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Insecticidal efficacy of pithraj (*Aphanamixis polystachya*) leaf and seed powders against *Tribolium castaneum* larvae in treated wheat

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Abstract

Background The red flour beetle, *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae), is recognized as one of the most prevalent and destructive pests infesting stored grain products. A wide range of studies has explored the use of various plant powders for their potential to manage infestations of *T. castaneum* and other storage pests. In response to growing concerns over the safety and environmental impact of synthetic insecticides, researchers have increasingly turned their attention to botanical alternatives. In this context, the present study investigates the insecticidal potential of leaf and seed powders derived from pithraj (*Aphanamixis polystachya*), a medicinally important plant, against the larval stage of *T. castaneum* under laboratory conditions.

Results For the experiment, larvae of different ages (1, 3, and 5 days old) were exposed to varying doses (1.25–20 mg/g) of treated wheat (Kanchan and Pradip varieties), and their developmental parameters were monitored. Treatments significantly reduced pupal and adult recoveries in a dose-dependent manner, with seed powders exhibiting stronger inhibitory effects than leaf powders. The highest dose (20 mg/g) of seed powder caused complete inhibition of pupation in 1- and 3-day-old larvae. Both powders also significantly prolonged larval and pupal developmental periods and induced deformities in pupae and adults, particularly at higher doses and in younger larvae. Factorial ANOVA confirmed significant interactions among larval age, dose, and wheat variety. The inhibition rate (IR) was calculated to quantify reductions in pupal and adult emergence. The seed powder was more potent in inhibiting the formation of pupae and adult emergence, and lengthening the developmental period.

Conclusion These findings demonstrate that *A. polystachya* powders possess strong insecticidal and growth-disrupting properties, highlighting their potential as eco-friendly alternatives to synthetic insecticides for the management of storage pests like *T. castaneum*.

Keywords *Tribolium castaneum*, *Aphanamixis polystachya*, Botanical insecticide, Stored grain pest, Larval inhibition, Plant powder, Seed powder

Introduction

Stored grain insect pests are among the leading causes of both qualitative and quantitative losses of stored commodities worldwide, accounting for losses ranging from 10 to 40% (Fields, 2006; Lorini and Filho, 2004). One of the most destructive pests in this context is the red flour beetle, *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae), which can reduce wheat flour weight by up

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to 40% (Ajayi & Rahman, 2006; Rees, 2004). This species primarily feeds on the endosperm of seeds, imparting a mouldy odour and clumped consistency to the grain (Keskin & Ozkaya, 2013). Effective pest management strategies are therefore essential to protect stored grains from such degradation.

Currently, synthetic insecticides are commonly employed as grain protectants. However, their continued use raises serious concerns due to their environmental toxicity and potential health hazards to consumers (Salem et al., 2007). Moreover, the extensive and selective application of these chemicals has led to the development of resistance in many stored-product pests, including *T. castaneum*. In light of these challenges, there is a growing need to explore natural, eco-friendly alternatives that are both effective in pest control and safe for human health and grain quality (Mahdi and Rahman, 2008; Salem et al., 2007; Fields, 2006).

In response to increasing resistance and concerns regarding chemical residues, alternative pest control strategies, particularly those involving biological agents and plant-derived substances are being actively investigated. Numerous plant species have shown promising insecticidal activity against *T. castaneum*. Research has examined various plant parts—such as leaves, seeds, bark, and essential oils—either in powdered form or as extracts. Prior studies have reported significant mortality and protective effects with plant powders from *Eucalyptus globulus*, *Moringa oleifera*, and *Annona squamosa*, with increased efficacy at higher concentrations (Singh et al., 2012). Similarly, *Tephrosia purpurea* powder demonstrated notable repellency (Pugazhvendan et al., 2009), while powders of sugar apple and desert date leaves significantly reduced beetle infestation at 7.5 g/25 g of millet grain (Sule, 2009). Combinations of *Zingiber officinale* and *Allium sativum* with rice grains effectively reduced grain damage and adult emergence, while *Azadirachta indica* mixed with wheat grains significantly curtailed adult beetle production (Ahmad et al., 2019). Furthermore, ground black pepper and other plant powders such as neem, eucalyptus, and tulsi have been reported to control *T. castaneum* effectively without impairing seed germination (Krishna & Yadav, 2023; Singh et al., 2022; Ushasri et al., 2022).

Among the lesser-explored botanical candidates is the pithraj tree (*Aphanamixis polystachya*, family Meliaceae), which has shown potential as a natural insecticidal agent. Earlier studies have reported that crude seed extracts of *A. polystachya* exhibit moderate toxicity, strong repellency, and feeding deterrence against rice weevils (Talukder & Howse, 1994a, 1994b). Additionally, methanolic extracts have demonstrated significant toxicity against rice green leafhoppers (Talukder & Miyata, 2002).

However, despite these promising findings, the efficacy of *A. polystachya* leaf and seed powders specifically against *T. castaneum* remains largely unexplored.

This study aims to assess the effects of pithraj (*Aphanamixis polystachya*) leaf and seed powders on the development and survival of *Tribolium castaneum* larvae, with the objective of evaluating the efficacy of pithraj as a plant-based agent for the management of stored-product pests, particularly *T. castaneum*.

Materials and methods

The insect

Mass rearing of red flour beetle

A starter population of the red flour beetle (*Tribolium castaneum* Herbst) was obtained from the stock culture maintained at the Integrated Pest Management (IPM) Laboratory, Institute of Biological Sciences, University of Rajshahi, Bangladesh. The insects were reared in an incubator at 30 ± 0.5 °C on wheat flour, without light or humidity control. Mass rearing followed the method of Mondal and Parween (1997), using glass beakers containing a standard food medium composed of wheat flour and Brewer's yeast in a 19:1 ratio. Crumpled filter paper was added to each beaker to aid insect movement, and the beakers were covered with cloth secured by rubber bands to prevent beetle escape while allowing ventilation. Two wheat varieties, Kanchan and Pradip, collected from the Bangladesh Agricultural Research Institute (BARI), Regional Station, Shyampur, Rajshahi, were used in the experiment. The food medium was prepared as per Park and Frank (1948) by passing both wheat flour and Brewer's yeast through a 250 µm sieve and sterilizing at 120 °C for six hours. The sterilized mixture was stored for at least 15 days to equilibrate with environmental conditions (Khan, 1981). As sterilization hardened the mixture, it was re-powdered and sieved again through a 250 µm mesh before use.

Egg collection and larval age classification

Approximately 500 adult beetles were placed in a beaker containing an adequate amount of standard food medium. The beaker was covered with a thin cloth secured by a rubber band and kept in an incubator at 30 ± 0.5 °C. The following day, eggs were collected by sieving the food through 600 µm and 300 µm mesh sieves to separate adults and eggs, respectively (Khan & Selman, 1981). The collected eggs were transferred to 9 cm diameter glass Petri dishes and incubated at 30 ± 0.5 °C. Newly hatched larvae were gently collected with a fine camel hair brush and transferred to separate Petridishes. For the bioassay, *T. castaneum* larvae of four distinct age groups—1, 3, 6, and 9 days old were used, corresponding approximately to the first, second, third, and fourth

instars, respectively. This age-based instar classification was adopted based on the typical developmental progression of *T. castaneum* larvae under laboratory conditions. To determine the effect of pithraj leaf and seed powders on various biological parameters of *T. castaneum* larvae of desired ages viz. 1, 3, 6 and 9- day old were transferred from the stock culture to Kanchon and Prodig wheat varieties.

Plant extract and dose preparation

Collection and preparation of test plant materials

Leaves and seeds of pithraj (*Aphanamixis polystachya*) were collected from the Rajshahi University Campus (Binodpur area) and Natore district, Rajshahi, Bangladesh. Mature green leaves were harvested, and seeds were collected at the ripening stage. Both were initially shade-dried. For seed preparation, fruit parts (valves and columella) and seed coverings were manually removed, followed by further drying to reduce moisture content. Prior to grinding, leaves and seeds were oven-dried at 40 °C for several hours to ensure complete dehydration, then powdered using an electric grinder.

Preparation of leaf and seed powders

Approximately 500 g of dried leaves and seeds were separately ground into fine powders using an electric grinder. The resulting powders were smooth and slightly sticky, and were passed through a 0.40 mm mesh sieve to obtain uniform dust. Both leaf and seed powders were stored in sealed packets and kept in a refrigerator at 5 °C until used for extract preparation and insect bioassays.

Preparation of doses

For each wheat variety, 30 g of coarsely broken grains was placed in separate 100 ml glass jars. The experimental doses of plant powders were 1.25, 2.5, 5.0, 10, and 20 mg/g of food. To prepare the doses, 2 ml of analytical-grade acetone was added to the required amount of powder, then mixed thoroughly with the coarsely broken wheat grains using a glass rod and hand shaking for approximately 10 min. Control treatments received the same amount of acetone without powder. The jars with treated food were left open for one hour to allow the complete evaporation of acetone, with occasional stirring to ensure proper evaporation. After evaporation, the treated food was divided into three 10 g replicates for further testing.

Experimental procedures

A total of 90 larvae from each age group were separately exposed to 10 g of treated food (from both Kanchon and Prodig wheat varieties) in 9 cm diameter Petri dishes until adult emergence. Control groups consisted of an

equal number of larvae exposed to acetone-treated food (without extract) for both wheat varieties. Each treatment was replicated three times, with 90 larvae per dose for each larval age and wheat variety.

The larvae were monitored for pupation, and the larval period was recorded. After pupation, pupae were counted and kept in the same Petri dishes for adult emergence, with the pupal period also noted. Pupal and adult recovery percentages were determined, and any teratogenic effects were observed in the pupae and adults.

All experiments were conducted in an incubator at 29 ± 1 °C without light or humidity control.

Data analyses

The data of different parameters were analysed using Factorial Analysis of Variance (ANOVA). Significant differences between the results of the doses were tested by Tukey's multiple comparison test (1949). The inhibition rate (IR) of pupal and adult recoveries was calculated by using the formula described by Tapondjou et al., (2005):

$$IR(\%) = C_n - T_n / C_n \times 100$$

where, IR = Inhibition rate, C_n = Number insects emerged in the Control batch, and T_n = Number of insects emerged in the treated batch.

Results

The results on the effect of leaf and seed powders on different parameters obtained from various ages of larvae of *T. castaneum* after exposure to treated wheat grains are discussed in the following paragraphs.

Effect on pupal and adult recoveries

Leaf and seed powders treatments significantly decreased the percentage of pupation ($F = 108.01$ and $F = 3016.0$, $P < 0.001$ respectively for LP (Leaf Powder) and SP (Seed Powder)). Pupal recovery (%) was found to affect more with the increase of both LP and SP treatments. The number of pupae obtained was differed among the ages of larvae exposed to treated wheat grains in case of both the treatment schedules ($F = 55.79$ and $F = 543.54$, $P < 0.001$ for LP and SP respectively), and in case of seed treatments wheat varieties deleteriously reduced the pupation of *T. castaneum* ($F = 71.82$, $P < 0.001$). Pupation was gradually reduced at all the doses of LP and SP treated wheat grains irrespective of the ages of larvae. It was observed that exposure of larvae of all ages to SP treated Kanchon and Prodig varieties, pupation was detrimentally reduced at all the doses and reduction was increased upto 100% at 20 mg/g dosage in comparison to Controls in 1- and 3-day old larvae (Table 1).

The results on adult recovery (%) obtained from LP and SP treatments are presented in (Table 2). Adult

Table 1 Formation (%) of pupae from *T. castaneum* larvae of different ages and F-value of factorial ANOVA on formation of pupae on wheats treated with leaf and seed powders

Plant parts	Doses mg/g	Kanchon				Prodip				F-values	
		1-day Mean ± SE	3-day Mean ± SE	6-day Mean ± SE	9-day Mean ± SE	1-day Mean ± SE	3-day Mean ± SE	6-day Mean ± SE	9-day Mean ± SE		
Leaf	0 (Control)	99.33 ± 0.67 ^a	100.00 ± 0.00 ^a	100.00 ± 0.00 ^a	100.00 ± 0.00 ^a	100.00 ± 0.00 ^a	100.00 ± 0.00 ^a	100.00 ± 0.00 ^a	100.00 ± 0.00 ^a	a108.01***	
	1.25	84.67 ± 2.40 ^{ab}	82.67 ± 1.76 ^b	86.67 ± 1.33 ^b	97.33 ± 1.76 ^a	73.33 ± 1.76 ^b	88.67 ± 2.40 ^{ab}	95.33 ± 1.76 ^{ab}	90.67 ± 1.76 ^{ab}	b55.79***	
	2.50	78.00 ± 5.29 ^c	80.00 ± 1.15 ^{bc}	75.33 ± 1.76 ^c	94.00 ± 2.00 ^a	69.33 ± 0.67 ^{bc}	85.33 ± 2.40 ^{ab}	89.33 ± 2.40 ^b	89.33 ± 1.76 ^b	c2.30 ^{NS}	
	5.00	74.00 ± 5.03 ^d	74.00 ± 1.15 ^{cd}	74.00 ± 1.15 ^{cd}	92.67 ± 2.67 ^{ab}	66.67 ± 1.76 ^{cd}	84.67 ± 2.91 ^{ab}	86.67 ± 3.53 ^{bc}	83.33 ± 1.76 ^{bc}		
	10.00	72.67 ± 4.67 ^e	70.00 ± 1.15 ^d	72.67 ± 1.76 ^{cd}	84.00 ± 2.31 ^b	64.67 ± 1.76 ^{cd}	76.67 ± 7.69 ^b	88.67 ± 0.67 ^{bc}	83.00 ± 2.08 ^{bc}		
	20.00	70.00 ± 5.29 ^f	70.00 ± 2.31 ^d	68.67 ± 0.67 ^d	84.67 ± 1.76 ^b	62.67 ± 1.33 ^d	78.67 ± 4.06 ^b	78.67 ± 2.40 ^c	76.67 ± 3.71 ^c		
Seed	0 (Control)	99.33 ± 0.67 ^a	100.00 ± 0.00 ^a	100.00 ± 0.00 ^a	100.00 ± 0.00 ^a	100.00 ± 0.00 ^a	100.00 ± 0.00 ^a	100.00 ± 0.00 ^a	100.00 ± 0.00 ^a	a3016.0***	
	1.25	72.67 ± 1.76 ^b	82.00 ± 1.15 ^b	80.67 ± 1.76 ^b	88.00 ± 1.15 ^b	78.00 ± 1.15 ^b	90.00 ± 1.15 ^b	84.00 ± 3.06 ^b	90.00 ± 1.15 ^b	b543.84***	
	2.50	64.67 ± 2.40 ^c	58.00 ± 2.31 ^c	72.67 ± 1.76 ^b	77.33 ± 1.76 ^c	69.33 ± 0.67 ^c	73.33 ± 2.91 ^c	74.67 ± 2.91 ^{bc}	80.67 ± 0.67 ^c	c71.82***	
	5.00	37.33 ± 1.76 ^d	32.67 ± 1.76 ^d	62.00 ± 2.00 ^c	71.33 ± 1.33 ^c	42.67 ± 1.76 ^d	46.67 ± 1.76 ^d	66.67 ± 3.53 ^c	74.00 ± 1.15 ^d		
	10.00	6.67 ± 1.33 ^e	6.67 ± 1.76 ^e	44.00 ± 3.06 ^d	56.67 ± 1.76 ^d	15.33 ± 1.76 ^e	15.33 ± 2.40 ^e	48.00 ± 1.15 ^d	58.00 ± 1.15 ^e		
	20.00	0.00 ± 0.00 ^e	0.00 ± 0.00 ^e	12.67 ± 0.67 ^e	36.67 ± 2.40 ^e	0.00 ± 0.00 ^f	0.00 ± 0.00 ^f	14.00 ± 2.31 ^e	40.00 ± 2.31 ^f		

Alphabets (a, b, c) are used in the F-value column to indicate the source of variation: a = between doses, b = between ages, c = between variety
Alphabets in other columns, which typically indicate groupings from Tukey's multiple comparison test, Means followed by the same letter within a column are not significantly different at p ≤ 0.05 according to Tukey's multiple comparison test. Different letters indicate statistically significant differences among treatment means

Table 2 Formation (%) of adults from *T. castaneum* larvae of different ages and F-value of factorial ANOVA on emergence of adults on wheats treated with leaf and seed powders

Plant parts	Doses mg/g	Kanchon			Prodip			F-values		
		1-day	3-day	6-day	9-day	1-day	3-day	6-day	9-day	
		Mean ± SE	Mean ± SE	Mean ± SE	Mean ± SE	Mean ± SE	Mean ± SE	Mean ± SE	Mean ± SE	
Leaf	0 (Control)	99.33 ± 0.67 ^a	100.00 ± 0.00 ^a	100.00 ± 0.00 ^a	100.00 ± 0.00 ^a	100.00 ± 0.00 ^a	100.00 ± 0.00 ^a	100.00 ± 0.00 ^a	100.00 ± 0.00 ^a	a ¹ 48.24***
	1.25	84.67 ± 2.40 ^{ab}	82.67 ± 1.76 ^b	86.67 ± 1.33 ^b	90.00 ± 2.31 ^b	73.33 ± 1.76 ^b	88.00 ± 2.00 ^b	94.67 ± 2.40 ^{ab}	85.33 ± 2.40 ^b	b ¹ 46.71***
	2.50	77.33 ± 5.46 ^b	79.33 ± 1.76 ^{bc}	74.67 ± 1.33 ^c	90.67 ± 2.67 ^b	66.67 ± 0.67 ^c	84.67 ± 2.91 ^{bc}	88.67 ± 1.76 ^b	87.33 ± 2.40 ^{bc}	c ¹ 3.62 ^{NS}
	5.00	74.00 ± 5.03 ^b	72.67 ± 0.67 ^{cd}	70.67 ± 2.40 ^c	90.67 ± 1.76 ^b	64.67 ± 0.67 ^{cd}	84.67 ± 2.91 ^{bc}	86.00 ± 3.06 ^{bc}	78.67 ± 1.33 ^{bc}	
	10.00	72.00 ± 4.00 ^b	69.33 ± 0.67 ^d	70.67 ± 1.33 ^c	80.67 ± 0.67 ^c	62.67 ± 0.67 ^{cd}	82.00 ± 2.00 ^{bc}	85.33 ± 2.40 ^{bc}	80.00 ± 1.15 ^{bc}	
	20.00	70.00 ± 5.29 ^b	68.00 ± 3.06 ^d	68.00 ± 1.15 ^c	79.33 ± 0.67 ^c	62.00 ± 1.15 ^d	76.67 ± 2.91 ^c	76.67 ± 2.40 ^c	74.00 ± 5.03 ^c	
Seed	0 (Control)	99.33 ± 0.67 ^a	100.00 ± 0.00 ^a	100.00 ± 0.00 ^a	100.00 ± 0.00 ^a	100.00 ± 0.00 ^a	100.00 ± 0.00 ^a	100.00 ± 0.00 ^a	100.00 ± 0.00 ^a	a ³ 203.00***
	1.25	70.67 ± 2.91 ^b	81.33 ± 1.33 ^b	81.33 ± 2.67 ^b	86.67 ± 1.76 ^b	77.33 ± 1.33 ^b	89.33 ± 0.67 ^b	83.33 ± 2.67 ^b	88.67 ± 1.33 ^b	b ³ 480.13***
	2.50	62.00 ± 1.15 ^c	55.33 ± 2.91 ^c	74.00 ± 2.00 ^b	72.00 ± 3.06 ^c	67.33 ± 0.67 ^c	71.33 ± 3.71 ^c	73.33 ± 3.53 ^{bc}	77.33 ± 0.67 ^c	c ³ 76.76***
	5.00	32.67 ± 1.76 ^d	30.67 ± 0.67 ^d	56.00 ± 2.00 ^c	66.67 ± 0.67 ^c	40.00 ± 0.00 ^d	44.00 ± 1.15 ^d	65.33 ± 2.91 ^c	69.33 ± 0.67 ^d	
	10.00	4.00 ± 1.15 ^e	6.00 ± 1.15 ^e	42.67 ± 2.67 ^d	52.00 ± 1.15 ^d	12.67 ± 1.33 ^e	14.00 ± 1.15 ^e	43.33 ± 1.76 ^d	54.00 ± 2.00 ^e	
	20.00	0.00 ± 0.00 ^e	0.00 ± 0.00 ^e	11.33 ± 1.33 ^e	31.33 ± 1.33 ^e	0.00 ± 0.00 ^f	0.00 ± 0.00 ^f	10.67 ± 1.76 ^e	36.00 ± 2.31 ^f	

Alphabets (a, b, c) are used in the F-value column to indicate the source of variation: a = between doses, b = between ages, c = between variety
Alphabets in other columns, which typically indicate groupings from Tukey's multiple comparison test, Means followed by the same letter within a column are not significantly different at p ≤ 0.05 according to Tukey's multiple comparison test. Different letters indicate statistically significant differences among treatment means
Degrees of freedom (df), between doses: 5, between ages: 3 and between variety: 1
*** : Significant at 0.001%, NS: Non-Significant

recovery was deleteriously reduced at all the doses of LP ($F = 148.24$, $P < 0.001$) and SP ($F = 3203.00$, $P < 0.001$) treatments. Similar to pupal recovery, significant variation in adult recovery was observed between the ages of larvae in case of both LP and SP treatments ($P < 0.001$) whereas among the wheat varieties ($F = 76.76$, $P < 0.001$) only for SP treatments. It was also observed that the effect of SP treatments was more detrimental than LP in the production of pupal and adult progenies. However, larvae of younger ages were more susceptible to both powder treated wheat varieties.

Effect on the developmental periods

When *T. castaneum* larvae of different ages were exposed to wheats treated with LP and SP the developmental period of the larvae was increased. The larvae of Control batches completed their development in Kan- chon at 23.50 ± 0.20 days and in Prodig at 24.00 ± 0.50 days, which were found to lower than the treated larvae (Table 3). The larval period was observed to increase significantly with the increase of doses of LP and SP ($F = 113.21$ and $F = 794.00$, $P < 0.001$ respectively), which was differed significantly among the ages of larvae and wheat varieties also ($P < 0.001$).

The developmental period of *T. castaneum* pupae developed from larvae of LP and SP treated wheat grains was also lengthened significantly ($F = 83.96$ and $F = 336.61$, $P < 0.001$ for LP and SP respectively). Statistically significant variations in the development of pupae were observed between the ages for LP and SP treatments ($F = 21.70$ and $F = 312.89$, $P < 0.001$) and varieties ($F = 8.83$, $P < 0.01$ for LP and $F = 32.16$, $P < 0.001$ for SP) (Table 4).

Effect on the production of pupal and adult deformities

Exposure of larvae to LP and SP treated wheat grains a significant number of deformed pupae and adults were produced ($P < 0.001$). Deformities such as larval-pupal intermediate stage, pupal-adult intermediate stage and deformed adult elytra were observed. Deformities between doses were highly significant for both larvae and adult. Comparatively more deformed individuals were produced from larvae of younger ages and at higher doses of both the treatment schedules and wheat varieties. In case of both leaf and seed treatments difference was observed in production of adult deformities between the larval ages. Deformities in either pupae or adults were noticed at all the doses of LP and SP, larval ages and wheat varieties (Tables 5 and 6).

Discussion

The present study demonstrated that both leaf and seed powders of *Aphanamixis polystachya* significantly increased the developmental periods of *Tribolium*

castaneum. The highest developmental delays were recorded at elevated doses and when applied to older larval stages. These findings suggest that the powders possess growth-disrupting properties that interfere with normal development. Furthermore, a significant reduction in progeny production was observed, indicating strong toxic effects and potential for long-term pest population suppression.

Numerous recent studies have investigated the efficacy of various botanical powders against *T. castaneum*, a major pest of stored grains. For instance, eucalyptus leaf powder at a 2% concentration caused 27.25% adult mortality (Tripathi & Patel, 2018). At higher concentrations (5%), eucalyptus powder also exhibited strong repellent activity on larvae (46.01%), while red pepper powder was most effective against adults, causing 71.46% mortality. Moringa powder demonstrated even greater efficacy, causing 66.67% mortality in both larvae and adults at 5% concentration. These powders, when applied at concentrations ranging from 1 to 7.5%, can cause adult mortality, reduce larval development, and suppress adult emergence (Abdullah et al., 2025).

Other botanicals have shown similar promise. *Azadirachta indica* (neem) powder applied at 20 g/250 g of seeds was found to be as effective as aluminum phosphide in protecting groundnut seeds, with only 0.75% weight loss after six weeks (Onoja, 2015). Likewise, powders of *Dracaena arborea* and *Vitex grandifolia* (5 g/500 g seeds) were reported to perform comparably to phosphoxin in minimizing seed damage (Epidi & Odili, 2009). Black pepper powder at a 6% concentration emerged as the most effective repellent and insecticide against *T. castaneum* larvae (Aljoboory, 2019).

In addition to powders, botanical insecticides from *Psidium guajava* and *Citrus reticulata*, along with synthetic agents such as methoprene, have also shown efficacy against *T. castaneum* (Naveed et al., 2013). Other commonly available botanicals like garlic, ginger, and neem seed powders have proven effective in reducing infestations in stored grains (Ahmad et al., 2019).

Plant powders, particularly sugar apple powder at a concentration of 30% w/w, have been shown to effectively control the red flour beetle (*Tribolium castaneum*) in stored millet by inhibiting larval development, reducing adult emergence, and inducing mortality (Ahmed et al., 2010). Studies on the effects of plant powders on deformities across different life stages of *Tribolium castaneum* are relatively scarce. However, another study reported that feeding *Rhyzopertha dominica* larvae on wheat grains treated with plant powders resulted in abnormalities at all developmental stages. Among the tested powders, *Nigella sativa* seed powder was found to be the most effective in inducing deformities compared

Table 3 Developmental period (days) of *T. castaneum* larvae of different ages and F value of factorial ANOVA on developmental period after exposure to wheats treated with leaf and seed powders

Plant part	Dosesmg/g	Kanchon				Prodip				F-values
		1-day	Mean ± SE	3-day	Mean ± SE	6-day	Mean ± SE	9-day	Mean ± SE	
Leaf	0 (Control)	23.50 ± 0.29 ^c	23.50 ± 0.29 ^c	23.50 ± 0.29 ^b	23.50 ± 0.29 ^e	24.00 ± 0.50 ^b	24.00 ± 0.50 ^b	24.00 ± 0.50 ^d	24.00 ± 0.50 ^d	a ¹ 13.21***
	1.25	24.83 ± 0.44 ^{bc}	24.50 ± 0.29 ^{bc}	27.33 ± 0.33 ^a	28.50 ± 0.58 ^d	26.00 ± 0.29 ^b	25.50 ± 1.00 ^{ab}	27.67 ± 0.67 ^a	28.50 ± 0.76 ^c	b ⁹ 6.65***
	2.50	26.83 ± 0.17 ^{ab}	25.00 ± 0.29 ^{abc}	27.83 ± 0.83 ^a	30.67 ± 0.88 ^{cd}	26.50 ± 0.76 ^b	26.67 ± 0.60 ^{ab}	28.67 ± 1.01 ^a	29.83 ± 0.44 ^{bc}	c ¹ 2.09***
	5.00	27.33 ± 0.33 ^{ab}	25.50 ± 0.29 ^{ab}	29.00 ± 0.87 ^a	31.33 ± 0.73 ^{bc}	26.50 ± 0.87 ^b	26.50 ± 0.58 ^{ab}	29.83 ± 0.44 ^a	30.83 ± 0.17 ^{abc}	
	10.00	29.00 ± 1.00 ^a	25.67 ± 0.33 ^{ab}	29.50 ± 0.87 ^a	32.50 ± 0.76 ^{ab}	30.33 ± 0.60 ^a	27.17 ± 1.01 ^{ab}	30.50 ± 0.87 ^a	32.33 ± 0.44 ^{ab}	
	20.00	29.50 ± 0.76 ^a	26.67 ± 0.73 ^a	30.50 ± 1.04 ^a	34.67 ± 0.17 ^a	31.33 ± 0.44 ^a	28.00 ± 1.04 ^a	30.50 ± 0.76 ^a	34.50 ± 0.87 ^a	
Seed	0 (Control)	23.50 ± 0.29 ^c	23.50 ± 0.29 ^d	23.50 ± 0.29 ^c	23.50 ± 0.29 ^d	24.00 ± 0.50 ^d	24.00 ± 0.50 ^d	24.00 ± 0.50 ^d	24.00 ± 0.50 ^d	a ⁷ 94.00***
	1.25	27.00 ± 1.15 ^b	27.00 ± 0.58 ^c	28.67 ± 0.33 ^b	29.33 ± 0.33 ^c	25.83 ± 0.73 ^{cd}	25.83 ± 0.44 ^{cd}	28.00 ± 0.58 ^b	28.67 ± 0.67 ^c	b ⁶ 72.03***
	2.50	28.33 ± 0.88 ^b	28.33 ± 0.60 ^{bc}	30.67 ± 0.17 ^{ab}	31.00 ± 0.58 ^{bc}	26.67 ± 0.67 ^{abc}	27.17 ± 0.44 ^{bc}	29.33 ± 0.60 ^{ab}	30.00 ± 0.58 ^{bc}	c ² 2.94***
	5.00	29.17 ± 0.44 ^{ab}	29.83 ± 0.60 ^{ab}	30.83 ± 0.33 ^{ab}	31.50 ± 0.50 ^b	28.00 ± 0.58 ^{bc}	28.17 ± 0.44 ^{ab}	29.67 ± 0.44 ^{ab}	31.00 ± 0.29 ^{abc}	
	10.00	30.00 ± 0.58 ^{ab}	30.33 ± 0.60 ^{ab}	31.50 ± 1.26 ^{ab}	32.83 ± 0.44 ^{ab}	29.00 ± 0.58 ^{ab}	29.50 ± 0.29 ^a	30.33 ± 0.73 ^{ab}	31.83 ± 0.44 ^{ab}	
	20.00	31.83 ± 0.44 ^a	0.00 ± 0.00 ^a	0.00 ± 0.00 ^a	34.50 ± 0.29 ^a	0.00 ± 0.00 ^a	0.00 ± 0.00 ^a	31.67 ± 0.33 ^a	32.83 ± 0.44 ^a	

Alphabets (a, b, c) are used in the F-value column to indicate the source of variation: a = between doses, b = between ages, c = between variety

Alphabets in other columns, which typically indicate groupings from Tukey's multiple comparison test. Means followed by the same letter within a column are not significantly different at p ≤ 0.05 according to Tukey's multiple comparison test. Different letters indicate statistically significant differences among treatment means

Degrees of freedom (df), between doses = 5, between ages = 3 and between variety = 1

*** = Significant at 0.001%, NS = Non-Significant

Table 4 Developmental period (days) of *T. castaneum* pupae developed from larvae of different ages and F value of factorial ANOVA on developmental period after exposure to wheats treated with leaf and seed powders

Plant parts	Doses mg/g	Kanchon		Prodip					F-values	
		1-day Mean $\pm$ SE	3-day Mean $\pm$ SE	6-day Mean $\pm$ SE	9-day Mean $\pm$ SE	1-day Mean $\pm$ SE	3-day Mean $\pm$ SE	6-day Mean $\pm$ SE		9-day Mean $\pm$ SE
Leaf	0 (Control)	6.67 $\pm$ 0.44 ^c	6.67 $\pm$ 0.44 ^c	6.67 $\pm$ 0.44 ^b	6.67 $\pm$ 0.44 ^d	7.67 $\pm$ 0.17 ^b	7.67 $\pm$ 0.17 ^c	7.67 $\pm$ 0.17 ^c	7.67 $\pm$ 0.17 ^d	a83.96***
	1.25	8.50 $\pm$ 0.50 ^{bc}	7.67 $\pm$ 0.17 ^b	9.33 $\pm$ 0.33 ^{ab}	9.50 $\pm$ 1.04 ^{cd}	8.50 $\pm$ 0.29 ^b	9.50 $\pm$ 0.29 ^{bc}	10.83 $\pm$ 0.93 ^{bc}	9.33 $\pm$ 0.44 ^{cd}	b21.70***
	2.50	10.17 $\pm$ 0.17 ^{ab}	8.00 $\pm$ 0.29 ^{bc}	11.00 $\pm$ 0.87 ^{ab}	10.67 $\pm$ 1.17 ^{bc}	8.83 $\pm$ 0.44 ^b	10.50 $\pm$ 0.29 ^{ab}	12.67 $\pm$ 1.33 ^{ab}	11.33 $\pm$ 0.44 ^{bc}	c8.83**
	5.00	10.50 $\pm$ 0.00 ^{ab}	9.50 $\pm$ 0.76 ^{abc}	12.33 $\pm$ 1.48 ^{ab}	13.17 $\pm$ 0.60 ^{abc}	9.33 $\pm$ 0.44 ^b	11.50 $\pm$ 0.58 ^{ab}	13.67 $\pm$ 0.17 ^{ab}	11.67 $\pm$ 0.88 ^{bc}	
	10.00	11.33 $\pm$ 0.44 ^a	10.83 $\pm$ 0.60 ^{ab}	13.17 $\pm$ 1.86 ^a	14.00 $\pm$ 0.50 ^{ab}	13.67 $\pm$ 0.44 ^a	11.33 $\pm$ 0.73 ^{ab}	14.00 $\pm$ 0.50 ^{ab}	13.33 $\pm$ 1.01 ^{ab}	
	20.00	11.67 $\pm$ 1.09 ^a	12.00 $\pm$ 1.04 ^a	14.50 $\pm$ 1.80 ^a	16.50 $\pm$ 0.58 ^a	13.83 $\pm$ 1.01 ^a	12.17 $\pm$ 0.88 ^a	14.50 $\pm$ 0.29 ^a	15.17 $\pm$ 0.33 ^a	
Seed	0 (Control)	6.83 $\pm$ 0.33 ^c	6.83 $\pm$ 0.33 ^e	6.83 $\pm$ 0.33 ^d	6.83 $\pm$ 0.33 ^e	7.50 $\pm$ 0.29 ^d	7.50 $\pm$ 0.29 ^d	7.50 $\pm$ 0.29 ^e	7.50 $\pm$ 0.29 ^e	a336.61***
	1.25	8.17 $\pm$ 0.44 ^c	9.67 $\pm$ 0.17 ^d	9.67 $\pm$ 0.17 ^c	10.17 $\pm$ 0.17 ^d	8.67 $\pm$ 0.44 ^{cd}	9.50 $\pm$ 0.29 ^c	9.00 $\pm$ 0.29 ^d	9.17 $\pm$ 0.44 ^{de}	b312.89***
	2.50	10.17 $\pm$ 0.44 ^b	10.50 $\pm$ 0.29 ^{cd}	11.50 $\pm$ 0.76 ^{bc}	11.83 $\pm$ 0.44 ^{cd}	9.00 $\pm$ 0.29 ^{cd}	10.67 $\pm$ 0.17 ^{bc}	9.83 $\pm$ 0.17 ^{cd}	10.33 $\pm$ 0.60 ^{cd}	c32.16***
	5.00	11.00 $\pm$ 0.29 ^b	11.67 $\pm$ 0.17 ^{bc}	12.83 $\pm$ 0.44 ^{ab}	13.00 $\pm$ 0.50 ^{bc}	10.00 $\pm$ 0.29 ^{bc}	11.50 $\pm$ 0.29 ^{ab}	10.83 $\pm$ 0.44 ^{bc}	11.67 $\pm$ 0.60 ^{bc}	
	10.00	11.50 $\pm$ 0.50 ^b	12.67 $\pm$ 0.17 ^{ab}	13.33 $\pm$ 0.44 ^{ab}	14.00 $\pm$ 0.29 ^{ab}	11.33 $\pm$ 0.33 ^{ab}	12.00 $\pm$ 0.29 ^{ab}	12.00 $\pm$ 0.29 ^{ab}	13.00 $\pm$ 0.29 ^{ab}	
	20.00	0.00 $\pm$ 0.00 ^a	0.00 $\pm$ 0.00 ^a	14.67 $\pm$ 0.33 ^a	15.50 $\pm$ 0.29 ^a	0.00 $\pm$ 0.00 ^a	0.00 $\pm$ 0.00 ^a	13.17 $\pm$ 0.17 ^a	14.00 $\pm$ 0.29 ^a	

Alphabets (a, b, c) are used in the F-value column to indicate the source of variation: a = between doses, b = between ages, c = between variety

Alphabets in other columns, which typically indicate groupings from Tukey's multiple comparison test, Means followed by the same letter within a column are not significantly different at $p \leq 0.05$ according to Tukey's multiple comparison test. Different letters indicate statistically significant differences among treatment means

Degrees of freedom (df), between doses = 5, between ages: 3 and between variety: 1

, Significant at 0.01%, *, Significant at 0.001%

Table 5 Deformities in *T. castaneum* pupae developed from larvae of different ages and F value of factorial ANOVA on deformity after exposure to wheats treated with leaf and seed powders

Plant parts	Doses mg/g	Kanchon				Prodip				F-values
		1-day Mean $\pm$ SE	3-day Mean $\pm$ SE	6-day Mean $\pm$ SE	9-day Mean $\pm$ SE	1-day Mean $\pm$ SE	3-day Mean $\pm$ SE	6-day Mean $\pm$ SE	9-day Mean $\pm$ SE	
Leaf	0 (Control)	0.00 $\pm$ 0.00 ^c	0.00 $\pm$ 0.00 ^b	0.00 $\pm$ 0.00 ^b	0.00 $\pm$ 0.00 ^a	0.00 $\pm$ 0.00 ^c	0.00 $\pm$ 0.00 ^b	0.00 $\pm$ 0.00 ^a	0.00 $\pm$ 0.00 ^c	^a 31.81***
	1.25	0.67 $\pm$ 0.67 ^{bc}	2.67 $\pm$ 1.33 ^{ab}	2.00 $\pm$ 1.15 ^{ab}	2.67 $\pm$ 0.67 ^a	1.33 $\pm$ 0.67 ^{bc}	1.33 $\pm$ 0.67 ^{ab}	2.67 $\pm$ 0.67 ^a	1.33 $\pm$ 0.67 ^{bc}	^b 2.58 ^{NS}
	2.50	4.67 $\pm$ 1.33 ^{ab}	4.00 $\pm$ 1.15 ^{ab}	2.00 $\pm$ 1.15 ^{ab}	2.00 $\pm$ 1.15 ^a	2.67 $\pm$ 0.67 ^{abc}	2.67 $\pm$ 0.67 ^{ab}	2.00 $\pm$ 1.15 ^a	1.33 $\pm$ 0.67 ^{bc}	^c 0.83 ^{NS}
	5.00	2.67 $\pm$ 0.67 ^{abc}	2.67 $\pm$ 0.67 ^{ab}	1.33 $\pm$ 0.67 ^{ab}	2.67 $\pm$ 1.76 ^a	3.33 $\pm$ 0.67 ^{abc}	3.33 $\pm$ 1.33 ^{ab}	2.67 $\pm$ 0.67 ^a	1.33 $\pm$ 0.67 ^{bc}	
	10.00	4.00 $\pm$ 1.15 ^{abc}	3.33 $\pm$ 0.67 ^{ab}	4.00 $\pm$ 1.15 ^{ab}	4.00 $\pm$ 1.15 ^a	6.00 $\pm$ 1.15 ^{ab}	4.67 $\pm$ 0.67 ^a	3.33 $\pm$ 0.67 ^a	3.33 $\pm$ 0.67 ^{ab}	
	20.00	6.00 $\pm$ 1.15 ^a	5.33 $\pm$ 0.67 ^a	4.67 $\pm$ 0.67 ^a	4.67 $\pm$ 0.67 ^a	5.33 $\pm$ 1.33 ^a	4.67 $\pm$ 0.67 ^a	3.33 $\pm$ 0.67 ^a	4.00 $\pm$ 0.00 ^a	
Seed	0 (Control)	0.00 $\pm$ 0.00 ^b	0.00 $\pm$ 0.00 ^c	0.00 $\pm$ 0.00 ^b	0.00 $\pm$ 0.00 ^c	0.00 $\pm$ 0.00 ^b	0.00 $\pm$ 0.00 ^a	0.00 $\pm$ 0.00 ^a	0.00 $\pm$ 0.00 ^b	^a 23.59***
	1.25	2.67 $\pm$ 0.67 ^{an}	2.67 $\pm$ 0.67 ^{ab}	0.67 $\pm$ 0.67 ^b	1.33 $\pm$ 1.33 ^{bc}	2.00 $\pm$ 0.00 ^{ab}	1.33 $\pm$ 0.67 ^a	1.33 $\pm$ 1.33 ^a	1.33 $\pm$ 0.67 ^{ab}	^b 2.69 ^{NS}
	2.50	3.33 $\pm$ 0.67 ^{ab}	2.67 $\pm$ 0.67 ^{ab}	2.67 $\pm$ 1.33 ^{ab}	1.33 $\pm$ 0.67 ^{bc}	3.33 $\pm$ 1.33 ^a	2.00 $\pm$ 1.15 ^a	2.67 $\pm$ 0.67 ^a	2.00 $\pm$ 1.15 ^{ab}	^c 1.85 ^{NS}
	5.00	2.67 $\pm$ 0.67 ^{ab}	2.00 $\pm$ 0.00 ^{bc}	2.67 $\pm$ 0.67 ^{ab}	2.00 $\pm$ 0.00 ^{bc}	2.00 $\pm$ 0.00 ^{ab}	3.33 $\pm$ 1.33 ^a	3.33 $\pm$ 1.33 ^a	3.33 $\pm$ 0.67 ^{ab}	
	10.00	4.00 $\pm$ 1.15 ^a	4.67 $\pm$ 0.67 ^a	4.67 $\pm$ 0.67 ^a	4.00 $\pm$ 0.00 ^{ab}	3.33 $\pm$ 0.67 ^a	2.67 $\pm$ 0.67 ^a	2.67 $\pm$ 0.67 ^a	2.67 $\pm$ 0.67 ^{ab}	
	20.00	00	00	5.33 $\pm$ 0.67 ^a	5.33 $\pm$ 0.67 ^a	00	00	4.00 $\pm$ 0.00 ^a	4.67 $\pm$ 0.67 ^a	

Alphabets (a, b, c) are used in the F-value column to indicate the source of variation: a = between doses, b = between ages, c = between variety

Alphabets in other columns, which typically indicate groupings from Tukey's multiple comparison test, Means followed by the same letter within a column are not significantly different at $p \leq 0.05$ according to Tukey's multiple comparison test. Different letters indicate statistically significant differences among treatment means

Table 6 Deformities in *T. castaneum* adults developed from larvae of different ages and F value of factorial ANOVA on deformity on wheats treated with leaf and seed powders

Plant parts	Doses mg/g	Kanchon				Prodip				F-values
		1-day Mean $\pm$ SE	3-day Mean $\pm$ SE	6-day Mean $\pm$ SE	9-day Mean $\pm$ SE	1-day Mean $\pm$ SE	3-day Mean $\pm$ SE	6-day Mean $\pm$ SE	9-day Mean $\pm$ SE	
Leaf	0 (Control)	0.00 $\pm$ 0.00 ^c	0.00 $\pm$ 0.00 ^b	0.00 $\pm$ 0.00 ^b	0.00 $\pm$ 0.00 ^b	0.00 $\pm$ 0.00 ^c	0.00 $\pm$ 0.00 ^b	0.00 $\pm$ 0.00 ^b	0.00 $\pm$ 0.00 ^a	^a 40.96***
	1.25	2.67 $\pm$ 0.67 ^{bc}	2.67 $\pm$ 0.67 ^{ab}	3.33 $\pm$ 0.67 ^{ab}	4.00 $\pm$ 1.15 ^{ab}	4.67 $\pm$ 0.67 ^{ab}	2.00 $\pm$ 0.00 ^{ab}	4.00 $\pm$ 1.15 ^a	2.67 $\pm$ 0.67 ^a	^b 2.70*
	2.50	6.00 $\pm$ 1.15 ^{ab}	3.33 $\pm$ 0.67 ^{ab}	4.00 $\pm$ 2.00 ^{ab}	3.33 $\pm$ 0.67 ^{ab}	5.33 $\pm$ 1.33 ^{ab}	1.33 $\pm$ 0.67 ^{ab}	2.00 $\pm$ 1.15 ^{ab}	2.67 $\pm$ 0.67 ^a	^c 2.28 ^{NS}
	5.00	2.67 $\pm$ 0.67 ^{bc}	2.67 $\pm$ 1.76 ^{ab}	4.00 $\pm$ 0.00 ^{ab}	2.67 $\pm$ 0.67 ^{ab}	2.67 $\pm$ 0.67 ^{bc}	4.00 $\pm$ 2.31 ^{ab}	2.67 $\pm$ 0.67 ^{ab}	2.67 $\pm$ 1.33 ^a	
	10.00	4.67 $\pm$ 0.67 ^{ab}	3.33 $\pm$ 0.67 ^{ab}	6.00 $\pm$ 0.00 ^a	5.33 $\pm$ 0.67 ^a	7.33 $\pm$ 0.67 ^a	5.33 $\pm$ 0.67 ^a	4.67 $\pm$ 0.67 ^a	4.67 $\pm$ 1.76 ^a	
	20.00	6.67 $\pm$ 0.67 ^a	6.00 $\pm$ 1.15 ^a	7.33 $\pm$ 0.67 ^a	6.67 $\pm$ 1.33 ^a	5.33 $\pm$ 0.67 ^{ab}	5.33 $\pm$ 0.67 ^a	4.00 $\pm$ 0.00 ^a	4.67 $\pm$ 0.67 ^a	
Seed	0 (Control)	0.00 $\pm$ 0.00 ^c	0.00 $\pm$ 0.00 ^b	0.00 $\pm$ 0.00 ^c	0.00 $\pm$ 0.00 ^c	0.00 $\pm$ 0.00 ^c	0.00 $\pm$ 0.00 ^b	0.00 $\pm$ 0.00 ^b	0.00 $\pm$ 0.00 ^c	^a 33.12***
	1.25	3.33 $\pm$ 0.67 ^b	2.67 $\pm$ 0.67 ^{ab}	1.33 $\pm$ 1.33 ^{bc}	2.67 $\pm$ 1.76 ^{abc}	2.67 $\pm$ 0.67 ^{bc}	2.00 $\pm$ 1.15 ^{ab}	1.33 $\pm$ 1.33 ^{ab}	1.33 $\pm$ 0.67 ^{bc}	^b 0.80 ^{NS}
	2.50	4.67 $\pm$ 0.67 ^{ab}	4.67 $\pm$ 0.67 ^a	2.67 $\pm$ 0.67 ^{abc}	1.33 $\pm$ 0.67 ^{bc}	3.33 $\pm$ 1.33 ^{ab}	2.67 $\pm$ 0.67 ^{ab}	2.00 $\pm$ 0.00 ^{ab}	1.33 $\pm$ 0.67 ^{bc}	^c 4.98*
	5.00	3.33 $\pm$ 0.67 ^b	3.33 $\pm$ 0.67 ^{ab}	3.33 $\pm$ 0.67 ^{abc}	3.33 $\pm$ 0.67 ^{abc}	4.00 $\pm$ 0.00 ^{ab}	4.00 $\pm$ 1.15 ^a	3.33 $\pm$ 0.67 ^{ab}	3.33 $\pm$ 0.67 ^{ab}	
	10.00	5.33 $\pm$ 0.67 ^{ab}	4.67 $\pm$ 1.33 ^a	4.67 $\pm$ 0.67 ^{ab}	4.67 $\pm$ 0.67 ^{ab}	4.67 $\pm$ 0.67 ^{ab}	4.00 $\pm$ 0.00 ^a	4.00 $\pm$ 1.15 ^a	3.33 $\pm$ 0.67 ^{ab}	
	20.00	00	00	6.00 $\pm$ 1.15 ^a	6.00 $\pm$ 0.00 ^a	00	00	4.67 $\pm$ 0.67 ^a	4.67 $\pm$ 0.67 ^a	

Alphabets (a, b, c) are used in the F-value column to indicate the source of variation: a = between doses, b = between ages, c = between variety

Alphabets in other columns, which typically indicate groupings from Tukey's multiple comparison test, Means followed by the same letter within a column are not significantly different at $p \leq 0.05$ according to Tukey's multiple comparison test. Different letters indicate statistically significant differences among treatment means

Degrees of freedom (df), between doses: 5, between ages: 3 and between variety: 1

*: Significant at 0.05%, ***: Significant at 0.001%, NS: Non-Significant

to various plant leaf powders (Mohal et al., 2006). A study reported that coffee powder significantly prolonged the larval and pupal durations of *Tribolium castaneum*, and also led to a marked reduction in pupal recovery and adult emergence following treatment (Mostakim & Khan, 2015).

Despite the wealth of research on plant-based powders, no prior studies have explored the efficacy of *A. polystachya* (pithraj) leaf and seed powders against *T. castaneum*. Previous work has only established the insecticidal and repellent effects of *A. polystachya* seed extracts against rice weevils and rice green leafhoppers (Talukder

& Howse, 1994a, 1994b; Talukder & Miyata, 2002). The findings from the present investigation fill this knowledge gap and reveal that both the leaf and seed powders of *A. polystachya* possess promising toxic and repellent properties against *T. castaneum*.

Conclusion

These results suggest the potential of *A. polystachya* powders as a sustainable and eco-friendly alternative to synthetic insecticides in the management of storage pests. However, further studies are essential to evaluate their cost-effectiveness for large-scale application, explore long-term storage safety, and conduct comparative analyses with other botanical powders to validate their efficacy under diverse storage conditions. The findings obtained under laboratory conditions may not necessarily translate to effective insect control on a larger, practical scale.

Abbreviations

ANOVA	Analysis of Variance (ANOVA)
SP	Seed Powder
LP	Leaf Powder
IR	Inhibition Rate

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Author contributions

SK: conceptualization, data collection, writing-original draft, formal analysis. SIF: conceptualization and supervising. SH: review and editing. All authors reviewed the manuscript.

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Ethics approval and consent to participate

No ethical approval is required.

Consent for publication

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