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Insecticidal Efficacy of Aqueous *Aegle marmelos* Extracts Against Brown Planthopper (*Nilaparvata lugens*) and Yellow Rice Stem Borer (*Scirpophaga incertulas*) and Their Effects on Rice Growth

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Abstract: This study evaluated the insecticidal potential of aqueous extracts of *Aegle marmelos* against brown planthopper (*Nilaparvata lugens*) and yellow rice stem borer (*Scirpophaga incertulas*), as well as their effects on rice growth under controlled laboratory–greenhouse conditions in Bojonegoro, Indonesia, from March 2020 to February 2021. Fruit pulp, fruit peel, and leaf extracts were applied at concentrations of 20%, 40%, and 60%, with synthetic insecticide and untreated controls included for comparison. Separate experimental units were used for each target pest species. Mortality observations indicated that higher extract concentrations generally produced greater insecticidal activity. The 60% peel extract treatment produced the highest mortality against yellow rice stem borer, whereas fruit pulp extracts at 40% and 60% showed mortality values comparable to the synthetic insecticide treatment against brown planthopper. Several plant growth parameters, including tiller number, plant height, leaf color, and damage intensity, also tended to improve following extract application. However, some measured variables were not statistically significant, indicating considerable variability among replicates. The findings suggest that Aegle marmelos extracts possess potential as botanical insecticides for rice pest management, particularly against yellow rice stem borer. Further studies under broader greenhouse and field conditions are recommended to confirm efficacy, optimize formulation stability, and evaluate long-term effects on rice productivity and pest suppression. These results indicate that Aegle marmelos extracts may contribute to environmentally friendly pest management strategies by reducing dependence on synthetic insecticides while maintaining rice growth performance. Nevertheless, additional phytochemical characterization and toxicological evaluation are necessary before large-scale application can be recommended confidently.

Introduction

Rice (*Oryza sativa* L.) is a primary staple food for more than 90% of the Indonesian population and remains central to national food security (1). At the global level, rice also plays a crucial role in supporting food security across Asia and other rice-producing regions worldwide (2). Sustaining rice productivity is therefore a major agricultural priority. However, rice production is continuously constrained by insect pests, particularly the brown planthopper (*Nilaparvata lugens*) (3) and the yellow rice stem borer (*Scirpophaga incertulas*) (4). which attack plants from vegetative to reproductive stages and can cause severe yield losses. Brown planthopper infestations induce hopperburn and plant desiccation, often leading to crop failure, while stem borer damage results in deadhearts and whiteheads that reduce grain formation (5). These pests remain among the most destructive constraints to stable rice production in Asia (6). Extensive reports of crop damage and yield loss further highlight the urgency of effective pest management strategies (7). In Indonesia, brown planthopper outbreaks have been associated with large-scale crop failure over the past decades (8). while yellow rice stem borer infestations frequently affect major rice-growing areas, particularly under climatic variability (9). Conventional pest control relies heavily on synthetic insecticides due to their rapid effectiveness (10). However, prolonged and intensive use has resulted in pest resistance, resurgence of pest populations, environmental contamination, pesticide residues in food products, and risks to human health (11), highlighting the urgent need for safer and more sustainable pest management strategies (12).

Botanical insecticides have emerged as promising alternatives due to their biodegradability, lower toxicity to non-target organisms, and reduced likelihood of resistance development (13). Among potential plant-based sources, *Aegle marmelos* (Maja), a member of the Rutaceae family, contains bioactive secondary metabolites such as flavonoids, tannins, alkaloids, and saponins, which are known for their insecticidal and antifeedant properties (14). Previous studies have demonstrated the pesticidal potential of plant extracts; however, their effectiveness against major rice pests such as *N. lugens* and *S. incertulas* remains insufficiently explored (15). Most previous studies have primarily focused on the general pesticidal or antimicrobial activities of *A. marmelos*, while investigations specifically targeting economically important rice pests are still scarce (16). In addition, earlier research generally evaluated only a single plant part or focused on one target pest species, resulting in limited understanding of the comparative insecticidal performance among different plant organs against multiple rice pests (17). Moreover, different plant parts of *A. marmelos* are known to vary in their phytochemical composition and biological activity (14). Fruit pulp, fruit peel, and leaves are reported to contain distinct metabolite profiles, which may influence their insecticidal efficacy, yet comparative evaluation of these plant parts against key rice pests remains limited. Furthermore, studies integrating insect mortality assessment with observations on rice plant growth under pest pressure are still rarely reported, even though such evaluation is important to determine the practical applicability of botanical insecticides in rice cultivation systems.

Therefore, this study aims to evaluate the insecticidal efficacy of aqueous extracts of *A. marmelos* (fruit pulp, peel, and leaves) at different concentrations against *N. lugens* and *S. incertulas*, while also assessing their effects on rice plant growth. It is hypothesized that higher extract concentrations, particularly from fruit-based parts, will result in greater pest mortality and reduced plant damage, thereby indirectly supporting improved plant growth performance under pest pressure. The novelty of this study lies in the comparative assessment of multiple *A. marmelos* plant parts using aqueous-based extracts against two major rice insect pests simultaneously, combined with the evaluation of their implications for rice plant growth performance. This approach is expected to provide a more comprehensive understanding of the potential utilization of *A. marmelos* as an environmentally friendly botanical insecticide for sustainable rice pest management.

Methodology

Study Design and Rationale

The experiment and preparation of *Aegle marmelos* extracts were conducted in Kedungdowo Village, Balen District, Bojonegoro Regency, Indonesia, from March 2020 to February 2021. This study employed a controlled laboratory–greenhouse experiment using a completely randomized design (CRD) to evaluate the insecticidal efficacy of *A. marmelos* extracts and their effects on rice plant growth. The CRD was selected to minimize experimental bias under homogeneous environmental conditions and to allow valid comparisons among treatments. The experiment consisted of eleven treatments with three replications, including a negative control (distilled water), a positive control (commercial synthetic insecticide applied at the manufacturer-recommended dosage), and aqueous extracts of *A. marmelos* derived from fruit pulp, fruit peel, and leaves at concentrations of 20%, 40%, and 60%. Each experimental unit consisted of a single rice (*Oryza sativa* L.) plant grown in a plastic pot and subjected to controlled pest infestation.

Experimental Materials and Biological Test Organisms

The experimental plant used in this study was rice (*Oryza sativa* L.) of the Ciherang variety, cultivated under controlled conditions until reaching an appropriate growth stage for infestation. The rice seeds were obtained from a local agricultural supplier in Bojonegoro, Indonesia. The test organisms included brown planthopper (*N. lugens*) at the second generation (G2) and yellow rice stem borer (*S. incertulas*) larvae at the third instar. The insects were collected from naturally infested rice fields and acclimatized under laboratory conditions for 24 h prior to experimentation to ensure stability and uniformity of test populations.

Preparation of Botanical Extracts

Fresh plant materials of *A. marmelos* (fruit pulp, fruit peel, and leaves) were collected from mature and healthy plants, washed thoroughly with distilled water, and air-dried at room temperature (27–30 °C) to remove surface moisture. The plant materials were then ground into a coarse paste using a sterile blender. For extraction, 200 g of each plant material was macerated in 1 L of distilled water for 24 h at room temperature with intermittent stirring to facilitate the release of bioactive compounds. The resulting mixtures were filtered sequentially using double-layer muslin cloth followed by Whatman No. 1 filter paper to obtain crude aqueous extracts. The extract concentrations were prepared on a weight/volume (w/v) basis to obtain 20%, 40%, and 60% solutions. Fresh extracts were prepared daily to maintain the stability and activity of the bioactive constituents.

Treatments and Experimental Setup

The experiment included eleven treatments consisting of a negative control (distilled water), a positive control (synthetic insecticide), and nine botanical extract treatments representing three plant parts (fruit pulp, fruit peel, and leaves) at three concentration levels (20%, 40%, and 60%). Each treatment was replicated three times. Each experimental unit consisted of one rice plant grown in a plastic pot and infested with a standardized number of insect pests. The allocation of treatments to experimental units was conducted randomly to ensure unbiased experimental conditions.

Application Procedures

Rice plants were artificially infested with 10 individuals of the target pest species. Separate experimental units were used for each pest species, and each rice plant was infested with only one target insect species during the experiment. and allowed a 24 h establishment period prior to treatment application. Botanical extracts and control treatments were applied using a handheld sprayer at a volume of 10 mL per plant to ensure uniform coverage of plant surfaces, including leaves and stems. Applications were conducted once daily for 10 consecutive days under controlled environmental conditions, with temperature maintained at 28 ± 2 °C and relative humidity at 70–80% to support both plant growth and pest activity.

Observed Variables and Data Collection

The primary variables observed in this study included pest mortality and rice plant growth parameters. Pest mortality was recorded daily and calculated as the percentage of dead insects relative to the initial number introduced per experimental unit. Plant growth responses were evaluated based on the number of tillers per plant, plant height, leaf color, and plant damage intensity. The number of tillers was determined by manual counting, while plant height was measured in centimeters using a ruler from the base of the plant to the tip of the highest leaf. Leaf color was assessed using a standardized visual scoring scale to indicate relative chlorophyll content and plant physiological condition. Plant damage intensity was expressed as a percentage and estimated based on visible symptoms of pest attack by comparing the proportion of affected plant tissue to the total plant area.

Data Analysis

Quantitative data on pest mortality, number of tillers, plant height, and plant damage intensity were analyzed using analysis of variance (ANOVA) at a 95% confidence level ($p < 0.05$) to evaluate the effects of treatment type and concentration. When significant differences were detected, mean comparisons among treatments were performed using Tukey's Honest Significant Difference (HSD) test. For data that did not meet the assumptions of normality, non-parametric analysis using the Kruskal–Wallis test was applied. All statistical analyses were conducted using standard statistical software for biological research.

Results and Discussion

Effect of Maja Plant Extract on Pest Mortality

This study evaluated the insecticidal efficacy of *Aegle marmelos* extracts against brown planthopper (*N. lugens*) and yellow rice stem borer (*S. incertulas*) using pest mortality as the primary indicator. The results demonstrated that all extract treatments induced varying levels of mortality in both pest species, indicating the presence of biologically active compounds (18). However, the magnitude of mortality differed depending on plant part and extract concentration.

Brown Planthopper (*Nilaparvata lugens*)

The mortality of brown planthopper following application of *A. marmelos* extracts is presented in **Table 1**. Mean mortality values ranged from 13.33% to 66.67% among botanical treatments, whereas the untreated control showed no mortality.

Application of Maja plant extracts resulted in observable mortality of brown planthopper, with higher mortality generally observed at increased extract concentrations. Fruit pulp extracts at 40% and 60% concentrations produced mortality values comparable to the synthetic insecticide treatment. However, statistical analysis using the Kruskal–Wallis test indicated no significant differences among treatments ($p > 0.05$), suggesting considerable variability among replicates.

The moderate response of *N. lugens* to *A. marmelos* extracts may be associated with the feeding characteristics of this pest. Brown planthopper is a phloem-feeding insect with piercing–sucking mouthparts, which likely reduces direct ingestion of phytochemicals deposited on plant surfaces. Previous studies on botanical insecticides have reported that sap-feeding insects are generally less susceptible than chewing insects because their feeding behavior limits exposure to toxic secondary metabolites. The relatively higher activity observed in fruit pulp extracts may indicate a greater abundance of soluble bioactive compounds, particularly flavonoids and alkaloids, which are known to interfere with insect metabolism, feeding behavior, and neural activity. In addition, tannins may

Table 1. Mortality percentage of brown planthopper after application of Maja plant extract.

Treatment	Mortality (%) Replicate 1	Replicate 2	Replicate 3	Mean Mortality (%) ± SD
M1 (Fruit pulp 20%)	20	60	80	53.33 ± 30.55
M2 (Fruit pulp 40%)	60	60	80	66.67 ± 11.55
M3 (Fruit pulp 60%)	80	40	80	66.67 ± 23.09
L1 (Peel 20%)	40	0	20	20.00 ± 20.00
L2 (Peel 40%)	40	20	80	46.67 ± 30.55
L3 (Peel 60%)	20	60	60	46.67 ± 23.09
N1 (Leaf 20%)	0	0	40	13.33 ± 23.09
N2 (Leaf 40%)	60	20	20	33.33 ± 23.09
N3 (Leaf 60%)	40	40	80	53.33 ± 23.09
K2 (Positive control)	80	80	40	66.67 ± 23.09
K1 (Negative control)	0	0	0	0.00 ± 0.00
Note: Kruskal–Wallis test, Asymp. Sig. = 0.768 ($p > 0.05$).				

reduce nutrient assimilation by binding digestive proteins, thereby weakening insect physiological performance even when mortality remains moderate.

Yellow Rice Stem Borer (*Scirpophaga incertulas*)

The mortality of the yellow rice stem borer following treatment with Maja plant extracts is presented in **Table 2**. In contrast to *N. lugens*, statistical analysis indicated significant differences among treatments (ANOVA, p = 0.001).

The highest mortality was observed in the 60% peel extract treatment, with mortality values comparable to the chemical insecticide. Mortality increased with extract concentration, particularly in peel extracts. This trend suggests a concentration-dependent response, where higher extract concentrations may increase exposure to bioactive compounds.

The stronger activity of peel extracts against *S. incertulas* suggests that the fruit peel contains higher concentrations of defensive phytochemicals. Fruit peels in Rutaceae species are commonly rich in phenolic compounds, tannins, and volatile metabolites that function naturally as protective barriers against herbivores. Stem borer larvae are chewing insects that consume plant

Table 2. Mortality percentage of yellow rice stem borer after application of Maja plant extract.

Treatment	Mortality (%) Replicate 1	Replicate 2	Replicate 3	Mean Mortality (%) ± SD	LSD Group
M1 (Fruit pulp 20%)	20	40	0	20.00 ± 20.00	ab
M2 (Fruit pulp 40%)	20	60	40	40.00 ± 20.00	ab
M3 (Fruit pulp 60%)	60	20	60	46.67 ± 23.09	ab
L1 (Peel 20%)	20	40	0	20.00 ± 20.00	ab
L2 (Peel 40%)	40	60	20	40.00 ± 20.00	ab
L3 (Peel 60%)	60	60	80	66.67 ± 11.55	b
N1 (Leaf 20%)	20	0	0	6.67 ± 11.55	ab
N2 (Leaf 40%)	40	20	60	40.00 ± 20.00	ab
N3 (Leaf 60%)	40	60	20	40.00 ± 20.00	ab
K2 (Positive control)	60	80	10	50.00 ± 36.06	a
K1 (Negative control)	0	0	0	0.00 ± 0.00	c
Note: Means followed by the same letter are not significantly different at LSD 5%. ANOVA, p = 0.001.					

Table 3. Growth performance of rice plants following application of *Aegle marmelos* extracts.

Treatment	Number of tillers (mean ± SD)	Plant height (cm) (mean ± SD)	Leaf color score	Plant damage (%) (mean ± SD)
	A	B	A	B
M1	24.3 ± 5.51	16.67 ± 5.51	66.0 ± 10.44	77.7 ± 4.16
M2	20.3 ± 6.03	23.67 ± 2.00	63.7 ± 8.15	62.0 ± 7.00
M3	29.0 ± 4.04	21.67 ± 4.51	64.7 ± 8.39	73.0 ± 10.44
L1	21.0 ± 4.36	20.67 ± 3.22	64.3 ± 10.97	64.7 ± 9.45
L2	25.0 ± 8.72	24.00 ± 7.00	64.6 ± 8.15	76.0 ± 4.00
L3	18.67 ± 5.51	28.00 ± 6.66	61.3 ± 7.51	64.7 ± 14.01
N1	22.3 ± 5.86	22.67 ± 4.73	66.0 ± 7.00	77.0 ± 3.60
N2	19.0 ± 4.58	27.00 ± 4.58	51.6 ± 8.51	70.3 ± 16.25
N3	28.3 ± 3.00	22.30 ± 4.16	54.0 ± 8.19	74.0 ± 5.57
K2	15.7 ± 5.51	18.70 ± 6.60	75.7 ± 5.86	79.3 ± 3.51
K1	16.3 ± 3.51	21.70 ± 7.09	50.6 ± 2.08	59.3 ± 3.51

Notes:
M1–M3 = fruit pulp extract (20%, 40%, 60%);
L1–L3 = fruit peel extract (20%, 40%, 60%);
N1–N3 = leaf extract (20%, 40%, 60%);
K1 = negative control (no treatment);
K2 = positive control (chemical pesticide);
A = brown planthopper;
B = yellow rice stem borer.

tissues directly, resulting in greater ingestion of toxic compounds compared with sap-feeding pests such as *N. lugens*. This feeding mechanism may explain the significantly higher susceptibility of *S. incertulas*. Similar observations have been reported in previous botanical insecticide studies, where tissue-feeding larvae exhibited stronger mortality responses due to higher phytochemical exposure (19, 20). Moreover, the dose-dependent increase in mortality indicates that the insecticidal activity of *A. marmelos* extracts is concentration-sensitive, supporting the hypothesis that toxicity is closely related to the quantity of active metabolites delivered to the target pest.

The ability of the 60% peel extract to achieve mortality comparable to or exceeding the synthetic insecticide is particularly important from an ecological perspective. Unlike synthetic pesticides that often rely on a single dominant active ingredient, botanical extracts contain multiple bioactive compounds that may act synergistically through different mechanisms, including feeding deterrence, digestive inhibition, and neurotoxicity. Such multi-target activity may reduce the likelihood of rapid resistance development in pest populations.

Effect of Maja Plant Extract on Rice Plant Growth

Rice plant growth parameters were evaluated to assess the indirect effects of Maja plant extract application in suppressing pest activity. Observed variables included number of tillers, plant height, plant damage intensity, and leaf color.

Number of Tillers

The number of tillers is an important indicator of vegetative growth and plant vigor in rice cultivation. Variation in tiller number was observed across treatments (**Table 3**), with higher extract concentrations generally associated with greater tiller production. Rice plants treated with higher concentrations of Maja plant extracts exhibited relatively higher tiller numbers. However, this increase should not be interpreted as a direct growth-promoting effect of the extracts. Instead, it is more likely an indirect result of reduced pest pressure, allowing plants to allocate resources more effectively toward vegetative development. This interpretation is consistent with previous findings that pest suppression can enhance plant growth performance by minimizing stress and maintaining photosynthetic capacity (21).

Rice tiller formation is highly dependent on physiological stability during vegetative growth. Pest infestation can disrupt assimilate distribution and reduce photosynthetic efficiency, thereby limiting tiller production. The improved tiller number observed in treated plants therefore likely reflects reduced physiological stress rather than direct stimulation by the extracts themselves. Similar trends have been observed in studies evaluating botanical pesticides, where improved vegetative growth was closely associated with lower pest intensity and reduced tissue damage.

Plant Height

Plant height is a key morphological parameter reflecting overall plant growth performance. The results (**Table 4**) indicate that plants treated with Maja extracts tended to exhibit greater height compared to the untreated control. Plant height showed a slight increasing trend with higher extract concentrations. However, statistical analysis indicated no significant differences among treatments ($p > 0.05$), suggesting that the observed variation may not represent a strong treatment effect.

Therefore, similar to tiller number, the apparent increase in plant height is more likely associated with reduced pest damage rather than direct physiological stimulation by the extracts. Pest-induced stress is known to reduce plant growth by disrupting nutrient uptake and photosynthesis (22). The absence of significant differences in plant height also indicates that the protective effect of the extracts may be more apparent in reducing pest injury than in substantially altering plant morphology. This distinction is important because increases in growth parameters under pest management treatments are often secondary responses resulting from lower biotic stress.

Table 4. Plant height of rice plants following application of Maja plant extract.

Treatment	Brown planthopper (mean ± SD)	Yellow rice stem borer (mean ± SD)
M1	24.3 ± 5.51	16.67 ± 5.51
M2	20.3 ± 6.03	23.67 ± 2.00
M3	29.0 ± 4.04	21.67 ± 4.51
L1	21.0 ± 4.36	20.67 ± 3.22
L2	25.0 ± 8.72	24.00 ± 7.00
L3	18.67 ± 5.51	28.00 ± 6.66
N1	22.3 ± 5.86	22.67 ± 4.73
N2	19.0 ± 4.58	27.00 ± 4.58
N3	28.3 ± 3.00	22.30 ± 4.16
K2	15.67 ± 5.51	18.67 ± 6.66
K1	16.3 ± 3.51	21.67 ± 7.09

Notes: M1–M3 = fruit pulp extract (20%, 40%, 60%); L1–L3 = fruit peel extract (20%, 40%, 60%); N1–N3 = leaf extract (20%, 40%, 60%); K1 = negative control (no treatment); K2 = positive control (chemical pesticide). ANOVA results: brown planthopper ($p = 0.072$); yellow rice stem borer ($p = 0.293$).

Consequently, the present findings suggest that *A. marmelos* extracts primarily function as pest-suppressive agents rather than biofertilizers or plant growth stimulants.

Plant Damage Intensity

Plant damage intensity is a key indicator of pest control effectiveness. The results (**Table 5** and **Table 6**) showed that all botanical extract treatments reduced damage compared to the negative control. Plant damage intensity tended to decrease with increasing extract concentration. However, statistical analysis ($p > 0.05$) indicated no significant differences among treatments, suggesting that the observed trend should be interpreted cautiously.

This suggests that although a decreasing trend is evident, the effect should be interpreted cautiously. Nevertheless, the consistently lower damage levels compared with the untreated control may indicate that Maja extracts contributed to reduced pest feeding activity. Similar findings have been reported where biological control strategies reduce pest damage and improve crop performance (23). The reduction in plant damage despite moderate mortality values suggests that the extracts may also exert sublethal effects on pest behavior. Botanical compounds such as tannins and alkaloids are known to reduce feeding intensity and interfere with digestion, thereby decreasing tissue destruction even when insects survive initial exposure. This characteristic suggests that

Table 5. Plant damage intensity of *Brown planthopper* following application of Maja plant extract.

Pest Species	Treatment	Damage (%) – Rep 1	Rep 2	Rep 3	Mean ± SD (%)	Damage Category
Brown planthopper	M1	33.3	22.2	0.0	18.5 ± 16.9	Low
	M2	33.3	16.7	0.0	16.7 ± 16.7	Low
	M3	11.1	0.0	33.3	14.8 ± 16.9	Low
	L1	33.3	22.2	11.1	22.2 ± 11.1	Low
	L2	33.3	22.2	0.0	18.5 ± 16.9	Low
	L3	33.3	8.4	8.4	16.7 ± 14.4	Low
	N1	33.3	22.2	22.2	25.9 ± 6.4	Moderate
	N2	33.3	11.1	11.1	18.5 ± 12.8	Low
	N3	33.3	0.0	22.2	18.5 ± 16.9	Low
	K2	0.0	11.1	33.3	14.8 ± 16.9	Low
	K1	33.3	25.0	33.3	30.5 ± 4.8	Moderate
Asymp. Sig. (ANOVA)						0.953

Notes: Values are expressed as mean ± standard deviation. Asymp. Sig. = significance value of ANOVA test ($p < 0.05$). M1–M3 = fruit pulp extract (20%, 40%, 60%); L1–L3 = peel extract (20%, 40%, 60%); N1–N3 = leaf extract (20%, 40%, 60%); K1 = negative control (no treatment); K2 = positive control (chemical insecticide).

Table 6. Plant damage intensity of yellow rice stem borer following application of Maja plant extract.

Pest Species	Treatment	Damage (%) – Rep 1	Rep 2	Rep 3	Mean ± SD (%)	Damage Category
Yellow rice stem borer	M1	33.3	22.2	11.1	22.2 ± 11.1	Low
	M2	33.3	22.2	8.4	21.3 ± 12.5	Low
	M3	16.7	33.3	8.4	19.5 ± 12.7	Low
	L1	33.3	22.2	11.1	22.2 ± 11.1	Low
	L2	0.0	33.3	22.2	18.5 ± 16.9	Low
	L3	33.3	0.0	16.7	16.7 ± 16.6	Low
	N1	22.2	33.3	22.2	25.9 ± 6.4	Moderate
	N2	33.3	22.2	8.4	21.3 ± 12.4	Low
	N3	33.3	16.7	11.1	20.4 ± 11.5	Low
	K2	11.1	22.2	11.1	14.8 ± 6.4	Low
	K1	33.3	25.0	22.2	26.8 ± 5.8	Moderate
Asymp. Sig. (ANOVA)						0.900

Notes: Values are expressed as mean ± standard deviation. Asymp. Sig. = significance value of ANOVA test ($p < 0.05$). M1–M3 = fruit pulp extract (20%, 40%, 60%); L1–L3 = peel extract (20%, 40%, 60%); N1–N3 = leaf extract (20%, 40%, 60%); K1 = negative control (no treatment); K2 = positive control (chemical insecticide).

plant-based insecticides may contribute to crop protection not only through direct mortality but also through suppression of feeding activity and pest fitness.

Leaf Color

Leaf color was used as an indicator of plant physiological condition following pest infestation and extract application. The results (**Table 7**) showed that leaf color scores improved with increasing extract concentration. Rice plants treated with higher concentrations of Maja extracts exhibited greener leaf coloration compared to the negative control. However, this improvement is more likely associated with reduced pest stress rather than direct enhancement of chlorophyll production.

Pest infestation is known to negatively affect leaf color by disrupting photosynthesis and causing tissue damage (20). Therefore, improved leaf coloration in treated plants likely reflects better physiological condition due to effective pest suppression (24). Brown planthopper infestation is particularly associated with chlorophyll degradation and impaired nutrient translocation due to damage to vascular tissues. Consequently, suppression of pest populations may help maintain chlorophyll stability and leaf physiological function.

Overall Interpretation

The findings demonstrate that *A. marmelos* extracts exhibit insecticidal activity against both *N. lugens* and *S. incertulas*, with efficacy varying according to plant part, concentration, and target species. Peel-derived extracts at higher concentrations showed comparatively greater activity against *S. incertulas*, whereas responses in *N. lugens* were lower and not statistically significant.

This differential response can be attributed to differences in insect feeding mechanisms and exposure pathways. Larvae of *S. incertulas* directly ingest treated plant tissues, resulting in higher intake of phytochemicals, whereas *N. lugens* utilizes a piercing–sucking feeding strategy that limits exposure to surface-applied bioactive compounds. Consequently, the observed insecticidal activity is better interpreted as an interaction between extract phytochemical composition and pest biology rather than a uniform toxic effect across species. In addition to direct mortality, the extracts also contributed to reduced feeding damage, indicating the presence of sublethal effects such as antifeedant or growth-inhibitory activity that may enhance overall crop protection outcomes.

Although the performance of the botanical extracts did not consistently exceed that of the synthetic insecticide, the results support their potential as complementary tools within integrated pest management frameworks. Further work should prioritize phytochemical characterization, standardization of extraction procedures, formulation optimization to improve bioavailability, and multi-location field validation to establish agronomic reliability and scalability.

Relatively high variability among replicates may have reduced statistical sensitivity in several measured parameters. Therefore, the observed trends should be interpreted cautiously and require further validation under broader experimental and field conditions. Rice plants were artificially infested with 10 individuals of the target pest species after reaching the appropriate growth stage. Separate experimental units were established for each pest species, and each rice plant was infested with only one target insect species during the experiment

Conclusion

This study demonstrated that aqueous extracts of *A. marmelos*, particularly fruit pulp and peel at higher concentrations (60%), exhibited insecticidal activity against *N. lugens* and *S. incertulas* under controlled laboratory–greenhouse conditions, as reflected by increased pest mortality and reduced plant damage. Certain treatments produced mortality levels comparable to a synthetic insecticide; however, the responses were not fully consistent across treatments and pest species. Statistically significant effects were observed only for *S. incertulas*, indicating a species-dependent response under the experimental conditions.

Table 7. Leaf color score of rice plants following application of Maja plant extract.

Treatment	Brown Planthopper	Yellow Rice Stem Borer
M1	1.0	0.5
M2	2.0	2.0
M3	3.5	2.5
L1	0.5	1.0
L2	1.0	2.5
L3	2.0	3.0
N1	0.5	0.5
N2	1.5	1.5
N3	2.0	2.0
K2	3.5	3.5
K1	0.0	0.0

Notes: M1–M3 = fruit pulp extract (20%, 40%, 60%); L1–L3 = peel extract (20%, 40%, 60%); N1–N3 = leaf extract (20%, 40%, 60%); K1 = negative control; K2 = chemical insecticide.

Improvements in plant growth parameters, including tiller number, plant height, and leaf color, are more plausibly attributed to reduced pest pressure than to any direct growth-promoting effect of the extracts. The observed bioactivity is presumed to be associated with phytochemical constituents such as flavonoids, tannins, alkaloids, and saponins, although their specific mechanisms of action were not experimentally verified in this study. Given that the experiment was conducted under controlled conditions, the results should be interpreted as indicative of potential efficacy rather than definitive field performance.

Declaration

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Contribution: Data Curation, Formal analysis, Writing - Original Draft, Writing - Review & Editing, Formal Analysis, Visualization, Writing – Original Draft.

Conflict of Interest
The authors declare no conflicting interest.

Data Availability
All data generated or analyzed during this study are included in this published article [and its supplementary information files]. Additional datasets are available in [repository name] at [DOI or link].

Ethics Statement
Ethical approval was not required for this study.

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