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RESEARCH ARTICLE

Potential use of indigenous medicinal weeds as grain protectants in hilly regions of North-East India

Devina Seram[1*], Haobijam James Watt[2], Aquiny B T Mawthoh[1], Chandrakumar Singh Khumukcham[3], Ganeshkumar D Rede[4] & Deepa Thangjam[5]

[1]Department of Entomology, School of Agriculture, Lovely Professional University, Phagwara 144 411, Punjab, India
[2]Department of Agricultural Economics and Extension, School of Agriculture, Lovely Professional University, Phagwara 144 411, Punjab, India
[3]Department of Natural Resource Management, College of Horticulture, Veer Chandra Singh Garhwali Uttarakhand University of Horticulture and Forestry, Ranichauri 246 123, Uttarakhand, India
[4]Symbiosis Institute of Business Management, Constituent of Symbiosis International (Deemed University), Pune 440 008, Maharashtra, India
[5]Department of Rural Development and Planning, School of Agricultural Sciences, Nagaland University, Dimapur 798 627, Nagaland, India

*Correspondence email - devnah@gmail.com

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Abstract

Seed beetles are widely prevalent and economically destructive storage pest that infest stored grains on a global scale. Apart from other climatic challenges, Northeast Indian farmers struggle with these pests, resulting in considerable losses in terms of both quantity and quality. The primary objective of this study was to identify environmentally sustainable, readily available and novel alternatives to synthetic insecticides for their management, in addition to neem. In this context, the effectiveness of 6 different indigenous medicinal weeds was studied against the storage beetle (*Callosobruchus chinensis*) and demonstrated through various experiments on its biological parameters, such as oviposition inhibition, adult mortality and adult emergence percentage, which also correlates with seed damage percentage. The results indicated that seeds treated with *Calotropis* exhibited the highest mean mortality, the lowest oviposition and the most seed damage, while *Zanthoxylum* emerged as the subsequent successful treatment, highlighting its first report of insecticidal properties against this storage pest. This was followed by *Argemone*, *Ageratum* and *Eupatorium*. *Lantana* leaf powder demonstrated the lowest adult mortality rate and highest grain damage; nevertheless, it may be utilised during periods when other plants are scarce. These findings indicate that utilising indigenous medicinal plants as grain protectants during storage can be a viable and environmentally safe alternative to chemicals, provided that they do not possess any potential toxicity risk to people and the grains are thoroughly washed after the treatment priorto consumption. This technique not only promotes sustainability but also preserves the use of native botanical resources, which may benefit local farmers. Further research and development are required to understand their chemical compositions completely and use them as valuable plants.

Keywords: good health; indigenous plants; medicinal weeds; North-East India; seed protectant; zero hunger

Introduction

Pulses play a significant role in human dietary needs due to their high protein content (20–30 %), minerals, vitamin B, amino acids, etc. (1). The provision of an adequate quantity of animal protein to a large population in developing nations presents several critical issues and the escalating demand for protein in response to a growing population has gotten progressively severe. India is a significant contributor to the production of various pulses, occupying an extensive land area of 31 million hectares (2). Additionally, official data from India indicates a substantial production output of 26.96 million tonnes (3). In India and other Asian countries, various cereals (rice, maize, sorghum, etc.) and leguminous crops are cultivated, namely green gram (*Vigna radiata* (L.) R.Wilczek), black gram (*V. mungo* (L.) Hepper), chickpea (*Cicer arietinum* L. var. *kabulium*), bengal gram (*Cicer arietinum* L.), lentil (*Lens culinaris* Medik. ssp. *culinaris*), cowpea (*Vigna unguiculata* (L.) Walp.), pigeon pea (*Cajanus cajan* (L.) Millsp.), pea (*Pisum sativum* L.), french bean (*Vicia faba* L.) etc., which are highly preferred and consumed. Given the rising demand for pulses in our dietary intake, it is imperative to assess the losses incurred at various phases spanning from harvest to consumption. According to estimates, the storage loss of pulses in India amounts to 8.5 % (4), of which insect accounts for 2–4.2 % (5).

Pulses experience significant deterioration during storage periods because of various abiotic and biotic factors such as temperature, humidity, storage structure, bacteria, fungi, insects, rodents and birds, which contributes to both quantitative and qualitative degradation. Within the category of insects, the storage beetle particularly in *Callosobruchus* genus poses a serious threat (6). This genus comprises several economically significant species, among which *C. maculatus* and *C. chinensis* are known to inflict considerable damage during several stages of crop growth, both in field and storage conditions (7). It is a significant pest in the tropical and sub-tropical regions and its presence has been documented in various countries including the Philippines, Japan, Indonesia, Sri Lanka, Pakistan, Burma, India, Africa, etc. (8). Substantial income losses are observed in storage facilities, particularly in rural regions of developing nations, where grain legumes are stored in outdated sacks or mud bins (9). The insect, being an endophagous pest, poses an important challenge in terms of pesticide control. Fumigation is well recognised as a highly efficacious technique, however, combining pesticides with food grains is not recommended due to their potential health hazards (10). Moreover, its implementation in rural and hilly regions is hindered due to the absence of hermetically sealed storage facilities, which are predominantly situated in residential or urban regions. The government grain agencies of tropical countries like India, the Food Corporation of India (FCI) and the Indian Grain Storage Management and Research Institute (IGMRI) only store about a fifth of the harvest in large-scale warehouses in urban centres (3). The vast majority are reserved for sustenance and held in conventional granaries (5). Farmers take significant financial and health risks when they use pesticides. Therefore, the use of fumigants or residual pesticides is unnecessary for controlling storage insects in small-scale agriculture. Native farmers in the poor world have long relied on plant remedies and recent research suggests that these remedies are both safe and effective (10). In the tropics, it has long been an accepted practice to store grains with local plants parts, especially neem. However, due to the lack of sophisticated instruments in the synthesis of necessary ingredients (e.g. powder, slurries) and compounds as botanical insecticides, the resource poor farmers generally utilize the indigenous plant resources, which are readily available and affordable.

Despite its reputation as a global centre of biodiversity and traditional knowledge of medicinal weeds, the Northeastern region of India has received comparatively little attention from researchers. Seed beetles in the genus *Callosobruchus* spp. are the most common storage insect pest in all parts of India including this hilly region. Several studies have been conducted on the development and growth as well as their management using commonly available natural plant oils and powders; however, most of these studies have focused on *C. maculatus* species. Moreover, there lacks a systematic study on the utilization of native plants as eco-friendly grain protectant. Hence, the present study aimed to evaluate the insecticidal potential of six indigenous medicinal weeds against the storage pest, *C. chinensis*, under laboratory conditions.

Materials and Methods

Investigation site, source of test insect and its maintenance

The current research was conducted at the Entomology laboratory, Centre for Plant Protection, Division of Crop Science, ICAR Research Complex for North-Eastern Hill (NEH) Region, Barapani, Meghalaya, India (Geographical coordinates at 25°41’ 21” N and 91°55’ 25” E and altitude of 1010 m above mean sea level). The test insect, pulse beetle (*Callosobruchus chinensis*), was obtained from stock cultures maintained in the Entomology laboratory, ICAR-RC-NEH Region. Insect cultures were maintained on whole grains of green gram (*V. radiata*) in 500 mL glass jars inside an incubator predetermined at 27 ± 1 °C temperature and 70 % RH (11). In the initial phase, 50 pairs of newly emerged 1–2 days old adults were introduced into a container with green gram seeds. Insects were closely confined for 7 days for the purpose of copulation and oviposition. Subsequently, the emerged progenies were isolated and the infested seeds were discarded. Progenies were then transferred to pristine seeds and the cycle was continued. Newly emerged adults were separated time to time from the cultures and sexing (males and females) was done (12).

Source of plants and its powder preparation

The study entailed conducting surveys in the fields of ICAR-Research Complex, NEH Region, Meghalaya, India and

Table 1. Details of medicinal weed plants of North-East India used in the present study

Sl. No.	Common name	Scientific name	Family	Part used	Medicinal Properties	References
1	Crown flower	*Calotropis gigantea* (L.) W. T. Aiton	Apocynaceae	Leaves	Antidote for snake bite, sinus fistula, rheumatism, mumps, burn injuries and body pain; treat asthma, colds, coughs, diarrhea, fever, indigestion, leprosy, leukoderma and rheumatism in Ayurveda, Chinese and homeopathic medicines	(13), (14)
2	Mexican prickly poppy	*Argemone mexicana* L.	Papaveraceae	Leaves	Treatment for eye inflammation, wounds; antidote for snake poisoning and when mixed with mustard oil, cure for itchy skin; Anticancer potential; Treatment for warts, cold sores, skin diseases, itching and jaundice	(15)
3	Lantana weed	*Lantana camara* L.	Verbenaceae	Leaves	Treatment for cuts, rheumatisms, ulcers, catarrhal infection, tetanus, rheumatism, malaria, cancer, chicken pox, asthma, ulcer, swelling, eczema, tumour, high blood pressure, bilious fever, ataxy of abdominal viscera, sores, measles, fevers, cold and high blood pressure; Treatment of skin itches and antiseptic for wounds and externally for leprosy and scabies	(16)
4	Goat weed	*Ageratum conyzoides* L.	Meliaceae	Flowers	Cure for kidney stones, cuts, wounds; Properties of antipneumonia, pain killer, anti-inflammatory agent, antiasthma, antispasmodic, haemostatic, gastrointestinal disorder, gynaecological disorder, antileprosy and many other skin diseases; medicine for diarrhea, scratches, inflammation, snakebite	(17)
5	Siam weed	*Eupatorium odoratum* (= *Chromolaena odorata* (L.) R.M.King & H.Rob.)	Asteraceae	Leaves	Treatment for wounds, burns, stomach problems and skin infections; Also shown to possess anticancer, antidiabetic, anti-hepatotoxic, anti-inflammatory, antimicrobial, antioxidant properties;	(18)
6	Prickly ash or Andaliman	*Zanthoxylum acanthopodium* DC.	Rutaceae	Leaves	Antibacterial, antifungal, anti-inflammatory, anticancer, cardio-protective, hepatoprotective, nephroprotective and wound healing properties; Health promoting properties such as anti-sickling, anticancer and anti-infectious disease activities; Treatment for gastritis, stomach colic, gastritis, liver disorder and toothache, etc.; usage as tonic in fever and bowel complaints, anti-typhoid; Treatment for fever, flu, stomachache, traumatic injury and mosquito bite, etc.	(19), (20)

collecting fresh leaves from medicinal weed plant species belonging to six different families, previously been documented to possess therapeutic characteristics (Table 1). The plants included lantana weed (*Lantana camara* L.), crown flower (*Calotropis gigantea* (L.) W.T.Aiton), Mexican prickly poppy (*Argemone mexicana* L.), siam weed (*Eupatorium odoratum* L. = *Chromolaena odorata* (L.) R.M.King & H.Rob.), goat weed (*Ageratum conyzoides* L.) and Andaliman or prickly ask (*Zanthoxylum acanthopodium* DC.) (Table 1). The leaves were washed with water and then shade dried for 15 days. Afterwards, dried leaves were ground into a fine powder using an electric grinder and then passed through a 25-mesh sieve to obtain a purified powder. The powders were stored in individual vials under hermetic conditions for further experimentation.

Effectiveness of medicinal weed leaf powders against seed beetle

An insect susceptible green gram variety of North-East Indian region (var. Tripura Mung 1) was used for testing the different effects of medicinal weed powders. Different dosages, namely 5, 10, 15, 20 and 25 g of the freshly prepared powders were added to separate containers, each having 1 kg of green gram seeds and mixed thoroughly by adding few drops of sunflower oil to ensure uniform coating or enhance the protective action of powders on seeds and to act as a carrier/adjuvant. The dosage was selected as per earlier reports on similar experiments using plant powders and to determine the minimum effective dose and potential phytotoxicity thresholds of the tested medicinal weeds (8).

Oviposition inhibition effect, adult mortality, adult emergence

Oviposition inhibition effects were evaluated by following standard methodology (21), with certain modifications. From each 1 kg lot of treated seeds, 100 seeds were randomly selected and kept in separate vials. To these vials, ten pairs (10 males, 10 females) of newly emerged 0–24 hr old adult beetles were transferred and kept undisturbed inside the incubator maintained at 30 °C and 70 % RH (22). Mortality of adult beetles was recorded separately for each treatment at 1, 3, 5 and 7 days after transfer (DAT) for calculating adult mortality per cent (11). Experiments were conducted in 3 replications and control was maintained without any treatment. Number of eggs laid was recorded after 3, 5 and 7 days using a special egg counting device. Egg hatching per cent and adult emergence per cent were recorded from all the treatments using following formulae (22).

$$\text{Adult mortality (\%)} = \frac{\text{No. of dead beetles}}{\text{Total no. of beetles released}} \times 100$$

$$\text{Egg hatching (\%)} = \frac{\text{Total no. of eggs hatched}}{\text{Total no. of eggs laid}} \times 100$$

$$\text{Adult emergence (\%)} = \frac{\text{Total no. of adults emerged}}{\text{Total no. of eggs hatched}} \times 100$$

Seed damage and percentage seed weight reduction

Number of damaged seeds and number of holes made by emerging adults were counted for calculating per cent seed damage (11, 23). To ascertain the extent of seed weight loss, data were collected for both initial seed weight and final seed weight before and after insect infestation in each treatment. Percentage weight reduction or seed weight loss was calculated using standard formula (24).

$$\text{Seed damage (\%)} = \frac{\text{No. of damaged seeds with holes}}{\text{Total no. of seeds taken}} \times 100$$

$$\text{Seed weight loss (\%)} = \frac{\text{(Initial weight-Final weight)}}{\text{Initial weight}} \times 100$$

Mortality of offsprings (days)

Mortality of newly emerged adults (F1 offsprings) from seeds of each treatment was checked daily by transferring and confining five pairs separately in empty containers and observations were made daily on dead and live offsprings until the death of all insects (25). This experiment was performed in three replicates without provision of host seeds.

Seed protein estimation (%)

After insect infestation, 30 g seeds from each treatment, including control, were pulverized and a 100 mg portion was placed in a 50 mL polyethylene screw cap bottle. Subsequently, 25 mL of 1 N NaOH was added. Protein dispersion was achieved by subjecting the mixture to 30 min of agitation in a wrist action shaker. A 10 mL volume of the suspension was transferred into a graduated test tube and employed as a blank to account for variations in the quantity of naturally occurring pigments extracted, as well as to compensate for the remaining suspension in the bottle. Subsequently, 0.25 mL of a 10 % copper sulphate solution was introduced to the bottle, which was then agitated for another 5 min to facilitate formation of colour complex. Solution was then transferred into a test tube and allowed to stand overnight, facilitating the sedimentation of dispersed material. Following a centrifugation period of 10 min, optical density (OD) of the transparent supernatant solution was assessed using an Optima UV-VIS spectrophotometer (Model SP-3000) equipped with a red filter (620 nm). Similar estimation was done for powdered infected seeds. Protein content was derived from mean OD value using the standard formula (26).

$$\text{Protein content (\%)} = 3.78 + (61.6 \times \text{OD value})$$

Seed germination test (%)

After three months of leaf powder treatment, the viability of treated and untreated seeds was compared. Fifty seeds showing no signs of insect damage were selected from each treatment and immersed in water for 8 hr. Seeds were then placed on blotting paper in petri dishes, kept moist for four days and placed inside the germination chamber set at 25 °C and 12:12 L:D conditions, which is suitable for seeds requiring light. Experiment was conducted in 3 replicates and germination of seeds was evaluated for each treatment. Total number of both sprouted and unsprouted seeds were counted and expressed as germination percentage (27). Germination tests and seed protein determination were conducted at the Centre for Biotechnology, Division of Crop Science, ICAR-Research Complex for NEH Region.

$$\text{Seed germination (\%)} = \frac{\text{No. of sprouted or germinated seeds}}{\text{Total No. of seeds taken}} \times 100$$

Statistical analysis of data

Data relevant to the current study were subjected to statistical analysis using Fisher's method of analysis of variance in a Completely Randomized Design (CRD). Determination of significant and non-significant outcomes of variance attributable to treatments and phases of observation was conducted by computing the relevant 'F' values (28). Calculation of standard error of the mean difference was performed by utilizing the following mathematical expression:

$$\text{S. Ed. } (\pm) = \sqrt{\frac{2 \text{ x Error mean square}}{\text{Number of replications}}}$$

Critical Difference (CD) was calculated to find out the significance or non-significance of mean of differences amongst treatments by using the following formula:

$$\text{Critical difference (CD)} = \text{S.Ed} \pm \text{x t}$$

Where, t = tabulated value of 't' at p = 0.05 level of significance for appropriate degrees of freedom.

Results and Discussion

Biological responses of seed beetle on treatment with different medicinal weed leaf powders

Oviposition (Number of eggs laid)

Results of the current study indicate a considerable reduction in oviposition when green gram seeds are treated with various medicinal weed leaf powders, compared to the control (untreated). For *Lantana* powder, the minimum oviposition (38.40 and 44.20 eggs) was observed on seeds treated with 25 g and 20 g and the maximum was recorded in 5 g/kg seed treatment (70.60) (Table 2). This trend was observed to be similar for all treatments. At the highest dose (25 g/kg), low oviposition record of 27.2 eggs, 24.2 eggs, 38.60 eggs, 31.80 eggs and 25.8 eggs were observed in the treatment with *Argemone* (Table 3), *Calotropis* (Table 4), *Eupatorium* (Table 5), Ageratum (Table 6) and *Zanthoxylum* (Table 7), respectively, indicating that powders of these plants were successful in deterring oviposition by the beetles on seeds, when compared to control (86.60 eggs) (untreated). Data presented in Tables 2–7 shows a consistent decline in oviposition with increasing powder concentration. It can be noted that egg-laying by beetles started from first day after transfer (DAT) and continued up to seven DAT.

It has been reported that use of plant powders significantly reduced the fecundity of *C. chinensis* (29). A study was conducted to evaluate the repellent and deterrent effects of some botanical powders on oviposition and adult emergence of *C. chinensis* (30). It was reported that *Murraya koenigii* (L.) Spreng. was the most effective in preventing oviposition, which could be due to the influence of chemical constituents found in the plant powder that might have altered insect behaviour and physiology. In the present study, the most effective plants which acted as oviposition deterrent were *Calotropis* followed by *Zanthoxylum* (Table 8). As *Zanthoxylum* species are rich in alkaloids and limonoids typical of Rutaceae, these compounds may account for the deterrent and ovicidal effects observed (19, 20). Several studies have also reported evidence of antioxidant, analgesic, anti-inflammatory, anti-diarrheal, anticonvulsant, anti-malarial, hepatoprotective, antitumour and antimicrobial properties of *Calotropis* spp. (13, 14, 24). A few species of *Calotropis* which are not widely recognized have shown different pharmacological actions, due to the presence of effective secondary metabolites (14).

Egg hatching (%)

Data on egg hatching percentage revealed that treatments with all the powders were significantly superior in reducing egg hatching (%) than the control and hatching of eggs decreased with the increase in concentration. At 25 g/kg, *Calotropis* recorded the lowest egg hatching (46.17 %), followed by *Zanthoxylum* (48.71 %), *Argemone* (49.21 %) and *Ageratum* (50.71 %) (Table 2). This reduction may be due to interference of plant secondary metabolites with the micropyle function or embryonic respiration. At 5 g powder dosage, higher egg hatching percentages were observed for all treatments, i.e. *Calotropis* (62.20 %), *Argemone* (71.05 %), *Eupatorium* (77.20 %), *Ageratum* (69.40 %) and *Zanthoxylum* (69.40 %) (Table 3–7). It has been reported that seed treatment with *Calotropis* decreases the egg hatching rate of *C. maculatus* when compared to control (31), which is in conformity with the present investigation. This may be possibly due to more effective adhesion of compounds on micropyle of eggs which either creates an obstacle in their rupturing or induces some unknown physiological changes resulting in the failure of hatching (32). Moreover, flavonoids derived from *Calotropis* leaves exhibit ovicidal activity against *C. chinensis* (24).

Table 2. Effectiveness of *Lantana camara* leaf powder against *Callosobruchus chinensis* infesting green gram seeds

Sl. No.	Dosage (g/kg of seeds)	Adult mortality (%) after release				Number of eggs/100 seeds			Egg hatching (%)	Adult emergence (Nos.)	*Seed damage (%)	Seed weight loss (%)
		1 DAT	3 DAT	5 DAT	7 DAT	3 DAT	5 DAT	7 DAT				
1	5	6 (14.04)^{a}	14 (21.47)^{a}	12 (19.87)^{bc}	16 (22.97)^{cd}	30.20^{b}	54.60^{b}	70.60^{b}	78.32 (54.35)^{b}	73 (51.92)^{b}	70.00^{b}	7.69 (15.89)b
2	10	4 (11.46)^{b}	12 (19.87)^{a}	14 (21.47)^{ab}	20 (25.71)^{bc}	28.00^{b}	50.40^{b}	59.00^{c}	76.60 (53.53)^{bc}	62 (46.96)^{c}	63.33^{c}	7.53 (15.73)b
3	15	8 (16.21)^{a}	10 (18.13)^{a}	14 (21.47)^{ab}	16 (22.97)^{cd}	24.40^{bc}	40.40^{c}	52.20^{d}	73.24 (51.94)^{c}	57 (44.88)^{cd}	56.67^{d}	6.47 14.58)bc
4	20	10 (18.13)^{a}	18 (24.38)^{a}	22 (26.98)^{ab}	30 (31.63)^{a}	25.80^{bc}	31.40^{d}	44.20^{e}	63.74 (47.63)^{d}	57 (44.70)^{cd}	53.33^{d}	6.27 (14.35)bc
5	25	18 (24.38)^{a}	22 (26.98)^{a}	26 (29.38)^{a}	36 (34.77)^{a}	20.80^{c}	30.80^{d}	38.40^{e}	64.29 (47.88)^{d}	55 (44.12)^{d}	47.33^{e}	5.95 (13.98)c
6	Control	0.00 (0.00)^{b}	2 (8.10)^{b}	4 (11.46)^{c}	6 (16.21)^{d}	40.20^{a}	71.80^{a}	86.60^{a}	89.57 (60.37)^{a}	80 (55.37)^{a}	80.00^{a}	11.63 (19.56)a
SEd (±)	-	4.82	3.25	3.25	3.00	2.08	2.18	2.46	0.88	0.99	1.45	0.57
CD (0.05)	-	13.50	9.10	9.10	8.40	5.81	6.10	6.89	2.46	2.76	2.56	1.60

Values are mean of 3 replications; Number of adults released in all the treatments = 20 (10 pairs). Figures within parenthesis are angular transformed values; DAT- Days after transfer (insect); Means having the same letters are not significantly different at p = 0.05 level; *In some cases, one or two insects emerged from a single seed.

Table 3. Effectiveness of *Argemone mexicana* leaf powder against *Callosobruchus chinensis* infesting green gram seed

Sl. No.	Dosage (g/kg of seeds)	Adult mortality (%) after release				Number of eggs/100 seeds			Egg hatching (%)	Adult emergence (Nos.)	*Seed damage (%)	Seed weight loss (%)
		1 DAT	3 DAT	5 DAT	7 DAT	3 DAT	5 DAT	7 DAT				
1	5	4 (11.46)^{ab}	10 (18.13)^{bc}	18 (24.38)^{b}	40 (36.76)^{a}	29.00^{b}	53.40^{b}	66.80^{b}	71.05 (50.93)^{b}	64 (48.18)^{b}	62.33^{b}	5.04 (12.87)^{b}
2	10	10 (18.13)^{a}	14 (21.47)^{ab}	22 (26.98)^{ab}	44 (38.67)^{a}	27.20^{bc}	42.20^{c}	58.80^{c}	65.22 (48.30)^{c}	58 (45.25)^{bc}	54.67^{bc}	4.79 (12.54)^{b}
3	15	14 (21.47)^{a}	22 (26.98)^{ab}	22 (26.98)^{ab}	48 (40.54)^{a}	24.40^{c}	33.80^{d}	46.00^{d}	58.18 (45.15)^{d}	53 (43.26)^{c}	51.67^{bc}	4.16 (11.68)^{bc}
4	20	18 (24.38)^{a}	30 (31.63)a	34 (33.75)^{a}	44 (38.67)^{a}	17.40^{d}	27.20^{e}	37.80^{e}	54.92 (43.69)^{d}	41 (37.60)^{d}	39.33^{de}	4.20 (11.75)^{bc}
5	25	18 (24.38)^{a}	30 (31.63)^{a}	36 (34.77)^{a}	56 (44.17)^{a}	13.40^{c}	19.40^{f}	27.20^{f}	49.21 (41.10)^{e}	39 (36.64)^{d}	35.67^{de}	3.23 (10.30)^{c}
6	Control	0 (0.00)^{b}	2 (8.10)^{c}	4 (11.46)^{c}	8 (16.21)^{b}	40.20^{a}	71.80^{a}	86.60^{a}	89.58 (60.37)^{a}	80 (55.37)^{a}	80.00^{a}	11.63 (19.56)^{a}
SEd (±)	-	4.70	3.96	3.31	3.58	1.42	2.01	2.01	0.83	1.13	1.45	0.53
CD (0.05)	-	13.16	11.09	9.25	10.01	3.98	5.62	5.63	2.31	3.17	2.56	1.49

Values are mean of 3 replications; Number of adults released in all the treatments = 20 (10 pairs). Figures within parenthesis are angular transformed values; DAT - Days after transfer (insect). Means having the same letters are not significantly different at p = 0.05 level; *In some cases, one or two insects emerged from a single seed.

Table 4. Effectiveness of *Calotropis gigantea* leaf powder against *Callosobruchus chinensis* infesting green gram seeds

Sl. No.	Dosage (g/kg of seeds)	Adult mortality (%) after release				Number of eggs/100 seeds			Egg hatching (%)	Adult emergence (Nos.)	*Seed damage (%)	Seed weight loss (%)
		1 DAT	3 DAT	5 DAT	7 DAT	3 DAT	5 DAT	7 DAT				
1	5	12 (19.47)^{a}	14 (21.47)^{a}	20 (25.71)^{a}	20 (41.46)^{a}	25.60^{b}	45.60^{b}	62.20^{b}	65.57 (48.45)^{b}	59 (45.77)^{b}	55.33^{bc}	5.11 (12.95)^{b}
2	10	16 (22.97)^{a}	16 (22.97)^{a}	20 (25.71)^{a}	48 (40.54)^{a}	24.60^{b}	35.60^{c}	51.40^{c}	63.78 (47.65)^{b}	55 (44.17)^{b}	51.67^{bc}	4.58 (12.26)^{bc}
3	15	16 (22.97)^{a}	18 (24.38)^{a}	26 (29.38)^{a}	48 (40.54)^{a}	17.00^{c}	27.80^{d}	36.00^{d}	55.32 (43.87)^{b}	46 (39.96)^{b}	40.00^{bc}	4.36 (11.96)^{bc}
4	20	22 (26.98)^{a}	24 (28.21)^{a}	32 (32.70)^{a}	58 (45.07)^{a}	13.60^{c}	25.40^{d}	32.60^{d}	54.49 (43.50)^{c}	46 (39.65)^{c}	39.67^{d}	3.27 (10.36)^{cd}
5	25	22 (26.98)^{a}	24 (28.21)^{a}	32 (32.70)^{a}	62 (46.85)^{a}	9.20^{d}	17.60^{e}	24.20^{e}	46.17 (39.70)^{d}	34 (34.08)^{d}	25.33^{e}	2.18 (8.47)^{d}
6	Control	0 (0.00)^{b}	2 (8.10)^{b}	4 (11.46)^{b}	8 (16.21)^{b}	40.20^{a}	71.80^{a}	86.60^{a}	89.57 (60.37)^{a}	80 (55.37)^{a}	80.00^{a}	11.63 (19.56)^{a}
SEd (±)	-	2.09	3.46	4.16	3.86	1.40	1.92	2.76	0.75	1.02	1.45	0.75
CD (0.05)	-	5.86	9.68	11.65	10.81	3.91	5.37	7.73	2.09	2.85	2.56	2.10

Values are mean of 3 replications; Number of adults released in all the treatments = 20 (10 pairs). Figures within parenthesis are angular transformed values; DAT - Days after transfer (insect); Means having the same letters are not significantly different at p = 0.05 level; *In some cases, 1 or 2 insects emerged from a single seed.

Table 5. Effectiveness of *Eupatorium odorata* leaf powder against *Callosobruchus chinensis* infesting green gram seed

Sl. No.	Dosage (g/kg seeds)	Adult mortality (%) after release				Number of eggs/100 seeds			Egg hatching (%)	Adult emergence (Nos.)	*Seed damage (%)	Seed weight loss (%)
		1 DAT	3 DAT	5 DAT	7 DAT	3 DAT	5 DAT	7 DAT				
1	5	0 (0.00)	2 (8.10)	10 (18.13)^{ab}	26 (29.38)^{a}	33.80^{b}	57.80^{b}	77.20^{b}	77.18 (53.80)^{b}	71 (51.13)^{b}	69.33^{b}	7.44 (15.64)^{b}
2	10	2 (8.10)	4 (11.46)	12 (19.87)^{ab}	30 (31.63)^{a}	27.40^{C}	54.00^{b}	70.80^{b}	74.23 (52.40)^{bc}	70 (50.62)^{b}	67.33^{b}	7.51 (15.70)^{b}
3	15	4 (11.46)	6 (14.04)	14 (21.47)^{ab}	38 (35.77)^{a}	26.20^{c}	45.80^{c}	59.60^{c}	69.49 (50.22)^{c}	62 (47.21)^{c}	58.67^{cd}	6.23 (14.31)^{bc}
4	20	4 (11.46)	6 (14.04)	14 (21.47)^{ab}	38 (35.77)^{a}	24.20^{c}	28.60^{d}	47.20^{d}	64.16 (47.82)^{d}	56 (44.56)^{cd}	51.33^{cd}	6.24 (14.31)^{bc}
5	25	6 (14.04)	8 (16.21)	20 (25.71)^{a}	40 (36.76)^{a}	17.60^{D}	23.40^{C}	38.60^{e}	60.98 (46.40)^{d}	52 (42.47)^{d}	48.33^{e}	5.93 (13.95)^{c}
6	Control	0 (0.00)	2 (8.10)	4 (11.46)^{b}	8 (16.21)^{b}	40.20^{a}	71.80^{a}	86.60^{a}	89.58 (60.37)^{a}	80 (55.37)^{a}	80.00^{a}	11.63 (19.56)^{a}
SEd (±)	-	NS	NS	5.14	4.06	1.62	1.79	2.41	0.84	0.97	1.45	0.53
CD (0.05)	-	-	-	-	11.38	4.54	5.02	6.75	2.35	2.70	2.56	1.49

Values are mean of 3 replications; Number of adults released in all the treatments = 20 (10 pairs). Figures within parenthesis are angular transformed values; DAT - Days after transfer (insect); Means having the same letters are not significantly different at p = 0.05 level; *In some cases, one or two insects emerged from a single seed.

Table 6. Effectiveness of *Ageratum conyzoides* leaf powder against *Callosobruchus chinensis* infesting green gram seed

Sl. No.	Dosage (g/kg seeds)	Adult mortality (%) after release 1 DAT	3 DAT	5 DAT	7 DAT	Number of eggs/100 seeds 3 DAT	5 DAT	7 DAT	Egg hatching (%)	Adult emergence (Nos.)	*Seed damage (%)	Seed weight loss (%)
1	5	6 (14.04)^{b}	10 (18.13)^{bc}	16 (22.97)^{b}	26 (29.38)^{b}	27.60^{b}	51.00^{b}	60.80^{b}	69.40 (50.18)^{b}	60 (46.22)^{b}	58.67^{b}	5.58 (13.53)^{b}
2	10	12 (19.87)^{ab}	20 (25.71)^{ab}	32 (32.70)^{ab}	38 (35.77)^{ab}	25.40^{bc}	4.60^{b}	55.00^{b}	66.78 (49.00)^{bc}	56 (44.36)^{bc}	53.67^{cd}	5.19 (13.05)^{b}
3	15	20 (25.71)^{ab}	26 (29.38)^{a}	30 (31.63)^{ab}	36 (34.77)^{ab}	23.40^{c}	37.60^{c}	48.20^{c}	62.97 (47.29)^{c}	54 (43.40)^{bc}	51.33^{cd}	5.01 (12.82)^{b}
4	20	22 (26.98)^{a}	28 (30.52)^{a}	36 (34.77)^{a}	42 (37.72)^{ab}	22.00^{c}	32.20^{c}	46.40^{c}	57.59 (44.88)^{d}	50 (41.79)^{c}	49.67^{cd}	4.30 (11.88)^{bc}
5	25	22 (26.98)^{a}	30 (31.63)^{a}	38 (35.77)^{a}	46 (39.61)^{a}	14.40^{d}	24.00^{d}	31.80^{d}	50.71 (41.78)^{e}	41 (37.40)^{d}	38.33^{e}	3.36 (10.51)^{c}
6	Control	0 (0.00)^{c}	2 (8.10)^{c}	4 (11.46)^{c}	8 (16.21)^{c}	40.20^{a}	71.80^{a}	86.60^{a}	89.58 (60.37)^{a}	80 (55.37)^{a}	80.00^{a}	11.63 (19.56)^{a}
SEd (±)	-	4.42	3.96	3.55	0.63	1.39	2.35	2.26	0.83	1.08	1.45	0.63
CD (0.05)	-	12.37	11.09	9.93	1.76	3.89	6.57	6.33	2.33	3.02	2.56	1.76

Values are mean of 3 replications; Number of adults released in all the treatments = 20 (10 pairs). Figures within parenthesis are angular transformed values; DAT - Days after transfer (insect); Means having the same letters are not significantly different at *p* = 0.05 level; *In some cases, one or two insects emerged from a single seed.

Table 7. Effectiveness of *Zanthoxylum acanthopodium* leaf powder against *Callosobruchus chinensis* infesting green gram seed

Sl. No.	Dosage (g/kg seeds)	Adult mortality (%) after release 1 DAT	3 DAT	5 DAT	7 DAT	Number of eggs/100 seeds 3 DAT	5 DAT	7 DAT	Egg hatching (%)	Adult emergence (Nos.)	*Seed damage (%)	Seed weight loss (%)
1	5	6 (14.04)^{b}	10 (18.13)^{bc}	15 (22.97)^{b}	26 (29.38)^{b}	25.60^{b}	50.00^{b}	60.70^{b}	69.40 (50.18)^{b}	60 (46.22)^{b}	58.33^{bc}	5.58 (13.53)^{b}
2	10	12 (19.87)^{ab}	21 (25.71)^{ab}	30 (32.70)^{ab}	38 (35.77)^{ab}	25.40^{bc}	4.60^{b}	54.00^{b}	66.78 (49.00)^{bc}	56 (44.36)^{bc}	53.67^{bc}	5.19 (13.05)^{b}
3	15	19 (25.71)^{ab}	25 (29.38)^{a}	30 (31.63)^{ab}	35 (34.77)^{ab}	22.40^{c}	36.60^{c}	49.20^{c}	62.97 (47.29)^{c}	54.29 (43.40)^{bc}	51.33^{bc}	5.01 (12.82)^{b}
4	20	22 (26.98)^{a}	26 (30.52)^{a}	36 (34.77)^{a}	43 (37.72)^{ab}	23.00^{c}	31.20^{c}	44.40^{c}	57.59 (44.88)^{d}	50 (41.79)^{c}	47.67^{d}	4.30 (11.88)^{bc}
5	25	22 (26.98)^{a}	29 (31.63)^{a}	37 (35.77)^{a}	59 (39.61)^{a}	15.40^{d}	18.00^{d}	25.80^{d}	48.71 (41.78)^{e}	36 (36.40)^{d}	28.67^{e}	2.36 (9.51)^{c}
6	Control	0 (0.00)^{c}	2 (8.10)^{c}	4 (11.46)^{c}	8 (16.21)^{c}	40.20^{a}	71.80^{a}	86.60^{a}	89.58 (60.37)^{a}	80 (55.37)^{a}	80.00^{a}	11.63 (19.56)^{a}
SEd (±)	-	3.46	3.94	3.65	3.63	1.89	2.35	2.85	0.72	0.69	1.45	0.63
CD (0.05)	-	5.67.	10.09	11.92	1.76	3.89	5..57	7.33	7.33	2.79	2.56	2.05

Values are mean of 3 replications; Number of adults released in all the treatments = 20 (10 pairs). Figures within parenthesis are angular transformed values; DAT - Days after transfer (insect); Means having the same letters are not significantly different at *p* = 0.05 level; *In some cases, one or two insects emerged from a single seed.

Table 8. Overall effectiveness of different medicinal weed leaf powders against *Callosobruchus chinensis* infesting green gram seed

Treatments	Dosage (g/kg of seeds)	Adult mortality (%) after release 1 DAT	3 DAT	5 DAT	7 DAT	Number of eggs/100 seeds 3 DAT	5 DAT	7 DAT	Egg hatching (%)	Adult emergence (Nos.)	*Seed damage (%)	Seed weight loss (%)
Lantana	25	18 (24.38)^{ab}	22 (26.98)^{ab}	26 (29.38)^{a}	36 (34.77)^{b}	20.80^{b}	30.80^{b}	38.40^{b}	64.29 (47.88)^{b}	55 (44.12)^{b}	47.33^{b}	5.95 (13.98)^{b}
Argemone	25	22 (24.38)^{a}	30 (31.63)^{a}	36 (34.77)^{a}	56 (44.17)^{ab}	13.40^{d}	19.40^{cd}	27.20^{cd}	49.21 (41.10)^{c}	39 (36.64)^{cd}	35.67^{cd}	3.23 (10.30)^{c}
Calotropis	25	22 (26.98)^{a}	24 (28.21)^{ab}	32 (32.70)^{a}	62 (46.85)^{a}	9.20^{e}	17.60^{d}	24.20^{d}	46.17 (39.70)^{c}	34 (34.08)^{d}	25.33^{e}	2.18 (8.47)^{d}
Eupatorium	25	6 (14.04)^{b}	8 (16.21)^{bc}	20 (25.71)^{ab}	40 (36.76)^{ab}	17.60^{bc}	23.40^{cd}	38.60^{b}	60.98 (46.40)^{b}	52 (42.47)^{b}	48.33^{b}	5.93 (13.95)^{b}
Ageratum	25	18 (26.98)^{ab}	30 (31.63)^{a}	38 (35.77)^{a}	46 (39.61)^{ab}	14.40^{cd}	24.00^{c}	31.80^{c}	50.71 (41.78)^{c}	41 (37.40)^{c}	38.67^{cd}	3.36 (10.51)^{c}
Zanthoxylum	25	22 (26.98)^{a}	29 (31.63)^{a}	37 (35.77)^{a}	59 (39.61)^{a}	15.40^{d}	18..00^{d}	25.80^{d}	48.71 (37.18)^{e}	36 (36.40)^{d}	28.33^{e}	2.36 (9.51)^{c}
Control	-	0 (0.00)^{c}	2 (8.10)^{c}	4 (11.46)^{b}	8 (16.21)^{c}	40.20^{a}	71.80^{a}	86.60^{a}	89.58 (60.37)^{a}	80 (55.37)^{a}	80.00^{a}	11.63 (19.56)^{a}
SEd (±)	-	3.95	4.91	3.66	3.81	1.35	1.86	2.18	1.01	1.13	1.45	0.59
CD (0.05)	-	11.06	13.74	10.24	10.67	3.79	5.20	6.11	2.84	3.18	2.56	1.66

Values are mean of 3 replications; Number of adults released in all the treatments = 20 (10 pairs). Figures within parenthesis are angular transformed values; DAT - Days after transfer (insect). Means having the same letters are not significantly different at *p* = 0.05 level; *In some cases, one or two insects emerged from a single seed.

Adult emergence (Number of adults emerged)

The percentage of *C. chinensis* adult emergence from green gram seeds treated with six different leaf powders was significantly less compared to control (80 adults) (Table 2). *Calotropis* leaf powder treatment at 25 g/kg seed was found to be the most effective in reducing adult emergence, recorded at 34 adults (Table 4 and 8), followed by *Zanthoxylum* (36 adults) and *Argemone* (39 adults). However, there was no significant difference (Table 8). *Lantana* and *Eupatorium* were recorded to be the least effective (87 and 60 adults), (Table 2 and 7). The semi chemical nature of botanical powders alters the behavior and physiology of the insects adversely affecting the process of egg-laying and F1 offspring emergence (30). But the failure of adult emergence could either be due to egg mortality or larval mortality or even reduction in hatching of eggs. The hatched larvae must penetrate the seed cotyledon to feed and survive inside the seeds, but the larvae are unable to do so unless eggs are firmly attached to the seed surface (33). While studying the potency of some indigenous plants against *C. chinensis* and *C. maculatus*, it was reported that plant biochemicals might have affected the physiological behavior such as ovipositional activity, growth inhibition and adult mortality (34). Moreover, since *Calotropis* contains alkaloids that inhibit ovarian development and vitellogenesis in females and sexual maturity in males, it is possible to understand how the treatments affected the emergence of *C. maculatus* (35). The same may be true in the case of medicinal weed leaf powder used in the present investigation. Moreover, the decrease in adult emergence could potentially be accomplished by integrating significant mortality rates of eggs and first instar larvae right after eclosion along with exposure to powder (30).

Adult mortality (%)

The adult mortality due to treatments with different medicinal leaf powders increased with the increase in dosage and time of exposure (Table 8). For all the treatments, the least mortality was observed on the first day of exposure and maximum after seven days (Table 2–7). The percent mortality in *Calotropis* treatment recorded the highest (62 %) at 25 g/kg after 7 DAT. However, it was not significantly different with its treatment doses at 5, 10, 15 and 20 g (Table 4) and with *Zanthoxylum* at 25 g powder (59 %) (Table 8). This was followed by seed treatment with *Argemone* and *Ageratum* recording at 56 % and 46 % (Table 8) but did not differ significantly. The lowest mortality was observed in *Eupatorium* (50 %) and *Lantana* (46 %) (Table 8), which was at par. The treatment of leaf powder on green gram seeds significantly reduced the longevity of *C. chinensis* adults. The present findings agree with previous researchers, who reported that *Calotropis* leaf and bark powder have repellent activity and can also cause mortality of *C. chinensis* (36). Moreover, the mortality could be attributed due to the high flavonoid contents, which may be one of the reasons for deterrence against insects (37). Such deterrence activity of plant powders is due to the diffusion of persistent odours capable of suffocating the beetles in the storage. Plant powders also reduced insect movement and caused death through desiccation or occlusion of their spiracles, preventing respiration via trachea (38). This paper, for the first time, revealed the insecticidal activity of *Zanthoxylum* against *C. chinensis*, which corroborates with previous findings, reported the first larvicidal property of *Zanthoxylum* against the lepidopteran stored insect, *Coryra cephalonica* (39). Such rapid adult mortality suggests potential as a short-term protectant during critical storage periods.

Seed weight reduction (%) and seed damage (%)

Percentage seed weight reduction was studied in terms of mass (weight) loss calculated using initial weight before insect infestation and final weight after infestation. All the treatments were superior to control percent of weight loss. Among all the treatments, the lowest weight loss was recorded in seeds treated at 25 g/kg with *Calotropis* (2.18 %), followed by *Zanthoxylum* (2.36 %), *Argemone* (3.23 %) and *Ageratum* (3.36 %) (Table 8); however, there were no significant differences between the treatments. From this analysis, it can be noted that *Calotropis* leaf powder was most effective in preventing seed weight loss due to *C. chinensis* infestation. These results are supported by the previous researchers, who reported the effectiveness of *Calotropis* in reducing weight loss due to infestations by *Callosobruchus* species (31, 40).

In terms of seed damage (%), the seeds are considered damaged when adults emerge from them, which is directly correlated. However, in some cases, one to two adults emerged from a single seed since *C. chinensis* adults were smaller in size compared to other *Callosobruchus* spp. (22). From the present study, it also revealed that the higher the dosage, the seed damage was less. In *Lantana* treatment (Table 2), the maximum (70 %) seed damage (%) was observed in 5 g leaf powder, which was also the highest among all the treatments (Table 8). Seed treatment with *Eupatorium*, *Ageratum* and *Argemone* also showed the same pattern (Table 3, 5 and 6), thus confirming that at higher dosage, the effectiveness of powders increases for most of the tested medicinal weed plants. Alternatively, the lowest seed damage (%) was recorded in seeds treated with *Calotropis* at 25 g (25.33 %) and *Zanthoxylum* (28.33 %) (Table 3 & 8).

Since ancient times, humans have relied on herbal remedies for both industrial and agricultural uses. Different methods of pest control, including the use of medicinal plants and their extracts or derivatives have been tested for their repellent, antifeedant, fumigant, growth-regulating and oviposition-deterring effects (41). Furthermore, unlike conventional insecticides based on a single active component, botanical insecticides comprising mixtures of chemical compounds can alter both behavioral and physiological processes. As a result, pests are unlikely to develop resistance to these plant compounds (23). The identification of biopesticides that are both efficacious and compatible with indigenous ecosystems and climatic conditions is of paramount importance for the successful implementation of pest control strategies (42). Moreover, in remote rural areas of North-East India, a limited proportion of individuals or farmers employ conventional techniques for managing stored insect pests, primarily due to their cost-effectiveness.

Simultaneously, the loss of traditional knowledge regarding insect control is occurring rapidly, primarily due to the underestimation of its value and advancements in living standards. It has been reported that mechanism of action of plant powders and oils is attributed to their ability to penetrate the chorion of insect eggs via micropyle and cause death of the developing embryos through asphyxiation (43). The active ingredients (a.i) present in these leaves can control larvae inside seed cotyledons, indicating that the powders might penetrate the cotyledons while

Table 9. Effect of different medicinal weed leaf powders on seed viability (germination)

Seeds treatment with	No. of seeds taken for viability test	Seed germination (%)	Seed protein content (%)
Lantana camara	50	73.33^{b}	20.27^{NS}
Calotropis gigantea	50	96.67^{c}	22.45^{NS}
Argemone mexicana	50	80.00^{c}	21.67^{NS}
Eupatorium odorata	50	76.67^{b}	20.45^{NS}
Ageratum conyzoides	50	76.67^{b}	20.57^{NS}
Zanthoxylum acanthopodium	50	93.33^{c}	22.34^{NS}
Control	50	52.33^{a}	18.67^{NS}
SEd (±)	-	3.75	2.15
CD (0.05)	-	4.80	3.65

Values are mean of three replications; NS: Non-significant. Germination test conducted after three months of leaf powder seed treatment. Estimation of seed protein content (%) after insect infestation. Means having the same letters are not significantly different at p = 0.05 level.

egg hatching and chemically inhibit or kill them inside the seeds (38). They also concluded that earlier developmental stages were more susceptible than later stages. This also might be the reason for the delay in *C. chinensis* development in powder-treated seeds. The reduction of infestation and seed damage in pulse seeds treated with botanicals is achieved mainly through reduced egg hatching and increased mortality (44).

Seed germination (%) and protein content (%)

In seed germination test conducted after three months of treatment, it was observed that there was only a small reduction in the germination percentage compared to control (52.33 %) (Table 9). Seeds treated with *Calatropis* and *Zanthoxylum* showed the lowest reduction (96.67 % and 93.33 %) and higher reductions were observed in *Lantana* (73.3 %), *Ageratum* (76.67 %) and *Eupatorium* (76.67 %), which did not differ significantly. The present findings agree with previous researchers, who found that stored seeds after treatment with several leaf powders provided excellent control of bruchids, conserved germination and seedling vigor (45). It also revealed that the studied medicinal weed leaf powders did not pose any adverse effects on seed viability even after months of treatment, the seeds can be stored for long-term purposes and that normal seed germination could be achieved without losing its integrity. However, it is necessary to conduct field trials in actual farmers' storage structures to confirm these results and provide suggestive measures for preventing losses due to storage pests. In an experiment conducted for testing the effectiveness of different pepper powders (46), it was reported that powders were successful in preventing oviposition on treated seeds and damage done by *C. maculatus* and that the seed quality and viability were unaffected. Data on the total seed protein content after insect infestation is presented in Table 9, which showed the values as non-significant for all treatments. Seeds without any treatment registered protein content of 18.67 %, whereas the protein contents of treated seeds recorded in the range 20.27 to 22.45 %, which did not differ significantly. Seed proteins include different types, such as storage proteins that are a major component in legumes, along with housekeeping proteins, biologically active enzymes and other proteins like protease inhibitors, lectins and allergens, which are regarded as minor proteins (47). The result revealed that treating grains with medicinal leaf powder does not affect the seed vigor since powders are present on the external seed coat and seed protein corresponds to seed cotyledons.

Overall effectiveness of medicinal weed leaf powders against *Callosobruchus chinensis*

Across various global locations, people are utilising leaves, roots, twigs, or petals from diverse native plant species, whether cultivated or wild, for traditional medicinal purposes and other applications in agriculture (32). In relation to crop protection, researchers have now employed these medicinal plants for managing various types of pests, both in field and storage conditions, as they are safer compared to insecticides and are eco-friendly (13). These plants possess a diverse range of compounds or secondary metabolites that, when present in appropriate quantities, exhibit remarkable effectiveness against several categories of insect pests, including those that infest stored products. This efficacy is due to their neurotoxic actions and processes (48). These botanicals function through various modes of action such as decreasing the acetylcholinesterase enzyme activity, blocking the GABA-gated chloride channels of the pest insects, which ultimately kills them (49). Other vulnerable areas that monoterpenes can affect, such as cytochrome P450-dependent mono-oxygenases, may potentially result in the eradication of pests (48). In terms of adult emergence, eggs that were laid on seeds after being exposed to the powder could not develop into adults as the powders might have passed through egg chorion and thereby disrupted normal developmental stages from eggs to adults. It is also possible that plant bioactive compounds rendered the male sterile, which caused females to lay infertile eggs (44). In general, despite the presence of plant powders, adult emergence increased with longer exposure time. The current findings are quite in line with previous work done (43), wherein medicinal leaf powders tested for insecticidal properties dramatically decreased seed damage and weight loss caused by *C. chinensis* and these leaf powders acted as seed protectant. Moreover, insects are to deposit their eggs on treated seeds since there may be a correlation between plants' potential ovicidal and larvicidal effects and the decline in number of adults emerged (50).

The present study revealed that all the medicinal weeds from different families conferred some negative effects on *C. chinensis* and showed moderate to maximum effectiveness. Based on different insect developmental parameters, the arrangement from most to least effective with respect to insecticidal potential can be shown as *Calotropis* > *Zanthoxylum* > *Argemone* > *Ageratum* > *Eupatorium* > *Lantana,* with the first two being the most effective. Plant powders covered the testa of treated seeds thereby serving as food poison to adult beetles (14). Moreover, the insects were likely deprived of sufficient nourishment from the seeds, which would have supported their normal growth and development, potentially leading to insect mortality (44). *Callosobruchus chinensis* is responsible for 40 % of damage to pulses and damage up to 100 % can be recorded if no preventive or control measures are taken up on time (23). Most insects breathe by means of trachea which usually opens at the lateral sides of the body through spiracles. These external openings might have been hindered from receiving enough oxygen into insect body, which eventually led to their asphyxiation and death (40). Even though the botanicals studied by several researchers were quite distinct from those used in the current studies, the direct toxicity effects observed on pests that attack stored grain was nearly the same. The evaluated medicinal plants may be recommended as viable options for use as grain protectants, provided that their phytochemical profile is performed to assess any potential toxicity to people. For instance, the toxicity and safety level of plants such as *Calotropis* (51) and *Ageratum* (52) must be well-studied as they have been reported to be poisonous when ingested. Additionally, it is essential to ensure that the grains are thoroughly washed after the powder treatment prior to consumption.

Conclusion

All the medicinal weed leaf powders showed substantial efficacy in reducing seed beetle infestation and damage. These plants are highly abundant in the Himalayan foothills of India, including north-eastern states. The resource-poor farmers can readily adopt this strategy as a non-chemical means of protecting their stored grains from pests and diseases. Furthermore, unless the grain is contaminated by insect excreta and bird or rodent droppings, plant products will not diminish the quality, quantity and viability of grains. Since the experiments were conducted under laboratory conditions, field trials are needed to determine and confirm these effects in real-time situations, especially in warehouses and storage godowns and additional research is required to explore the underlying mode of action and the exact insecticidal components. Moreover, an all-inclusive organic pest control solution for stored grains can also be achieved by combining sunflower oil with leaf powder. This combination employs both physical and chemical methods of control, with the oil providing a barrier and suffocating effect and the powder containing bioactive substances. These findings encourage the exploration of eco-safe bio-protectants for smallholder grain storage systems in the climate-resilient Northeast Himalayas.

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Authors' contributions

ABTM conducted the experiment. DS was responsible for conceptualisation, data analysis, manuscript writing and final editing. HJW handled data arrangement, while CSK contributed to data analysis. GDR prepared the tables and DT created the graphical abstract. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

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