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Research Article

Development and Laboratory Evaluation of a Slow Release Formulation of Fipronil against Subterranean Termites (*Odontotermes obesus* Rambur)

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Abstract | Subterranean termites *Odontotermes obesus* (Isoptera: Termitidae) are economically important agricultural and structural pests. A wide range of insecticides with different modes of action are being used against these termite pests including organochlorines, organophosphates and pyrethroids. However, pesticidal control of termites is usually not persistent and long-lasting due to rapid decomposition and loss of insecticidal molecules active against target pests. This study was aimed to develop and evaluate a slow-release formulation (SRF) of a persistent insecticide (fipronil) against *O. obesus*. Technical grade insecticide fipronil was applied in the form of cellulose-made pellets made up of compressed powdered sugarcane (*Saccharum officinarum* L.) bagasse and maize (*Zea mays* L.) cobs. This pellet formulation was evaluated against worker individuals of *O. obesus* under laboratory conditions using soil macrocosms. Mortality of termites was determined at different time intervals after their exposure to formulated pellets treated macrocosm soils. Results revealed that fipronil formulated with *Z. mays* substrate remained more effective for longer period of time against subterranean termites as compared to that formulated with *S. officinarum* bagasse material. The maximum mortality of termites was observed at 15 days of treatment application in T3MPF (maize cob powder plus fipronil) treatment after 48 h of bioassay. It was concluded that fipronil can be used as a slow acting toxicant by formulating it with some cellulose-based material such as powdered maize cobs in order to attract and kill the subterranean termites.

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Introduction

Termites are considered ecological engineers owing to their ability to breakdown the organic matter and recycling nutrients in tropical and subtropical ecosystems (Davies *et al*., 2003; Brauman *et al*., 2015; Duran-Bautista *et al*., 2020). However, many species of subterranean termites have been destructive agricultural and infrastructural pests wreaking considerable damage to crops, forest plantations and wooden infrastructures all over the world (Su and Scheffrahn, 2000; Rust and Su, 2012).

These invertebrates are crypto-biotic and are usually hard-to-control pests due to their obscure feeding and foraging activities beneath the soil and within mud galleries (Thorne *et al*., 1999; Bulmer and Traniello, 2002; Vargo and Husseneder, 2009).

Mostly liquid formulations of insecticides such as bifenthrin, cypermethrin, deltamethrin, chlorpyrifos, dichlorvos, chlorfenapyr, chlordane and fipronil are used against termite infestations (Hu, 2005; Ahmed *et al*., 2006; Akbar *et al*., 2019). However, one of the major drawbacks of using these liquid formulations is that they are highly susceptible to get off the target pests or surfaces either by evaporation losses or by leaching down or running off from the treated site (Fernández-Pérez, 2007). Secondly, these liquid formulations get readily decomposed by the climate extremities including temperature, light and humidity and by soil microbes if applied to soil (Singh, 2016; Huang *et al*., 2018).

One of the solutions to this pesticidal drawback is the development of more target-oriented and long-lasting formulations which can give the control of target pests for longer period of time with the minimum and slow rate of losses of active ingredients. These formulations are usually termed as slow-release release formulations (SRFs) (Gerstl *et al*., 1998; El-Nahhal *et al*., 2000; Undabeytia *et al*., 2000; Hermosin *et al*., 2001; Celis *et al*., 2002; Liu *et al*., 2011; Gautam *et al*., 2012). Due to low volatilization, less leaching and longer active periods, slow or controlled release formulations (SRFs) are far better than the conventional pesticides (Fernandez-Perez *et al*., 1999; Dailey, 2004). Many SRFs have been tested successfully against a wide range of insect pests including subterranean termites and other edaphic insect pests including ants, cockroaches, coleopterous grubs and fleas (Collins and Callcot, 1998; Overmyer *et al*., 2005; Gautam *et al*., 2012; Peters *et al*., 2019).

Nevertheless, research on SRFs has mainly focused on the release kinetics of pesticide and the use of sorbents in these formulations (Garrido-Herrera *et al*., 2006; Li *et al*., 2012). For controlled or slow release of pesticides, different polymers such as starch, alginate and silicate are used in the formulation matrix (Fernandez-Perez, 2007; Singh *et al*., 2009; Chen *et al*., 2017; Ashitha and Mathew, 2020). In many studies of pesticide formulations, urea is used as an additive which not only affects the release kinetics but also improves the properties of formulation (Wang and Wu, 2003; Cao *et al*., 2005). Moreover, SRFs against subterranean termites become more effective when baited with cellulose material (Su, 2005; Zhang *et al*., 2009; Dhang, 2011; Eger *et al*., 2012; Peters *et al*., 2019).

The objective of this study was to develop and evaluate a slow-release bait formulation of fipronil against subterranean termite *Odontotermes obesus* (Isoptera: Termitidae) which are economically important agricultural and structural pests in Indo-Pak regions (Ahmed *et al*., 2007; Manzoor and Mir, 2010; Akbar *et al*., 2019). Fipronil is a non-repellent broad-spectrum phenylpyrazole insecticide and is used to control a wide range of chewing and sucking insect pests (Scott and Wen, 1997; Collins and Callcot, 1998; Elbert *et al*., 1998; Overmyer *et al*., 2005; Iqbal and Evans, 2017).

Materials and Methods

Collection and laboratory maintenance of termites

An intact colony of a healthy and active colony of subterranean termites was dug out and collected from a sugarcane (*Saccharum officinarum* L. var. BF-237) field (32°07'58"N; 72°41'32"E) in the vicinity of College of Agriculture, University of Sargodha. It was ensured that there was no insecticide application at the collection site for last two months. The collected termite species was identified as *O. obesus* Ramb. In order to acclimatize the termite individuals to laboratory conditions, this colony was maintained for about two weeks in a transparent rearing box under controlled conditions (at 27±2°C, 65% relative humidity and 16:8 h light-dark photoperiod). Only healthy and active worker termites were used in all bioassays.

Preparation of fipronil pellets

Technical grade (99.5% pure) fipronil was procured from FMC United (Pvt.) Ltd. Pakistan. Slow-release formulation was prepared in the form of compressed pellets. For this purpose, sugarcane (*S. officinarum* L.) bagasse and maize (*Zea mays* L.) cobs were used as sources of cellulose and attractant for subterranean termites. These were collected and dried in sunlight and then in shade for 48 hours. After drying, these materials were ground to powder form separately with the help of an electric grinder. Some other additives were also used to enhance the properties of formulation and discharge kinetics of insecticide from the slow-release formulation. These additives were starch, sodium silicate, sodium alginate and urea. Four types of pellets were formulated *viz*; treatment 1 (T1SPF) containing sugarcane bagasse powder mixed with fipronil (5%), treatment 2 (T2SPC) containing sugarcane bagasse without fipronil (control), treatment 3 (T3MPF) containing maize cob powder mixed with fipronil (5%) and treatment 4 (T4MPC) containing maize cob powder without fipronil (control). The detailed composition of these pellets is given Table 1. The dimensions and average weight of each formulated pellet were 20×14 mm and 4 g, respectively.

Table 1: *Composition of ingredients used for the preparation of slow-release formulation pellets.*

Ingredients	Treatment 1 (T1SPF)	Treatment 2 (T2SPC)	Treatment 3 (T3MPF)	Treatment 4 (T3MPC)
Fipronil (TG)	5g	-	5g	-
Sugarcane bagasse powder	70g	75g	-	-
Maize cob powder	-	-	70g	75g
Sodium alginate	3g	3g	3g	3g
Sodium silicate	2g	2g	2g	2g
Urea	2g	2g	2g	2g
Starch	18g	18g	18g	18g

TG: technical grade; T1SPF: sugarcane bagasse powder + fipronil; T2SPC: only sugarcane bagasse powder; T3MPF: maize cob powder + fipronil; T4MPC: only maize cob powder.

Bioassay protocol

For determining the efficacy of Slow-release formulation (pellets) of fipronil against *O. obesus* termites, macrocosms (210 × 150 mm Pyrex™ borosilicate glass beakers with capacity of 3 L) were half-filled with sterilized soil. One formulated pellet was introduced in the soil at a depth of 5 cm in the centre of each macrocosm. After that, tap water was applied by hand-sprinkler in the morning and in the evening to moisten the soil till the end of the experiment. Due to moisture, the fipronil present in the pellets was assumed to be relocated and disturbed gradually and slowly in the surrounding soil.

The effectiveness of fipronil released in the soil profile of each macrocosm was tested against subterranean termites by exposing them to the treated soil taken from macrocosm at 3, 7, 15, 30 and 60 days post-application. In brief, treated soil was taken from the immediate surroundings of the pellet and was put in glass Petri-dishes (100 × 15 mm). Then, ten healthy and active worker termites were released into each Petri-dish and data regarding their mortality were recorded at 6, 12, 24 and 48 hours post-exposure of termites to soil. Similar bioassays were conducted at 7, 15, 30 and 60 days after the pellets application in the soil. All these experiments were performed at 27°C±2 and 70% relative humidity. Four independent replications were maintained for each treatment.

Statistical analysis

Statistical interpretation of the data was performed using Statistix® version 8.1 analytical software (Statistix, Tallahassee, FL). Data was subjected factorial one-way analysis of variance (ANOVA) using treatment (pellet formulation type) and time (post-application exposure time) as factors. Following ANOVA, the treatment means were compared using Fisher's least significant difference (LSD) post-hoc test at standard level of significance (P = 0.05). Moreover, median lethal time (LT^{50}) values were calculated by probit analysis using POLO-PC® (LeOra Software, 1987) regression software.

Results and Discussion

Results of these laboratory bioassays revealed a significant effect of both factors, *i.e.* the treatments ($F_{(3,300)} = 297.64$, $p < 0.001$) and time intervals ($F_{(4,300)} = 79.45$, $p < 0.001$), on the percent mortality of *O. obesus* termite individuals (Table 2). Similarly, the interaction of treatments and time intervals ($F_{(12,300)} = 17.05$, $p < 0.001$) also exhibited a significant effect on percent mortality of termites (Table 2). Maximum average termite mortality (70.83 ± 4.31%) was recorded for maize cob pellets containing 5% fipronil (T3MPF) recorded at 15 DAT, followed by the treatment containing sugarcane bagasse and 5% fipronil (T1SPF) exhibiting 56.67 ± 4.06% average mortality of termites (Figure 1). Average termite mortality recorded at 30 and 60 DAT were 42.50 ± 2.68 and 13.33 ± 2.11 for T2SPF and 50.25 ± 3.44 and 20.67 ± 2.72 for T3MPF, respectively. Minimum average termite mortality was recorded for the treatments without fipronil insecticide (*i.e.* 2.50 ± 1.03% and 4.17 ± 1.24% for T2SPC and T4MPC, respectively) recorded at 3 DAT (Figure 1).

Similar trend of termite mortality was recorded for individual bioassays conducted at 3, 7, 15, 30 and 60

DAT. For each DAT bioassay, fipronil mixed formulations (*i.e.* T1SPF and T3MPF) showed significantly high mortality of *O. obesus* termite individuals as compared to the pellets without insecticide (Figure 2). Similarly, termite mortality increased along with the exposure time for all bioassays. Maximum termite mortality (76.67 and 90% for T1SPF and T3MPF, respectively) was recorded at 48 h post-exposure at 15 DAT, while minimum mortality (3.33 and 10% for T1SPF and T3MPF, respectively) was found at 6 h post-exposure time intervals at 3 DAT. There was no or negligible mortality of termites recorded at 6 and 12 h post-exposure for both T2SPC and T4MPC treatments (Figure 2).

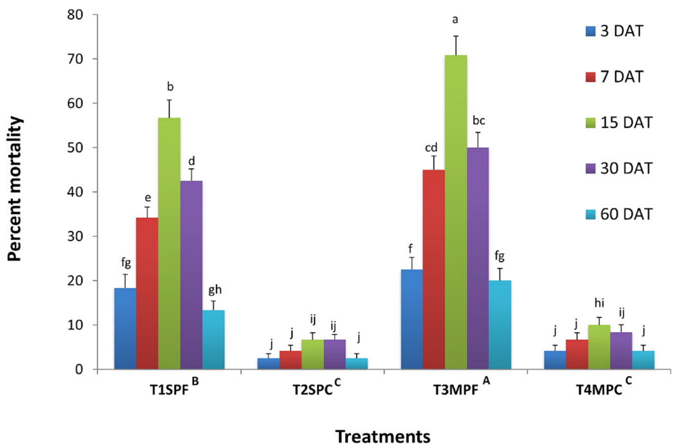

Figure 1: *Percent mortality (mean ± SE; sample size n = 16) of worker individuals of subterranean termite Odontotermes obesus in response to different treatments recorded at different post-exposure time intervals. Treatments included different formulated pellets containing sugarcane bagasse powder with (T1SPF) and without (T2SPC) fipronil, and maize cob powder with (T3MPF) and without (T4MPC) fipronil. Different lettersindicate the significant difference among treatments (factorial (two factor) one-way ANOVA at α = 0.05).*

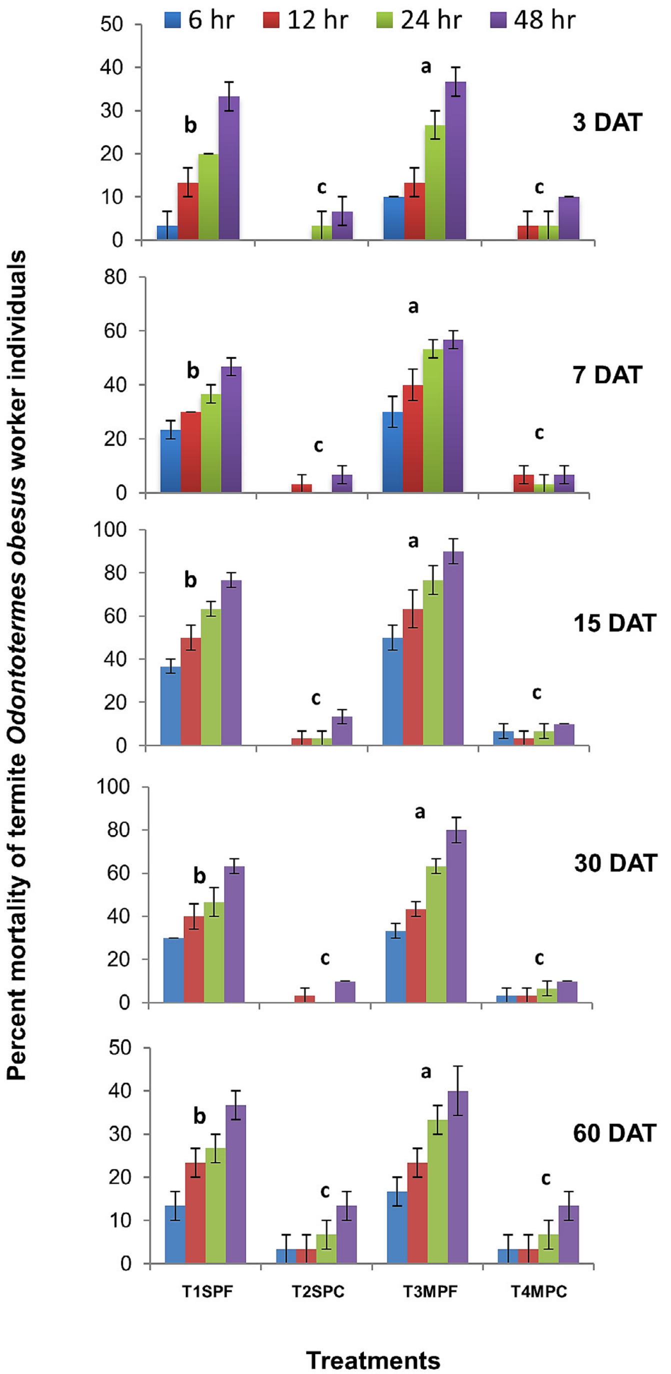

Figure 2: *Percent mortality (mean ± SE; sample size n = 4) of worker individuals of subterranean termite Odontotermes obesus in response to different treatments recorded at different post-exposure time intervals. Treatments included different formulated pellets containing sugarcane bagasse powder with (T1SPF) and without (T2SPC) fipronil, and maize cob powder with (T3MPF) and without (T4MPC) fipronil. Different letters indicate the significant difference among treatments (factorial (two factor) one-way ANOVA at α = 0.05). DAT: days after treatment.*

Table 2: *Analysis of variance table regarding the impact of different treatments on the mortality of termite Odontotermes obesus individuals bioassayed at different post-exposure time intervals.*

Source	DF	SS	MS	F-value	P-value
Treatment	3	83837	27945.7	297.64	< 0.001
Time	4	29839	7459.7	79.45	< 0.001
Treatment×Time	12	19210	1600.9	17.05	< 0.001
Error	300	28167	93.9		
Total	319	161054			
GM / CV	21.46 /	45.16			

Factorial one-way ANOVA followed by least significant difference (LSD) post-hoc test at α = 0.05; DF: Degree of freedom; SS: Sum of squares; MS: Mean sum of squares; F: F-statistic; GM: Grand mean; CV: Coefficient of variation.

Regarding, median lethal time (LT_{50}) values determined for *O. obesus* termite worker individuals exposed to the soils treated with different fipronil formulations was shown in Table 3. After 15 days of treatment application, treatment T3MPF appeared to be most toxic with minimum LT_{50} value (5.76 h) followed by T1SPF (11.90 h). Similarly, treatment T3MPF was most effective with minimum LT_{50} value (22.86 h) followed by T1SPF (33.39 h) recorded after 30 days of treatment application (Table 3).

In the pest management industry, although termite control primarily relies on the application of liquid formulations, baiting techniques appear recently as promising tactics particularly in situations where liquid applications are unsuccessful on sustained basis (Kistner and Sbragia, 2001). For effective long-term control of subterranean termites with a minimized risk of offsite pesticide movements, slow-releases insecticidal bait formulations offer promising solutions. Many studies on bait and SRF systems have proved that they can completely eliminate the entire colony of the subterranean termites (Grace *et al.*, 1996; Su and Scheffrahn, 1996; Tsunoda *et al.*, 1998; Peters and Fitzgerald, 1999; Prabhakaran, 2001; Evans, 2010; Neoh *et al.*, 2011; Osbrink *et al.*, 2011; Eger *et al.*, 2012). Huang *et al.* (2006) demonstrated that fipronil baited with white sugar and straw pulp was highly effective against the colonies of *Odontotermes formosanus* in the field.

The present study encompassed a preliminary attempt to develop and evaluate a slow-release formulation of fipronil, a well-known synthetic contact insecticide, against subterranean termite *O. obesus*. Small pellets (4 g 20 × 14 mm) were formulated by compressing mixtures of cellulose-material, starch, sodium alginate, sodium silicate and urea with and without 5% technical grade fipronil. Cellulose-based materials used in formulation were sugarcane (*S. officinarum* L.) bagasse and maize (*Z. mays* L.) cobs which were used to provide adsorbing matrix for fipronil molecules. Termite mortality was bioassayed by exposing them to treated soils taken from the macrocosms at 3, 7, 15, 30 and 60 days of slow release pellets application.

In this study, fipronil was found effective against the subterranean termites (*O. obesus*) individuals as a slow acting toxicant even till two months post-application of the formulated pellets applied in the soil. Many previous studies have been conducted regarding the development and evaluation of different types of slow-release insecticidal baits for controlling subterranean termites (Haverty *et al.*, 2010; Neoh *et al.*, 2011; Peters *et al.*, 2019). Different formulations of bifenthrin, fipronil, hexaflumuron, thiamethoxam and imidacloprid showed significant suppression of many termite species (Sheets *et al.*, 2000; Delgarde and Rouland-Lefevre, 2002; Ahmed *et al.*, 2005; Remmen and Su, 2005; Rashid *et al.*, 2012; Saljoqi *et al.*, 2014) evaluated different insecticides including fipronil, pyriproxyfen, chlorpyrifos, hexaflumuron, imidacloprid and indoxacarb against subterranean termites and showed that fipronil was the most effective slow acting toxicant for controlling termites followed by imidacloprid and indoxacarb. Our results are in line with previous studies showing that fipronil is very effective even at a very low concentration (Kaakeh *et al.*, 1997; Valles *et al.*, 1997; Durier and Rivault, 2000).

Table 3: *Median lethal time (LT_{50}) values for the worker individuals of subterranean termite Odontotermes obesus exposed to soils treated with different formulations of fipronil and bioassayed at different post-exposure time intervals.*

Treatments	DAT	LT_{50} (hr)	Lower and Upper 95% Confidence Limits (hr)	X^2 (df = 14)*	P-value	Slope ± SE	Intercept ± SE
T1SPF (sugar-cane bagasse plus fipronil)	3	88.31	61.37 – 164.47	33.44	0.002	1.40±0.12	2.73±0.17
	7	66.73	47.61 – 115.36	9.56	0.793	0.71±0.10	1.29±0.13
	15	11.90	10.29 – 13.52	17.60	0.225	1.18±0.10	1.27±0.12
	30	33.39	24.04 – 58.90	22.64	0.66	0.66±0.10	1.00±0.12
	60	255.66	109.10 – 2557.07	42.06	0.000	1.00±0.13	2.40±0.17
T3MPF (maize cob plus fipronil)	3	98.92	72.77 – 154.79	11.24	0.667	1.04±0.11	2.09±0.15
	7	24.72	18.83 – 35.89	26.56	0.022	0.80±0.10	1.11±0.12
	15	5.76	2.60 – 8.50	78.73	0.000	1.28±0.11	0.97±0.13
	30	22.86	19.65 – 27.22	11.70	0.630	0.97±0.10	1.19±0.12
	60	111.71	72.68 – 236.13	24.15	0.044	1.10±0.11	2.25±0.15

**Since the significance level is less than 0.15, a heterogeneity factor is used in the calculation of confidence limits.*

Secondly, material used in baits also have considerable effects on the target insects' mortality. Many studies have payed attention towards the cardboard and wood baiting systems and few have focused to check the difference between the effectiveness of different materials used in baiting systems (Lenz *et al*., 2011; Wang and Henderson, 2012). According to our results, maximum mortality of termites for longer period of time was observed in treatment containing maize cob powder which proved that maize cob powder have more ability to hold-on or retain pesticidal (fipronil) molecules for longer period of time than sugarcane bagasse. Nevertheless, Wang and Henderson (2012) using different choice and no-choice experiments have demonstrated that subterranean termites prefer maize cob material over cardboard or wooden chips. According to the findings of Azubuike *et al*. (2011) and Shogren *et al*. (2011), it is evaluated that agricultural by product/waste such as maize cob contains reasonable amount of cellulose. Together with our results, these findings suggest that maize cob powder as baiting matrix would be with triple advantages for developing a controlled-release pesticidal formulation in future to be tested under field conditions. On one hand, it can retain pesticide active ingredients for long period of time, and on the other hand, it could be an effective attractant for termites as it contains more cellulose, amino-acids and sugar contents (Chen and Henderson, 1996; Lenz and Evans, 2002; Wang and Henderson, 2012). Moreover, it is also cost-effective as maize cobs are easily available and abundant waste material of agricultural products (Varvel and Wilhelm, 2008; Wilaipon, 2008).

A study conducted by Li *et al*. (2001) showed that sugarcane bagasse powder is not effective and attractant for subterranean termites (*Coptotermes formosanus* and *Reticulitermes flavipes* species) until unless it is infected with *Gloeophyllum trabeum* fungi. This also corroborates our study results about effectiveness of maize cob powder as compared to sugarcane bagasse powder.

Conclusions and Recommendations

In conclusion, this laboratory study showed that fipronil mixed with maize cob substrate remained more effective for longer period of time against subterranean termites as compared to sugarcane bagasse material. The maximum mortality (90%) of termites and minimum median lethal time (LT_{50}) of 5.76 h observed at 15 days post-treatment suggest that fipronil can be used as a slow acting toxicant by formulating it with some cellulose-based material such as powdered maize cobs in order to attract and kill subterranean termites for longer period of time. However, lack of HPLC determination of the release dynamics of fipronil and its metabolites into the surrounding soil of macrocosms treated with fipronil formulated pellets and lack of field evaluation of this formulation with different concentrations of fipronil as active ingredient render this study as a pilot preliminary study. Although these determinations were envisaged but could not be performed due to unavoidable reasons, these two deficiencies, indeed, encompass the future perspectives of this study.

Novelty Statement

This laboratory study validated that the insecticidal efficacy of fipronil can be enhanced and prolonged in the soil (up to two months) against subterranean termites (*O. obesus*) when baited with the matrix of maize (*Z. mays*) cob powered as cellulose source.

Author's Contribution

SAS and MZM conceived the idea and planned the experiment. SAS and MZM performed experiments and wrote the first draft of the manuscript. SNO performed statistical analyses. ML prepared graphs. MAR technically revised the manuscript. SA provided the technical assistance and proofread the manuscript. All authors read and approved the final manuscript.

Conflict of interest

The authors have declared no conflict of interest.

References

Ahmed, S., A. Naseer and S. Fiaz. 2005. Comparative efficacy of botanicals and insecticides on termites in sugarcane at Faisalabad. Pak. Entomol., 27: 23-25.

Ahmed, S., R.R. Khan and M.A. Riaz. 2007. Some studies on the field performance of plant extracts against termites (*Odontotermes guptai* and *Microtermes obesi*) in sugarcane at Faisalabad. Int. J. Agric. Biol., 9: 398-400.

Ahmed, S., T. Mustafa, M.A. Riaz and A.

Hussain. 2006. Efficacy of insecticides against subterranean termites in sugarcane. Int. J. Agric. Biol., 8: 508-510.
Akbar, M.S., M.Z. Majeed and M. Afzal. 2019. Comparative toxicity of selected new-chemistry insecticides against subterranean termites *Odontotermes obesus* Ramb. (Isoptera: Termitidae). Sarhad J. Agric. 35: 20-26. https://doi.org/10.17582/journal.sja/2019/35.1.20.26
Ashitha, A. and J. Mathew. 2020. Characteristics and types of slow/controlled release of Pesticides. In: *Controlled release of pesticides for sustainable agriculture*. Springer-Verlag, Berlin, Germany, pp. 141-153. https://doi.org/10.1007/978-3-030-23396-9_6
Azubuike, C.P.C., A.O. Okhamafe and A. Falodun. 2011. Some Pharmacopoeial and diluent-binder properties of cellulose derived from maize cob in selected tablet formulations. J. Chem. Pharm. Res., 3: 481-488.
Brauman, A., M.Z. Majeed, B. Buatois, A. Robert, A.L. Pablo and E. Miambi. 2015. Nitrous oxide (N_2O) emissions by termites: does the feeding guild matter? PLoS One, 10: e0144340. https://doi.org/10.1371/journal.pone.0144340
Bulmer, M.S. and J.F.A. Traniello. 2002. Lack of aggression and spatial association of colony members in *Reticulitermes flavipes*. J. Insect Behav., 15: 121-126. https://doi.org/10.1023/A:1014440414618
Cao, Y., L. Huang, J. Chen, J. Liang, S. Long and Y. Lu. 2005. Development of a controlled release formulation based on a starch matrix system. Int. J. Pharm., 298: 108-116. https://doi.org/10.1016/j.ijpharm.2005.04.005
Celis, R., M.C. Hermosin, M.J. Carrizosa and J. Cornejo. 2002. Inorganic and organic clays as carriers for controlled release of the herbicide hexazinone. J. Agric. Food Chem., 50: 2324-2330. https://doi.org/10.1021/jf011360o
Chen, J. and G. Henderson. 1996. Determination of feeding preference of Formosan subterranean termite (*Coptotermes formosanus*Shiraki) for some amino acid additives. J. Chem. Ecol., 22: 2359-2369. https://doi.org/10.1007/BF02029552
Chen, K., G. Yu, F.He, Q. Zhou, D. Xiao, J. Li and Y. Feng. 2017. A pH-responsive emulsion stabilized by alginate-grafted anisotropic silica and its application in the controlled release of λ-cyhalothrin. Carbohyd. Polym., 176: 203-213. https://doi.org/10.1016/j.carbpol.2017.07.046
Collins, H.L. and A.M.A. Callcott. 1998. Fipronil: an ultra-low-dose bait toxicant for control of red imported fire ants (Hymenoptera: Formicidae). Fla. Entomol., 81: 407-415. https://doi.org/10.2307/3495930
Dailey, O.D., 2004. Volatilization of alachlor from polymeric formulations. J. Agric. Food Chem., 52: 6742-6746. https://doi.org/10.1021/jf040034g
Davies, R.G., P. Eggleton, D.T. Jones, F.J. Gathorne-Hardy and L.M. Hernández. 2003. Evolution of termite functional diversity: analysis and synthesis of local ecological and regional influences on local species richness. J. Biogeogr., 30: 847-877. https://doi.org/10.1046/j.1365-2699.2003.00883.x
Delgarde, S. and C. Rouland-Lefevre. 2002. Evaluation of the effects of thiamethoxam on three species of African termite (Isoptera: Termitidae) crop pests. J. Econ. Entomol., 95: 531-536. https://doi.org/10.1603/0022-0493-95.3.531
Dhang, P., 2011. A preliminary study on elimination of colonies of the mound building termite *Macrotermes gilvus* (Hagen) using a chlorfluazuron termite bait in the Philippines. Insects, 2: 486-490. https://doi.org/10.3390/insects2040486
Duran-Bautista, E.H., I. Armbrecht, A.N.S. Acioli, J.C. Suárez, M. Romero, M. Quintero and P. Lavelle. 2020. Termites as indicators of soil ecosystem services in transformed amazon landscapes. Ecol. Indic., 117: 106550. https://doi.org/10.1016/j.ecolind.2020.106550
Durier, V. and C. Rivault. 2000. Secondary transmission of toxic baits in German cockroach (Dictyoptera: Blattellidae). J. Econ. Entomol., 93: 434-440. https://doi.org/10.1603/0022-0493-93.2.434
Eger, J.E., M.D. Lees, P.A. Neese, T.H. Atkinson, E.M. Thoms, M.T. Messenger, J.J. Demark, LC. Lee, E.L. Vargo and M.P. Tolley. 2012. Elimination of subterranean termite (Isoptera: Rhinotermitidae) colonies using a refined cellulose bait matrix containing noviflumuron when monitored and replenished quarterly. J. Econ. Entomol., 105: 533-539. https://doi.org/10.1603/EC11027
Elbert, A., R. Nauen and W. Leichet. 1998. Insecticides with novel modes of action.

Springer, New York, pp. 50-73. https://doi.org/10.1007/978-3-662-03565-8_4

El-Nahhal, Y., S. Nir, C. Serban, O. Rabinovitch and B Rubin. 2000. Montmorillonite-phenyltrimethyl ammonium yields environmentally improved formulations of hydrophobic herbicides. J. Agric. Food Chem., 48: 4791-4801. https://doi.org/10.1021/jf000327j

Evans, T.A., 2010. Rapid elimination of field colonies of subterranean termites (Isoptera: Rhinotermitidae) using bistrifluron solid bait pellets. J. Econ. Entomol., 103: 423-432. https://doi.org/10.1603/EC09067

Fernández-Pérez, M., 2007. Controlled release systems to prevent the agro-environmental pollution derived from pesticide use. J. Environ. Sci. Health. J. Environ. Sci. Hlth., 42: 857-862. https://doi.org/10.1080/03601230701555138

Fernández-Pérez, M., M. Villafranca-Sanchez, E. Gonzalez-Pradas and F. Flores-Cespedes. 1999. Controlled release of diuron from an alginate–bentonite formulation: water release kinetics and soil mobility study. J. Agric. Food Chem., 47(2): 791-798. https://doi.org/10.1021/jf980878y

Garrido-Herrera, F.J., E. Gonzalez-Pradas and M. Fernández-Pérez. 2006. Controlled release of isoproturon, imidacloprid, and cyromazine from alginate–bentonite–activated carbon formulations. J. Agric. Food Chem., 54(26): 10053-10060. https://doi.org/10.1021/jf062084m

Gautam, B.K., G. Henderson and R.W. Davis. 2012. Toxicity and horizontal transfer of 0.5% fipronil dust against Formosan subterranean termites. J. Econ. Entomol., 105: 1766-1772. https://doi.org/10.1603/EC12165

Gerstl, Z., A. Nasser and U. Mingelgrin. 1998. Controlled release of pesticides into soils from clay– polymer formulations. J. Agric. Food Chem., 46: 3797-3802. https://doi.org/10.1021/jf980185h

Grace, J.K., C.H.M. Tome, T.G. Shelton, R.J. Oshiro and J.R. Yates. 1996. Baiting studies and consideration with *Coptotermes formosanus* (Isoptera: Rhinotermitidae) in Hawaii. Sociobiol., 28: 511-520.

Haverty, M.I., R.L. Tabuchi, E.L. Vargo, D.L. Cox, L.J. Nelso and V.R. Lewis. 2010. Response of *Reticulitermes hesperus* (Isoptera: Rhinotermitidae) colonies to baiting with lufenuron in northern California. J. Econ. Entomol., 103: 770-780. https://doi.org/10.1603/EC09088

Hermosin, M.C., M.J. Calderón, J.P. Aguer and J. Cornejo. 2001. Organoclays for controlled release of the herbicide fenuron. Pest Manage. Sci., 57: 803-809. https://doi.org/10.1002/ps.359

Hu, X.P., 2005. Evaluation of efficacy and nonrepellency of indoxacarb and fipronil-treated soil at various concentrations and thicknesses against two subterranean termites (Isoptera: Rhinotermitidae). J. Econ. Entomol., 98: 509-517. https://doi.org/10.1093/jee/98.2.509

Huang, Q.Y., C.L. Lei and D. Xue. 2006. Field evaluation of a fipronil bait against subterranean termite *Odontotermes formosanus* (Isoptera: Termitidae). J. Econ. Entomol., 99: 455-461. https://doi.org/10.1093/jee/99.2.455

Huang, Y., L. Xiao, F. Li, M. Xiao, D. Lin, X. Long and Z. Wu. 2018. Microbial degradation of pesticide residues and an emphasis on the degradation of cypermethrin and 3-phenoxy benzoic acid: A review. Molecules, 23: 2313. https://doi.org/10.3390/molecules23092313

Iqbal, N. and T.A. Evans. 2017. Evaluation of fipronil and imidacloprid as bait active ingredients against fungus-growing termites (Blattodea: Termitidae: Macrotermitinae). Bull. Entomol. Res., 108: 14-22. https://doi.org/10.1017/S000748531700044X

Kaakeh, W., B.L. Reid and G.W. Bennett. 1997. Toxicity of fipronil to German and American cockroaches. Entomol. Exp. Appl., 84: 229-237. https://doi.org/10.1046/j.1570-7458.1997.00220.x

Kistner, D.H. and R.J. Sbragia. 2001. The use of the Sentricon(TM) termite colony elimination system for controlling termites in difficult control sites in Northern California. Sociobiology, 37: 265-280.

Lenz, M., C.Y. Lee, M.J. Lacey, T. Yoshimura and K. Tsunoda. 2011. The potential and limits of termites (Isoptera) as decomposers of waste paper products. J. Econ. Entomol., 104: 232-242. https://doi.org/10.1603/EC10155

Lenz, M. and T.A. Evans. 2002. Termite bait technology: Perspectives from Australia. In: Proceedings of the 4th International Conference on Urban Pests, pp. 7-10.

LeOra, S. 1987. Polo-Plus, POLO for Windows.

LeOra Software, Petaluma, CA, 431.

Li, J., J. Yao, Y. Li and Y. Shao. 2012. Controlled release and retarded leaching of pesticides by encapsulating in carboxymethyl chitosan/ bentonite composite gel. J. Environ. Sci. Health Part B, 47(8): 795-803. https://doi.org/10.1080/03601234.2012.676421

Li, S.N., Y.L. Yu, D.Y. Zhang, D.F. Fan, J. He, Y. Genrong and G.R. Yuan. 2001. Effect of Brown-rot Fungi, *Gloeophyllum trabeum*, on trail-following responses to several insecticides and on field efficacy for dam termite control. Chinese J. Pest. Sci., 3: 35-40.

Liu, J.M., G. Wei, Q.C. Huang, F. Yang, Z.S. Liu and T.Q. Qin. 2011. Current status and prospects of bait for termites. J. Anh. Agric. Sci., 39: 14666-14667.

Manzoor, F. and N. Mir. 2010. Survey of termite infested houses, indigenous building materials and construction techniques in Pakistan. Pak. J. Zool., 42: 693-696.

Neoh, K.B., N.A. Jalaludin and C.Y. Lee. 2011. Elimination of field colonies of a mound-building termite *Globitermes sulphureus* (Isoptera: Termitidae) by bistrifluron bait. J. Econ. Entomol., 104: 607-613. https://doi.org/10.1603/EC10161

Osbrink, W.L., M.L. Cornelius and A.R. Lax. 2011. Area wide field study on effect of three chitin synthesis inhibitor baits on populations of Coptotermes formosanus and *Reticulitermes flavipes* (Isoptera: Rhinotermitidae). J. Econ. Entomol., 104: 1009-1017. https://doi.org/10.1603/EC10217

Overmyer, J.P., B.N. Mason and K.L. Armbrust. 2005. Acute toxicity of imidacloprid and fipronil to a nontarget aquatic insect, *Simuliumvittatum* Zetterstedt cytospecies IS-7. Bull. Environ. Contam. Toxicol., 74: 872-879. https://doi.org/10.1007/s00128-005-0662-7

Peters, B.C. and C.J. Fitzgerald. 1999. Field evaluation of the effectiveness of three timber species as bait stakes and the bait toxicant hexaflumuron in eradicating *Coptotermes acinaciformis* (Froggatt) (Isoptera: Rhinotermidae). Sociobiology, 33: 227-238.

Peters, B.C., D. Wibowo, G.Z. Yang, Y. Hui, A.P. Middelberg and C.X. Zhao. 2019. Evaluation of baiting fipronil-loaded silica nanocapsules against termite colonies in fields. Heliyon, 5: e02277. https://doi.org/10.1016/j.heliyon.2019.e02277

Prabhakaran, S.K., 2001. Eastern subterranean termite management using baits containing hexaflumuron in affected University of Iowa structures (Isoptera: Rhinotermitidae). Sociobiology, 37: 221-233.

Rashid, M., A.S. Garjan, B. Naseri and F. Saberfar. 2012. Comparative toxicity of five insecticides against subterranean termite, *Amitermesvilis* (Isoptera: Termitidae) under laboratory conditions. Munis Entomol. Zool., 7: 1044-1050.

Remmen, L.N. and N.Y. Su. 2005. Time trends in mortality for thiamethoxam and fipronil against Formosan subterranean termites and eastern subterranean termites (Isoptera: Rhinotermitidae). J. Econ. Entomol., 98: 911-915. https://doi.org/10.1603/0022-0493-98.3.911

Rust, M.K. and N.Y. Su. 2012. Managing social insects of urban importance. Ann. Rev. Entomol., 57: 355-375. https://doi.org/10.1146/annurev-ento-120710-100634

Saljoqi, A.U.R., N. Muhammad, I.A. Khan, M. Nadeem and M. Salim. 2014. Effect of different insecticides against termites, *Heterotermes indicola* L. (Isoptera: Termitidae) as slow acting toxicants. Sarhad J. Agric., 30: 333-339.

Scott, J.G. and Z. Wen. 1997. Toxicity of fipronil to susceptible and resistant strains of German cockroaches (Dictyoptera: Blattellidae) and house flies (Diptera: Muscidae). J. Econ. Entomol., 90: 1152-1156. https://doi.org/10.1093/jee/90.5.1152

Sheets, J.J., L.L. Karr and J.E. Dripps. 2000. Kinetics of uptake, clearance, transfer, and metabolism of hexaflumuron by eastern subterranean termites (Isoptera: Rhinotermitidae). J. Econ. Entomol., 93: 871-877. https://doi.org/10.1603/0022-0493-93.3.871

Shogren, R.L., S.C. Peterson, K.O. Evans and J.A. Kenar. 2011. Preparation and characterization of cellulose gels from corn cobs. Carbohyd. Polym., 86: 1351-1357. https://doi.org/10.1016/j.carbpol.2011.06.035

Singh, B., D.K. Sharma and A. Gupta. 2009. A study towards release dynamics of thiram fungicide from starch–alginate beads to control environmental and health hazards. J. Hazard. Mater., 161: 208-216. https://doi.org/10.1016/j.jhazmat.2008.03.074

Singh, S.N., 2016. Microbe-induced degradation of pesticides. Springer International Publishing, Switzerland. https://doi.org/10.1007/978-3-319-45156-5

Su, N.Y., 2005. Response of the Formosan subterranean termites (Isoptera: Rhinotermitidae) to baits or nonrepellent termiticides in extended foraging arenas. J. Econ. Entomol., 98: 2143-2152. https://doi.org/10.1093/jee/98.6.2143

Su, N.Y. and R.H. Scheffrahn. 1996. Comparative effects of two chitin synthesis inhibitors, hexaflumuron and lufenuron, in a bait matrix against subterranean termites (Isoptera: Rhinotermitidae). J. Econ. Entomol., 89: 1156-1160. https://doi.org/10.1093/jee/89.5.1156

Su, N.Y. and R.H. Scheffrahn. 2000. Termites as pests of buildings. In: Termites: evolution, sociality, symbioses, ecology. Springer, Dordrecht, Netherlands, pp. 437-453. https://doi.org/10.1007/978-94-017-3223-9_20

Thorne, B.L., J.F.A. Traniello, E.S. Adams and M. Bulmer. 1999. Reproductive dynamics and colony structure of subterranean termites of the genus Reticulitermes (Isoptera Rhinotermitidae): A review of the evidence from behavioral, ecological, and genetic studies. Ethol. Ecol. Evol., 11: 149-169. https://doi.org/10.1080/08927014.1999.9522833

Tsunoda, K., H. Matsuoka and T. Yoshimura. 1998. Colony elimination of *Reticulitermes speratus* (Isoptera: Rhinotermitidae) by bait application and the effect on foraging territory. J. Econ. Entomol., 91: 1383-1386. https://doi.org/10.1093/jee/91.6.1383

Undabeytia, T., S. Nir and B. Rubin. 2000. Organo-clay formulations of the hydrophobic herbicide norflurazon yield reduced leaching. J. Agric. Food Chem., 48: 4767-4773. https://doi.org/10.1021/jf9907945

Valles, S.M., P.G. Koehler and R.J. Brenner. 1997. Antagonism of fipronil toxicity by piperonyl butoxide and S,S,S-tributyl phosphorotrithioate in the German cockroach (Dictyoptera: Blattellidae). J. Econ. Entomol., 90: 1254-1258. https://doi.org/10.1093/jee/90.5.1254

Vargo, E.L. and C. Husseneder. 2009. Biology of subterranean termites: insights from molecular studies of *Reticulitermes* and *Coptotermes*. Ann. Rev. Entomol., 54: 379-403. https://doi.org/10.1146/annurev.ento.54.110807.090443

Varvel, G.E. and W.W. Wilhelm. 2008. Cob biomass production in the western corn belt. Bioenerg. Res., 1: 223-228. https://doi.org/10.1007/s12155-008-9026-6

Wang, C. and G. Henderson. 2012. Evaluation of three bait materials and their food transfer efficiency in Formosan subterranean termites (Isoptera: Rhinotermitidae). J. Econ. Entomol., 105: 1758-1765. https://doi.org/10.1603/EC12201

Wang, X. and Y. Wu. 2003. Preparation of urea–dialdehyde starch glue. Fin. Spec. Chem., 13: 18-20.

Wilaipon, P., 2008. Density equation of bio-coal briquettes and quantity of maize cob in Phitsanulok, Thailand. Am. J. Appl. Sci., 5: 1808-1811. https://doi.org/10.3844/ajassp.2008.1808.1811

Zhang, J.H., Z.L. Liu and L. Huang. 2009. A review on the termite bait monitoring system. J. Hunan Univ. Art. Sci., 3: 026-032.