2.93	1.85
	CV (%)	13.54	13.82	13.69

Values are arcsine-transformed means with back-transformed percentages in parentheses. Means followed by a common letter do not differ significantly by Tukey's HSD test at P = 0.05

Table 4 Effect of organic amendments with *M. anisopliae* on termite numbers on eucalyptus bait sticks (mean of weekly observations, 1–14 weeks after sowing)

Tr. no.	Treatment	Termites per stick		
		2024–25	**2025–26**	**Pooled**
T1	FYM + *M. anisopliae*	5.33b (27.91)	5.36b (28.23)	5.34b (28.02)
T2	Vermicompost + *M. anisopliae*	4.07cd (16.06)	4.32c (18.16)	4.19d (17.06)
T3	Mustard cake + *M. anisopliae*	4.38c (18.68)	4.45c (19.30)	4.41cd (18.95)
T4	Castor cake + *M. anisopliae*	4.46c (19.39)	4.66c (21.22)	4.56c (20.29)
T5	Tobacco dust + *M. anisopliae*	3.70de (13.19)	3.76d (13.64)	3.73e (13.41)
T6	Neem cake + *M. anisopliae*	2.65f (6.52)	2.85e (7.62)	2.75f (7.06)
T7	Poultry manure + *M. anisopliae*	3.51e (11.82)	3.39d (10.99)	3.45e (11.40)
T8	Sand + *M. anisopliae*	5.35b (28.12)	5.60b (30.86)	5.47b (29.42)
T9	Untreated control	6.69a (44.26)	6.49a (41.62)	6.59a (42.93)
	SEm ±	0.09	0.09	0.07
	HSD ($P = 0.05$)	0.41	0.42	0.31
	CV (%)	12.95	13.22	13.15

Values are √(x + 0.5)-transformed means with back-transformed values in parentheses. Means followed by a common letter do not differ significantly by Tukey's HSD test at $P = 0.05$

Table 5 Grain and straw yield of wheat, increase over control and avoidable loss (pooled over 2024–25 and 2025–26)

Tr. no.	Treatment	Grain yield (kg/ha)	Straw yield (kg/ha)	Increase in grain yield over control (%)	Avoidable loss in grain yield (%)	Avoidable loss in straw yield (%)
T1	FYM + *M. anisopliae*	3500abcd	4250bcd	27.50	18.51	19.05
T2	Vermicompost + *M. anisopliae*	4250ab	5150ab	54.83	1.05	1.90
T3	Mustard cake + *M. anisopliae*	3650abc	4445abcd	32.97	15.02	15.33
T4	Castor cake + *M. anisopliae*	3850abc	4650abc	40.26	10.36	11.43
T5	Tobacco dust + *M. anisopliae*	3455bcd	4150cde	25.87	19.56	20.95
T6	Neem cake + *M. anisopliae*	4295a	5250a	56.47	0.00	0.00
T7	Poultry manure + *M. anisopliae*	3950ab	4855abc	43.90	8.03	7.52
T8	Sand + *M. anisopliae*	3045cd	3645de	10.93	29.10	30.57
T9	Untreated control	2745d	3245e	–	36.09	38.19
	SEm ±	172.10	206.50			
	HSD ($P = 0.05$)	810	973			
	CV (%)	11.75	11.82			

Means followed by a common letter do not differ significantly by Tukey's HSD test at $P = 0.05$. Increase over control and avoidable loss were calculated from pooled yields

Table 6 Economics of organic amendments with *M. anisopliae* against termites in wheat (pooled yields)

Tr. no.	Treatment	Cost of treatment (₹/ha)	Grain (kg/ha)	Straw (kg/ha)	Gross return (₹/ha)	Net return (₹/ha)	Net gain over control (₹/ha)	ICBR
T1	FYM + *M. anisopliae*	11,839	3500	4250	1,21,500	1,09,661	15,076	1:1.3
T2	Vermicompost + *M. anisopliae*	6,839	4250	5150	1,47,450	1,40,611	46,026	1:6.7
T3	Mustard cake + *M. anisopliae*	16,839	3650	4445	1,26,810	1,09,971	15,386	1:0.9
T4	Castor cake + *M. anisopliae*	9,839	3850	4650	1,33,450	1,23,611	29,026	1:3.0
T5	Tobacco dust + *M. anisopliae*	6,839	3455	4150	1,19,575	1,12,736	18,151	1:2.7
T6	Neem cake + *M. anisopliae*	13,839	4295	5250	1,49,375	1,35,536	40,951	1:3.0
T7	Poultry manure + *M. anisopliae*	4,839	3950	4855	1,37,590	1,32,751	38,166	1:7.9
T8	Sand + *M. anisopliae*	1,839	3045	3645	1,05,285	1,03,446	8,861	1:4.8
T9	Untreated control	–	2745	3245	94,585	94,585	–	–

Prices: wheat grain ₹ 25/kg; straw ₹ 8/kg. Gross return = grain × 25 + straw × 8. Net gain over control = net return of treatment − gross return of control. ICBR = net gain ÷ cost of treatment

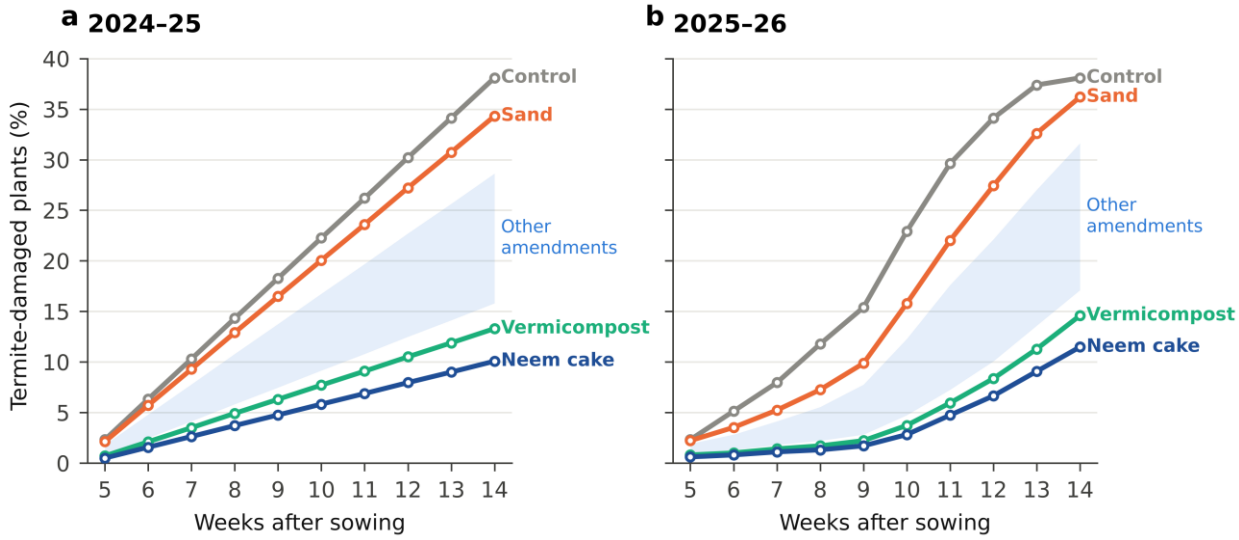


Fig. 1 *Progress of termite damage in wheat from the 5th to the 14th week after sowing in* ***a)*** *2024–25 and* ***b)*** *2025–26. Lines show back-transformed means of three replications for neem cake, vermicompost and sand carrying Metarhizium anisopliae (Ma) and for the untreated control. The shaded band spans the other five organic amendments + Ma*

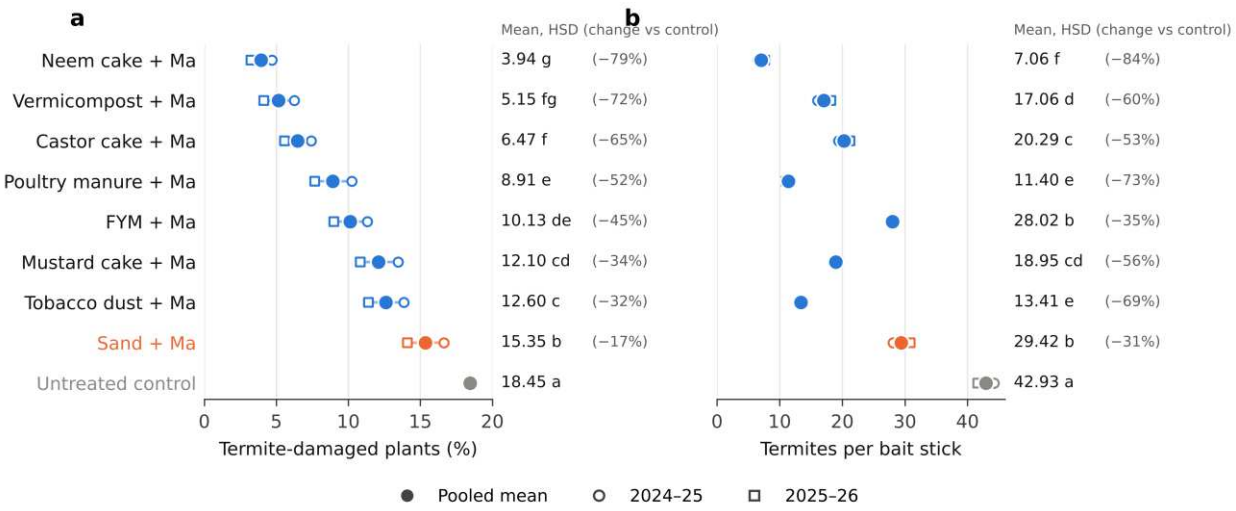


Fig. 2 *Pooled effect (2024–25 and 2025–26) of organic amendments carrying Metarhizium anisopliae (Ma) on* ***a)*** *termite-damaged plants and* ***b)*** *termites per bait stick. Filled circles are pooled means; open symbols are the means of each season. Both panels follow the order of panel a. Letters are from Tukey's HSD test (P = 0.05); values in parentheses are the change relative to the untreated control*

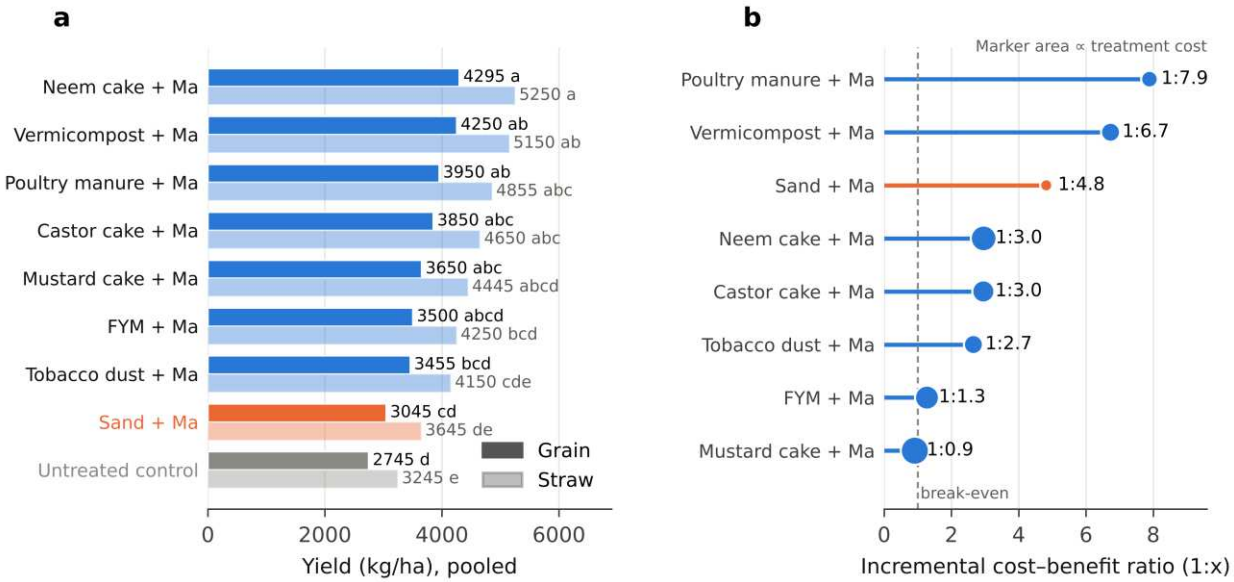


Fig. 3 ***a)*** *Pooled grain and straw yield of wheat and* ***b)*** *incremental cost–benefit ratio (ICBR) of organic amendments carrying Metarhizium anisopliae (Ma). Letters in a are from Tukey's HSD test (P = 0.05), separately for grain and straw. In b, marker area is proportional to treatment cost and the dashed line marks break-even (1:1)*

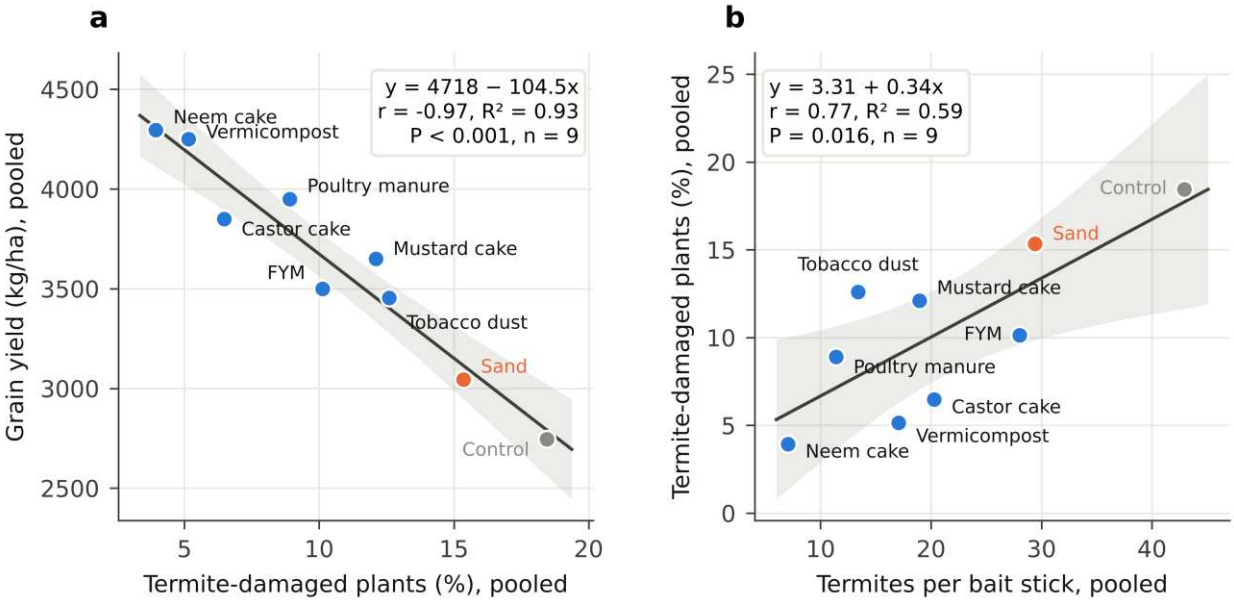


Fig. 4 *Relationships among treatment means (n = 9, pooled over two seasons):* ***a)*** *grain yield against termite-damaged plants and* ***b)*** *termite-damaged plants against termites per bait stick. Lines are least-squares regressions with 95% confidence bands. Blue, organic amendment + Ma; orange, sand + Ma; grey, untreated control*

Supplementary Files

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- Additionalfile11.docx