TROPICAL LIFE SCIENCES RESEARCH

Allelopathic Potential of the Aromatic Plants *Cymbopogon nardus* and *Lantana camara* Against Distinct Malaysian Weedy Rice Biotypes

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Highlights

- *Cymbopogon nardus* demonstrated a stronger allelopathic effect than *Lantana camara* across volatilisation, leachate and root exudation bioassays, indicating its higher inhibitory potential.

- The allelopathic activity of *C. nardus* selectively suppressed the growth of weedy rice (WRN and WRE) while exerting only mild effects on the cultivated MR220 CL2 variety, suggesting possible selectivity.

- GC–MS profiling revealed that volatile monoterpenes and semivolatile fatty acid methyl esters were the principal allelochemicals contributing to both vapor- and water-mediated inhibition.

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EARLY VIEW

Allelopathic Potential of the Aromatic Plants *Cymbopogon nardus* and *Lantana camara* Against Distinct Malaysian Weedy Rice Biotypes

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Running head: Allelopathic Potential of C. nardus and L. camara

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Abstract: Weedy rice (*Oryza sativa* complex) remains one of the major constraints in Malaysian rice production, as continuous herbicide dependence has intensified resistance issues and increased environmental concerns. This study evaluated the allelopathic potential of two aromatic plants, *Cymbopogon nardus* and *Lantana camara*, against two weedy rice variants (WRN and WRE) and the cultivated MR220 CL2 variety. Volatilisation, foliage leachate and plant-box root exudation assays were conducted to determine their inhibitory effects under different exposure pathways. *C. nardus* consistently produced stronger and more selective inhibition than *L. camara*, with the greatest reduction in radicle elongation recorded in WRN and WRE at shorter distances from the donor plant. Regression analysis

further demonstrated a distance-dependent inhibitory pattern, particularly in the weedy rice variants, whereas MR220 CL2 showed comparatively lower sensitivity. GC–MS analysis revealed that the methanolic extract of *C. nardus* was dominated by volatile monoterpenes, including geraniol, citral, citronellol, caryophyllene and geranyl acetate, while the aqueous extract contained mainly semivolatile fatty acid methyl esters such as methyl palmitate, methyl stearate and 9,12-octadecadienoic acid methyl ester. The contrasting chemical profiles suggest that *C. nardus* expresses both volatile- and water-mediated allelopathic activity through multiple classes of secondary metabolites. Overall, the stronger inhibitory effects observed against the weedy rice variants indicate that *C. nardus* may serve as a promising allelopathic donor species for future studies on sustainable weed management in rice production systems.

Keywords: Allelopathy, Allelochemicals, *Cymbopogon nardus*, GC–MS, *Lantana camara*, MR220 CL2, Sustainable Weed Management, Weedy Rice

INTRODUCTION

The emergence of weedy rice (*Oryza sativa* complex) in Malaysia was first reported in the agricultural areas of the Selangor Northwest Project (PBLS) around 1988. Since then, the species has become one of the major biological constraints affecting rice production in Peninsular Malaysia due to its aggressive competition with cultivated rice and its production of poor-quality grains. Weedy rice can also be distinguished from cultivated rice by several morphological and physiological characteristics, including seed shattering ability, high seed dormancy, and variations in hull colour and awn morphology (Liang et al., 2025; Mahmod et al., 2024). The persistence of seed dormancy further complicates field management because buried seeds may remain viable in the soil for prolonged periods, contributing to recurring infestations across planting seasons. Since its introduction, extensive control efforts have been implemented by farmers and institutions such as MARDI; however, management costs remain high (Mispan et al., 2019), while recent surveys indicate that infestation levels continue to increase across major rice granary areas in Malaysia, resulting in considerable economic losses and threatening long-term yield stability (Huang, 2024; Mahmod et al., 2024).

The management of weedy rice remains particularly difficult because the species shares close genetic and physiological similarities with cultivated rice, thereby limiting the selectivity of conventional weed-control strategies. Although integrated management approaches such as water management, crop rotation, stale seedbed techniques, and certified seed usage are commonly practised, herbicides remain one of the major control components used in direct-

seeded rice systems (Mispan et al., 2019). Nevertheless, continuous herbicide dependence may contribute to agroecosystem imbalance, environmental contamination, and increasing risks of herbicide-resistant weed populations. These concerns have encouraged growing interest in alternative weed-management approaches based on naturally derived phytotoxic compounds. Natural products containing allelochemicals are increasingly being investigated for sustainable weed management because many of these compounds are biodegradable and generally exhibit lower environmental persistence than synthetic herbicides (Mushtaq et al., 2020; Bhadoria, 2011; Duke et al., 2024; Scavo & Mauromicale, 2023).

The concept of allelopathy has therefore received increasing attention as a potential approach for sustainable weed suppression. Allelopathy refers to the direct or indirect effects of plant-released secondary metabolites that influence the growth and development of neighbouring plants (Bond, 2002). In agricultural systems, certain allelopathic species have demonstrated the ability to suppress weed emergence and seedling growth through volatile compounds, root exudates, and decomposing plant residues (Saxena et al., 2016). Aromatic and medicinal plants are particularly relevant in allelopathy research because they often produce high concentrations of terpenoids, phenolics, and volatile organic compounds with phytotoxic activity (Fujii et al., 1991; Zouaoui et al., 2020). In the present study, *Cymbopogon nardus* (citronella grass) and *Lantana camara* (lantana) were selected due to their documented allelopathic potential and their richness in biologically active secondary metabolites (Suwitchayanon et al., 2013; Gindri et al., 2020). Accordingly, this study aimed to evaluate the allelopathic effects of *C. nardus* and *L. camara* through volatilisation, foliage leachate, and root exudation assays on two weedy rice variants from Peninsular Malaysia and the cultivated MR220 CL2 rice variety, as well as to assess their potential relevance in future sustainable weed-management research.

MATERIALS AND METHODS

Donor and Bioassay Plants

The donor species used in this study were two aromatic plants, namely *Cymbopogon nardus* (citronella grass) and *Lantana camara* (lantana). *C. nardus* was collected from the surrounding area of Saujana Impian, Kajang, Selangor (3.014°N, 101.793°E), whereas *L. camara* was sampled from the vicinity of Universiti Kebangsaan Malaysia, Bangi, Selangor (2.921°N, 101.784°E).

The bioassay plants consisted of two weedy rice variants and one cultivated rice variety,

MR220 CL2. The designation, sampling locations, coordinates, and morphological characteristics of the bioassay plants are presented in Table 1. Seeds of WRN and WRE were collected from multiple mature plants within each sampling location to minimise bias associated with individual plant variation. Only fully matured and visually healthy seeds were selected for the bioassays. Prior to experimentation, all seeds were air-dried and stored under laboratory conditions. To reduce the influence of seed dormancy and improve germination uniformity, all seeds were pre-soaked in distilled water for 24 h before use in the dish-pack, sandwich, and plant-box assays.

Table 1: Designation, sampling locations, and morphological characteristics of the bioassay weedy rice biotypes and the modern cultivar.

Bioassay designation	Type	Sampling location	Coordinate	Morphological characteristics
WRN	Weedy rice	Kg. Chermai, Arau, Perlis	6.400°N 100.271°E	Awnless; brown-hulled; closed panicle
WRE	Weedy rice	Teluk Mesira, Bachok, Kelantan	6.143°N 102.343°E	Awned; straw-hulled; open/horizontal panicle
MR220 CL2	Modern cultivar	MARDI Seberang Perai	5.540°N 100.470°E	Awnless; straw-hulled; compact panicle

Dish Pack Method

This method was developed by Fujii (2005) to identify the potential of leaf volatilisation from selected aromatic plants (*C. nardus* and *L. camara*), which acted as donor plants, towards the growth of weedy rice variants and the MR220 CL2 variety (bioassay plants). Following this method, a multi-dish plate (Thermo Scientific Inc.) with six wells (10 cm² each) was used. The donor plant leaf samples were washed, collected, and oven-dried at 50°C for three days before use. A total of 2 g of donor plant dried leaf samples were inserted into the first well (source well). Next, the other five wells were lined with Whatman No. 1 filter paper with three replications carried out for each species. Each lined well was then filled with 0.7 mL of distilled water using a pipette. A total of three seeds of each bioassay plant isplaced on the surface of the filter paper. The distances between the source well and the other neighbouring wells are 41, 58, 82, and 92 mm. For control treatment, the source well was not filled with any sample

of the donor plants. Once all the samples and seeds are placed in the lined wells, the multi-dish was tightly sealed with adhesive tape to prevent the release of volatile materials. Then, each multi-dish was labeled and incubated in a growth chamber at 28°C under a 12-hour light and 12-hour dark photoperiod for seven days. The radicle and coleoptile lengths of the bioassay plants were measured and recorded seven days after sowing.

Sandwich Method

The sandwich method was introduced by Fujii et al. (2003) and aims to assess the allelopathic potential of leaf litter leachate from donor plants on the growth of weedy rice variants and the MR220 CL2 rice variety. In this experiment, two concentrations (10 and 50 mg) of oven-dried leaf of the donor plants were used. For each multi-dish (Thermo Scientific Inc.), three wells were filled with 10 mg of oven-dried leaf of the donor plants, and the remaining three wells were filled with 50 mg of the respective donor plants. Agar (Nacalai Tesque Inc., Kyoto, Japan) was used as the growth medium (0.75% w/v) in this method. The agar mixture then was autoclaved for 15 minutes at 121°C and 121 kPa and the agar solution were cooled to 40-45°C. A total of 5 mL of agar solution was poured into each well containing 10 mg and 50 mg of donor plant oven-dried leaves and left to cool until a gelatin layer formed. After the first layer of agar gelatinised, another 5 ml of agar solution was poured to form a second layer of gelatin. Three seeds of the bioassay plant seeds were added to the top layer of the gelatinized agar in each multi-dish well. For the control treatment (0 mg), no oven-dried leaf of the donor plants was placed into the multi-dish wells. The multi-dish was then sealed tightly using adhesive tape and incubated in the growth chamber at 28°C for seven days. Each concentration (0.10, 50 mg) was replicated three times in a complete randomised design (CRD). The radicle and coleoptile length of the bioassay species were recorded seven days after sowing.

Plant Box Method

The plant box method was used in this experiment to evaluate the allelopathic activity of the root exudation from the donor plants towards the growth of weedy rice variants and the MR220 CL2 rice variety. This method was introduced by Fujii et al. (2007). Seedlings of donor plants (*C. nardus* and *L. camara*) were grown for two months in the greenhouse located at Plants Biotechnology Lab, Universiti Kebangsaan Malaysia. The two-month-old donor plant seedlings were then harvested,, and the root part was cleaned using distilled water. Next, an individual donor plant was then placed in a PVC tube equipped with a nylon net (root zone separating tube) located at the corner of the magenta box (6 x 6 x 10 cm; Magenta Corporation, Chicago, USA). Autoclaved agar (Nacalai Tesque Inc., Kyoto, Japan) was used

as the growth medium (0.75% w/v; 40°C) and poured into the magenta box, where it was left to form a gelatin. Thirty-three bioassay seeds were placed on the surface of the gelatinised agar, based on the distance of each seed from the donor plant. The base of the plant box then covered with aluminium foil prior to root phototropism. The top of the plant box was sealed with transparent plastic to avoid fungal contamination. The plant boxes without donor plants were designated as the untreated control. All plant boxes were then incubated for seven days in the growth chamber at 28°C. Each treatment was replicated three times in complete randomised design (CRD). The radicle and coleoptile length of bioassay species were recorded at seven days after sowing.

Extraction of *Cymbopogon nardus*

The extraction of *C. nardus* was conducted and modified according to Suwitchayanon & Kato-Noguchi (2014). A total of 100 g of air-dried *C. nardus* leaves were placed in a conical flask. Each flask was filled with 500 mL of methanol and heated at 64°C on a hot plate for 15 minutes. After heating, the flasks were shaken using an orbital shaker for 24 hours. The resulting extract was filtered through Whatman No. 1 filter paper and transferred into centrifuge tubes (Thermo Fisher Scientific, Waltham, USA). The extracts were centrifuged for 15 minutes using an Allegra X-22R centrifuge (Beckman Coulter, Inc., Switzerland) to separate the solid residues. The supernatant obtained was further filtered using a 0.22 µm syringe filter (Merck KGaA, Darmstadt, Germany) and transferred into 1.5 mL glass vials with PTFE plastic septa (Shimadzu Europa GmbH, Duisburg, Germany). The vials were stored in a cold room at –20°C until they were injected into the GC–MS instrument for analysis.

GC–MS Analysis

GC–MS analysis (Agilent Technologies, Inc., Santa Clara, USA) was performed using a gas chromatograph (Agilent 7890A) coupled to an inert mass selective detector (MSD, Agilent 5975C) equipped with a triple-axis detector. Helium (99.999%) was used as the carrier gas at a constant flow rate of 1.0 mL/min. An injection volume of 0.5 µL was introduced in split mode (10:1) with the injector temperature set at 250°C and the ion source temperature at 280°C. The GC oven temperature was initially programmed at 110°C (isothermal for 2 min), followed by a 10°C/min increase to 200°C, then a 5°C/min increase to 280°C, and held isothermally at 280°C for 9 min. The total GC–MS run time was 30 min. Mass spectra were acquired in electron ionisation (EI) mode at 70 eV, with a scan interval of 0.5 s and a mass range of 40–550 Da.

Statistical Analysis

Statistical analyses were conducted using SPSS version 23 (IBM Corp., Armonk, USA). Prior to analysis, all data were tested for normality using the Shapiro–Wilk test and for homogeneity of variances using Levene's test to ensure compliance with ANOVA assumptions. Data transformation was applied only when these assumptions were not satisfied. For the dish-pack and sandwich assays, differences among treatments, donor species, concentrations, and recipient rice genotypes were analysed using one-way analysis of variance (ANOVA), followed by Tukey's Honestly Significant Difference (HSD) test at $p < 0.05$ for pairwise mean separation. Both post-hoc tests were applied to improve the robustness and consistency of treatment comparisons.

Relative growth response was calculated by comparing each treatment mean with its corresponding untreated control. The percentage of control (%) was calculated as:

Percentage of control (%) = (Mean seedling length in treatment / Mean seedling length in control) × 100

Values below 100% were interpreted as inhibition, whereas values above 100% were interpreted as stimulation relative to the untreated control. Percentage inhibition and stimulation were further calculated using the following equations:

Inhibition (%) = [(Control mean − Treatment mean) / Control mean] × 100
Stimulation (%) = [(Treatment mean − Control mean) / Control mean] × 100

These calculations were applied separately for radicle and coleoptile elongation across all bioassays.

For the plant-box assay, the relationships between seedling growth and distance from the donor plant were evaluated using Pearson's correlation analysis at $p < 0.01$. Linear regression analysis was subsequently applied to assess the distance-dependent inhibition pattern and determine the coefficient of determination (R^2). Graphs and regression plots were prepared using OriginPro version 2023 (OriginLab Corporation, Northampton, USA).

RESULTS

Allelopathic Effects of Leaf Volatilization

Volatilization from *Cymbopogon nardus*

The volatiles released by *C. nardus* exerted a clear distance-dependent influence on seedling growth (Figure 1). At the closest distance (41 mm), radicle elongation of the two weedy rice variants, WRN and WRE, was markedly inhibited by approximately 17 % and 60 % relative to their controls, respectively. In contrast, the cultivated rice variety MR220 CL2 exhibited a slight stimulation of approximately 5% at this proximity. As the distance increased, a gradual recovery and even stimulation occurred. At the farthest distance (94 mm), the radicle length of WRN and MR220 CL2 surpassed the control by 24 % and 12 %, respectively, while WRE remained largely comparable to its control.

A similar trend was observed for coleoptile growth (Figure 1). Volatiles of *C. nardus* inhibited coleoptile elongation of WRN and WRE by about 35 % and 42 %, respectively, at 41 mm, whereas MR220 CL2 showed only a minor reduction (8 %). Interestingly, even at 94 mm, residual inhibitory effects persisted, with coleoptile lengths reduced by 9% (WRN), 11% (WRE), and 20% (MR220 CL2) compared with their respective controls. These results indicate that *C. nardus* volatiles possess strong phytotoxic activity toward the weedy rice variants, while the cultivated rice exhibited partial tolerance and occasional compensatory stimulation at greater distances.

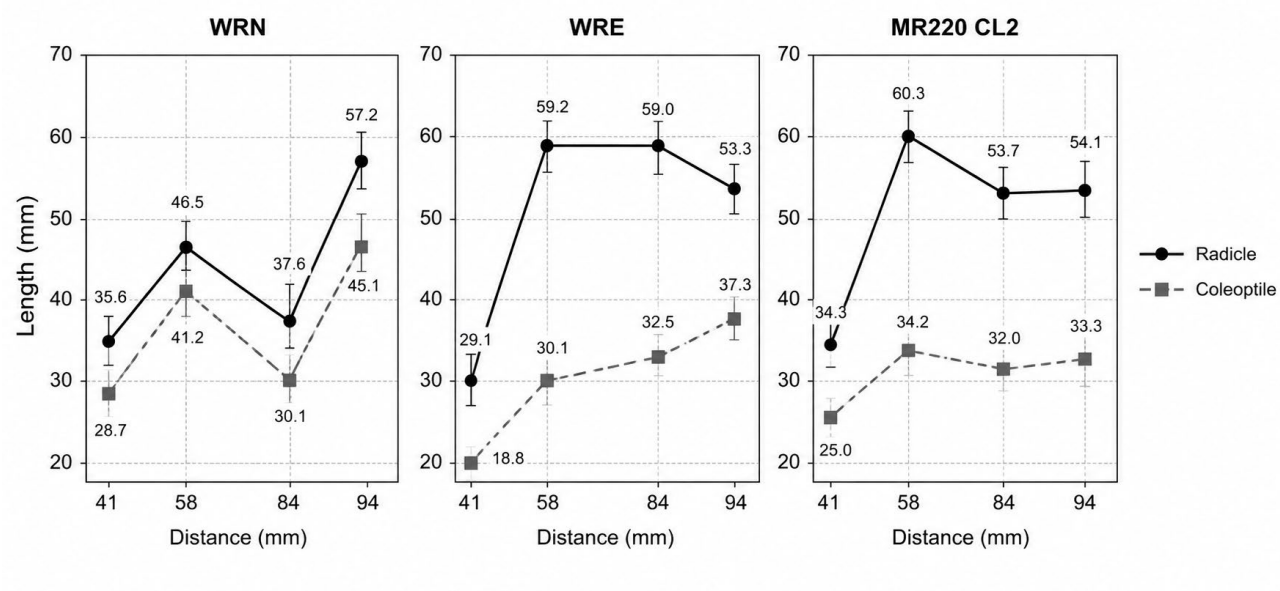


Figure 1: Effects of leaf volatilisation from *Cymbopogon nardus* on radicle and coleoptile elongation of WRN, WRE, and MR220 CL2 rice seedlings under the dish-pack assay at increasing distances from the donor plant. Values are expressed relative to the untreated

control after seven days of incubation.

Volatilisation from *Lantana camara*

Figure 2 illustrates that volatile from *L. camara* leaves also affected early seedling growth, but with slightly different intensity and direction compared with *C. nardus*. At the nearest distance (41 mm), radicle elongation of WRN, WRE, and MR220 CL2 was suppressed by approximately 11 %, 46 %, and 14 % relative to their controls, respectively. At the farthest distance (94 mm), inhibition of WRN radicle persisted (6 %), whereas both WRE and MR220 CL2 showed mild stimulation of 13 % and 4 % beyond control levels.

For coleoptile growth, *L. camara* volatiles generally produced weaker effects. At 41 mm, coleoptile lengths of WRN and MR220 CL2 were reduced by 11 % and 14 %, respectively, whereas WRE displayed a marginal increase of about 1 %. At the greatest distance (94 mm), WRN coleoptile remained 9 % shorter than the control, while WRE and MR220 CL2 were stimulated by 48 % and 1 %, respectively. These patterns suggest that *L. camara* emissions exerted moderate inhibitory activity at short range but tended to induce compensatory elongation at wider distances, especially in the WRE variant.

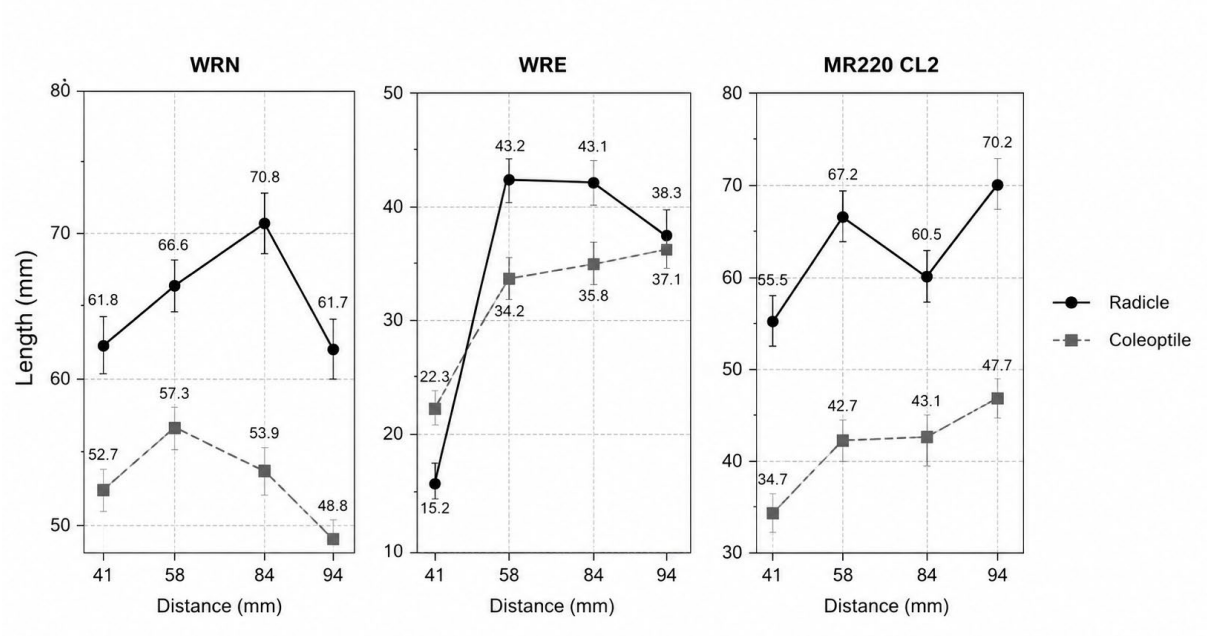


Figure 2: Effects of leaf volatilisation from *Lantana camara* on radicle and coleoptile elongation of WRN, WRE, and MR220 CL2 rice seedlings under the dish-pack assay at increasing distances from the donor plant. Values are expressed relative to the untreated control after seven days of incubation.

The selectivity test revealed that the inhibitory effects of leaf volatiles were donor- and recipient-dependent (Table 2). Among all combinations, *Cymbopogon nardus* exhibited the strongest suppression, particularly toward the weedy rice variant WRE, where both radicle and coleoptile growth were drastically reduced to 28.5 % and 22.4 % of the control, respectively ($p < 0.001$). The WRN variant was moderately inhibited by *C. nardus*, resulting in a 49–68% reduction, which was significant for coleoptile elongation ($p < 0.01$). In contrast, the cultivated rice MR220 CL2 was relatively tolerant, with radicle and coleoptile lengths slightly stimulated (118–103% of the control) and no significant difference from the control. The volatiles from *L. camara* caused milder inhibition, with the most notable effect observed on WRE radicle growth (49.5% of the control, $p < 0.001$). The other bioassay plants exposed to *L. camara* exhibited non-significant changes. Overall, *C. nardus* demonstrated stronger and more selective phytotoxicity toward weedy rice variants, while the cultivated MR220 CL2 maintained resilience against both donor plants.

Table 2: Selective effects of *Cymbopogon nardus* and *Lantana camara* leaf volatiles on the radicle and coleoptile growth of rice bioassay plants at the closest exposure distance (41 mm).

Donor plant	Recipient	Radicle inhibition (%)	Sig.	Coleoptile inhibition (%)	Sig.
C. nardus	MR220 CL2	118.6		103.3	
	WRE	28.5	***	22.4	***
	WRN	68.4		50.7	**
L. camara	MR220 CL2	88.6		78.0	
	WRE	49.5	***	78.9	
	WRN	89.4		89.3	

Note: Values represent percentage of control at the closest exposure distance (41 mm). Positive values indicate inhibition relative to the untreated control, whereas negative values indicate stimulation. Statistical significance was determined by comparison with the untreated control within each rice genotype separately. Asterisks indicate FDR-adjusted significance levels following multiple-comparison correction (*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$).

Allelopathic Effects of the Foliage Leaching

Effects of *Cymbopogon nardus* leaf leachate on seedling growth

The aqueous leaf leachate of *C. nardus* markedly influenced the early seedling growth of both weedy and cultivated rice genotypes (Figure 3). Overall, the allelopathic effects were concentration-dependent and more pronounced on the radicle than on the coleoptile. In the WRN variant, radicle elongation declined progressively from 61.0 mm in the control to 42.6 mm and 34.9 mm at 10 mg and 50 mg, respectively, corresponding to reductions of 30–43 % relative to the control. Coleoptile growth showed a milder response, with only slight inhibition at the highest concentration. Similarly, the WRE variant exhibited substantial suppression of both radicle and coleoptile elongation at increasing concentrations. Mean radicle length decreased from 56.1 mm in the control to 33.2 mm at 50 mg, while coleoptile length fell from 61.8 mm to 33.1 mm over the same range, indicating severe phytotoxic effects on this weedy biotype.

In contrast, the cultivated rice MR220 CL2 displayed greater tolerance to the *C. nardus* extract. At 10 mg, the radicle and coleoptile lengths (69.4 mm and 48.7 mm, respectively) were statistically similar to those of the control, suggesting no significant inhibition at this low concentration. A pronounced reduction occurred only at 50 mg, where the radicle shortened to 39.7 mm (55 % of control) and the coleoptile to 40.9 mm (89 % of control). This pattern indicates a threshold-type response rather than a linear inhibition, implying that the cultivar possesses a degree of physiological resilience against moderate leachate exposure.

The findings reveal that *C. nardus* leaf leachate exerts selective allelopathic activity, strongly suppressing the radicle and coleoptile elongation of weedy rice (WRN and WRE) while exerting comparatively weaker effects on the cultivated MR220 CL2. The radicle consistently emerged as the more sensitive organ, reflecting its direct exposure to soluble phytochemicals diffusing through the medium. Such selectivity highlights the potential of *C. nardus* aqueous extracts as a natural bioherbicidal source for targeted suppression of weedy rice species in paddy ecosystems.

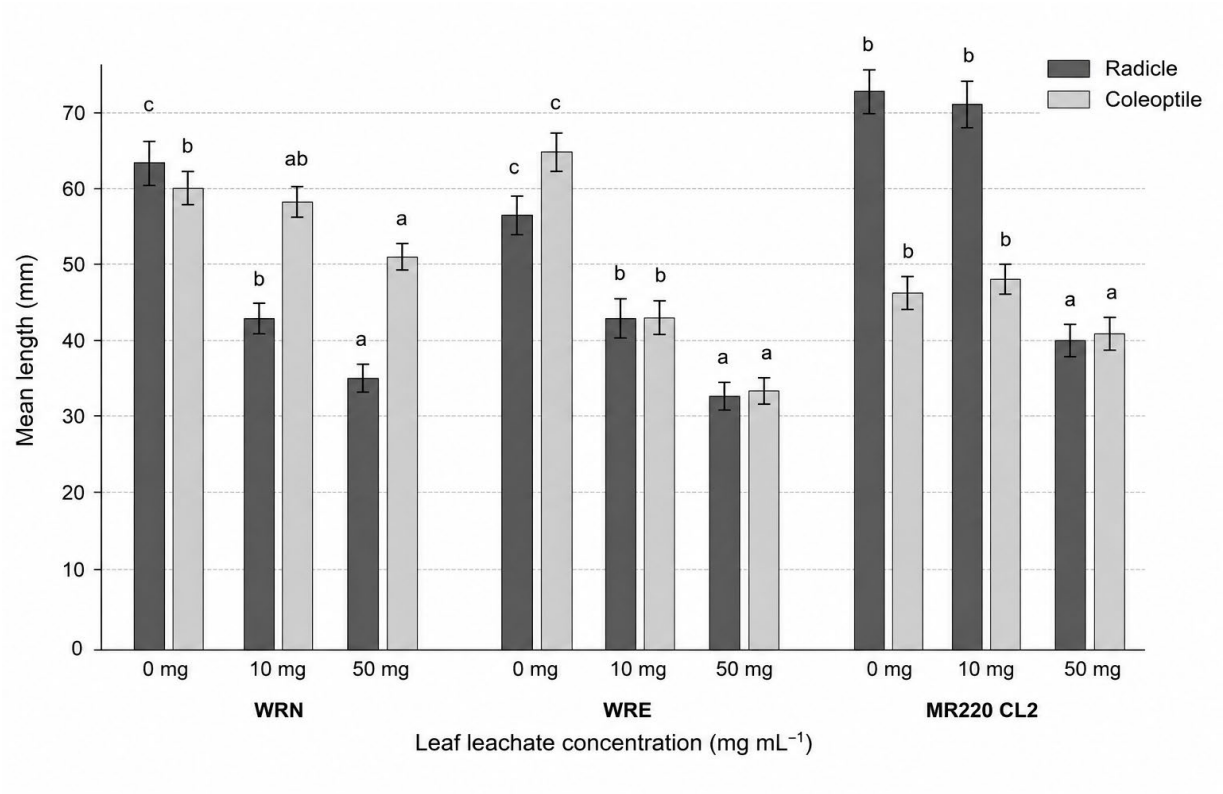


Figure 3: Effects of *Cymbopogon nardus* leaf leachate on radicle and coleoptile growth of WRN, WRE, and MR220 CL2 rice seedlings. Bars represent mean ± standard error (n = 18–28). Different letters above bars indicate significant differences among treatments according to Tukey's HSD test ($p < 0.05$).

Effects of *Lantana camara* leaf leachate on seedling growth

The aqueous leaf leachate of *Lantana camara* exhibited measurable but relatively moderate inhibitory effects on the seedling growth of all recipient rice genotypes (Figure 4). Overall, the phytotoxic influence was concentration-dependent and varied among genotypes and plant organs. In the WRN variant, radicle elongation decreased gradually from 52.2 mm in the control to 49.2 mm at 10 mg and 43.0 mm at 50 mg, corresponding to 94% and 82% of the control, respectively. Coleoptile length showed a similar but less pronounced pattern, with a slight stimulation at 10 mg followed by moderate inhibition at 50 mg. The WRE variant displayed a comparable but more sensitive response: radicle length declined from 55.6 mm in the control to 54.7 mm at 10 mg and 36.5 mm at 50 mg (66 % of control), while coleoptile length decreased from 61.2 mm to 51.3 mm (84 % of control) at the highest concentration. Statistical analyses confirmed that inhibition was significant only at 50 mg for both weedy rice variants.

The cultivated rice MR220 CL2 exhibited a stronger and more distinct pattern of inhibition.

While radicle elongation was unaffected at 10 mg (104 % of control), it decreased sharply to 38.4 mm (60 % of control) at 50 mg. The coleoptile, however, was more sensitive; its length was significantly reduced even at 10 mg (47.5 mm; 78% of the control) and declined further to 40.3 mm (66% of the control) at 50 mg. This organ-specific response indicates that L. camara leachate constituents may interfere more strongly with shoot elongation processes, such as cell expansion or hormonal regulation, than with root growth.These findings showed that *L. camara* leaf leachate exerts selective, concentration-dependent phytotoxic effects on rice seedlings, with the cultivated MR220 CL2 showing greater sensitivity than the weedy variants. Compared to *C. nardus*, the overall inhibitory potential of *L. camara* was weaker, but its effects were more pronounced on the coleoptile than on the radicle, suggesting differing modes of allelopathic action between the two donor species.

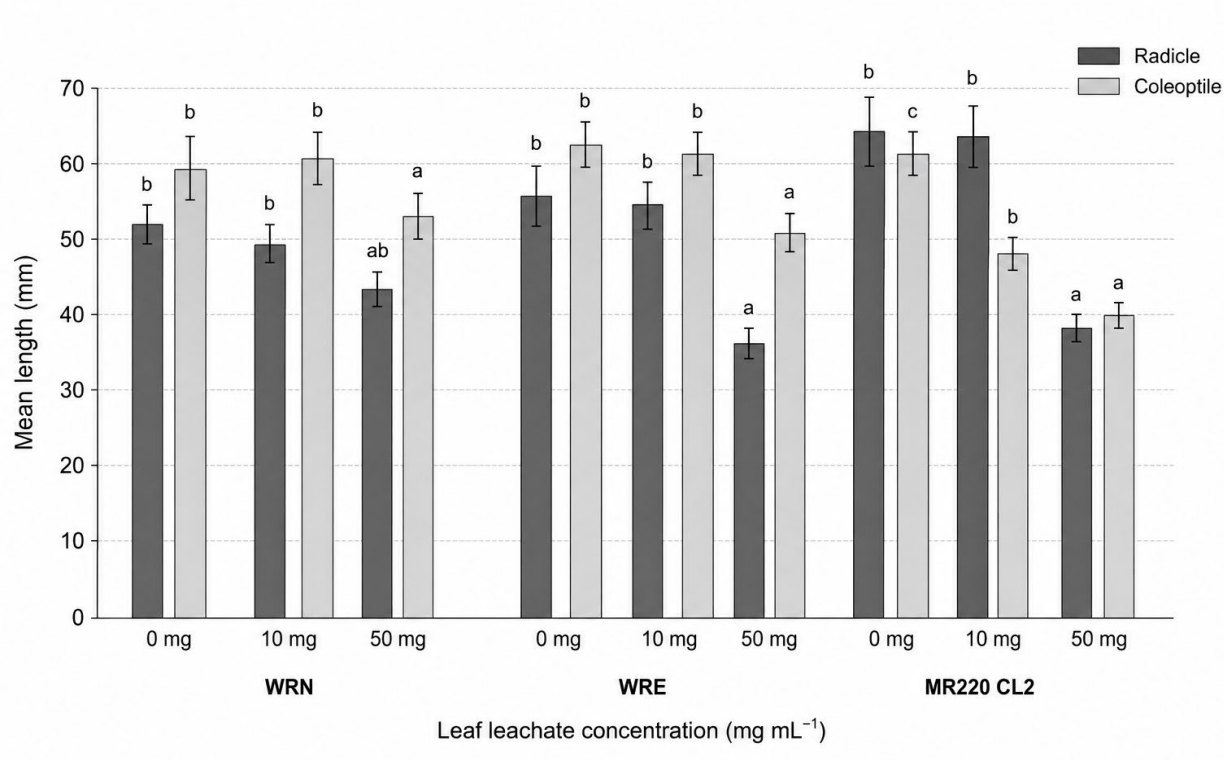


Figure 4: Effects of *Lantana camara* leaf leachate on radicle and coleoptile growth of WRN, WRE, and MR220 CL2 rice seedlings. Bars represent mean ± standard error (n = 18–28). Different letters above bars indicate significant differences among treatments according to Tukey's HSD test ($p < 0.05$).

The selectivity matrix (Figure 5) presents the overall response of the three rice genotypes to the leaf leachates of *C. nardus* and *L. camara*. The pattern shows that inhibition increased with concentration; however, the strength and direction of the response differed according to both the donor and recipient plants. Among the bioassay species, *C. nardus* caused stronger

suppression, particularly in WRE, which recorded the lowest radicle and coleoptile growth at higher concentrations. The WRN variant showed moderate inhibition, while the cultivated MR220 CL2 responded more variably, with slight stimulation at lower exposure levels. This pattern suggests a selective effect of *C. nardus* leachate, likely related to the activity of phenolic and terpenoid compounds that act more intensely on genotypes with wild characteristics.

In comparison, *L. camara* leachate produced milder and less consistent effects. Only WRE showed apparent radicle inhibition, while WRN and MR220 CL2 displayed minor reductions or near-normal growth. The lighter colour tones in the matrix, representing 80 to 90 per cent of the control, reflect the weaker phytotoxic potential of *L. camara*. These differences indicate that *L. camara* contains fewer or less mobile allelochemicals than *C. nardus*.The overall pattern demonstrates that *C. nardus* leachate exerts more selective allelopathic pressure across the tested rice genotypes, with stronger activity against the weedy variants. This selective inhibition suggests that *C. nardus* may offer greater potential as a bioherbicidal source for managing weedy rice under laboratory and field conditions.

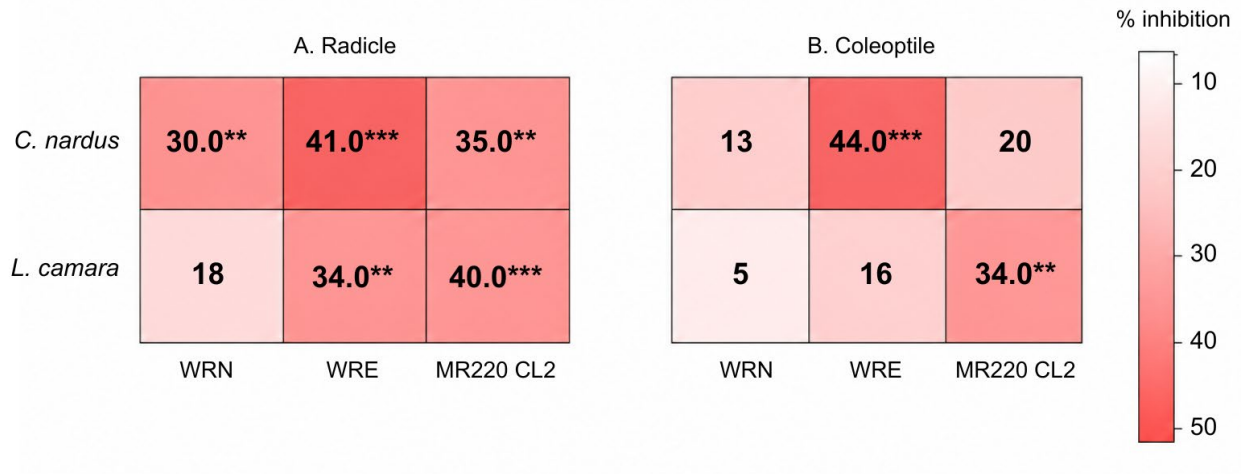


Figure 5: Percentage inhibition matrix showing the effects of *Cymbopogon nardus* and *Lantana camara* leaf leachates on the radicle (A) and coleoptile (B) growth of WRN, WRE, and MR220 CL2 rice seedlings relative to the untreated control. Darker red shading indicates stronger inhibitory effects, whereas lighter shading indicates weaker inhibition. Asterisks indicate significant differences from the untreated control (*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$).

Allelopathic Effects of the Root Exudation

Exudates from *Cymbopogon nardus*

As shown in Figure 6, the root exudates released by *Cymbopogon nardus* influenced the radicle elongation of all recipient rice cultivars, although the magnitude of inhibition varied among genotypes. In general, the seedlings positioned nearer to the donor plant exhibited shorter radicles, reflecting a spatial gradient of allelopathic influence. The strength of this relationship, however, differed considerably across cultivars.

For the WRN variant, radicle length tended to increase only slightly with distance from the donor, with a low coefficient of determination ($R^2 = 0.0936$), indicating weak sensitivity to root-derived allelochemicals. In contrast, the WRE cultivar exhibited a clearer positive correlation ($R^2 = 0.5148$), indicating that its growth response was more consistently influenced by proximity to *C. nardus*. The regression line indicates that inhibition was most evident within the first 10 mm from the donor plant, where root exudate concentrations are presumed to be highest. Meanwhile, the MR220 CL2 variety displayed only a slight distance effect ($R^2 = 0.0673$), implying that this modern cultivar possessed greater tolerance or physiological resilience against allelochemical interference.

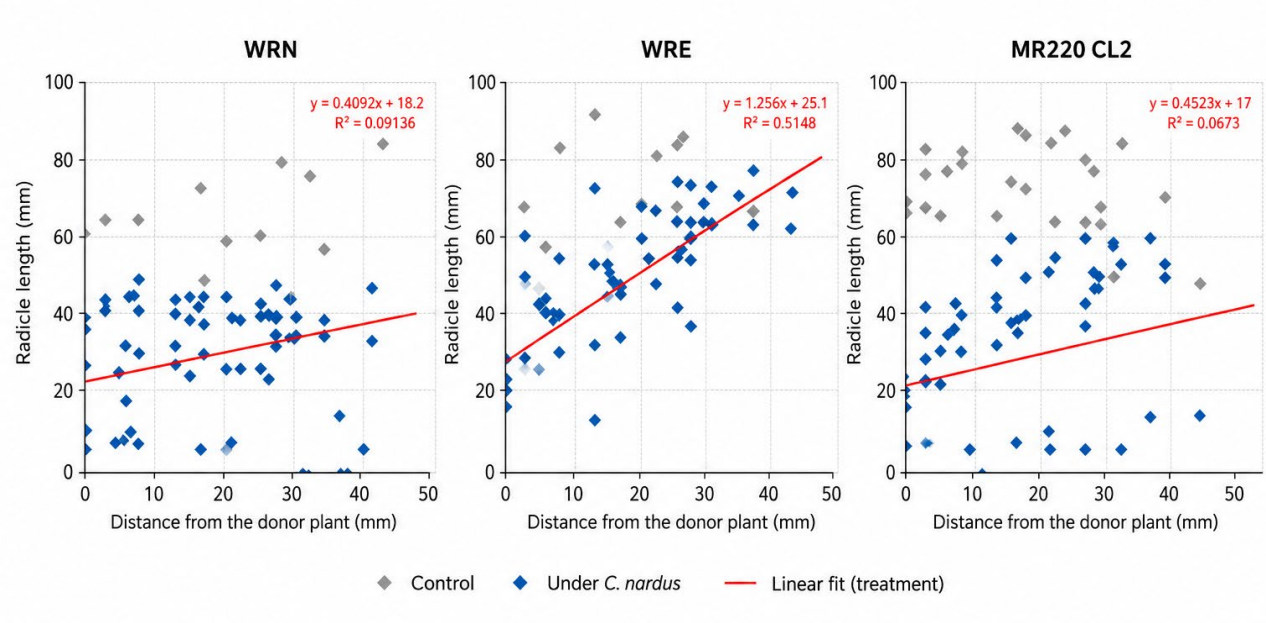


Figure 6: Radicle elongation responses of WRN, WRE, and MR220 CL2 rice seedlings grown at increasing distances from the donor plant *Cymbopogon nardus* under the plant-box assay. Linear regression analysis illustrates the relationship between donor proximity and radicle growth response.

Exudates from *Lantana camara*

As shown in Figure 7, the root exudation from *Lantana camara* affected radicle elongation in

all recipient rice cultivars, although the intensity of inhibition varied markedly among genotypes. A consistent distance-dependent pattern was observed, in which seedlings located closer to the *Lantana* donor exhibited shorter radicles, while growth gradually recovered with increasing distance from the donor root zone. This response reflects the diffusion gradient of allelochemicals released into the growth substrate and their declining concentration with spatial separation.

For the WRN cultivar, radicle elongation showed a weak association with donor distance (R^2 = 0.0189), indicating a limited and inconsistent response to *L. camara* exudates. The WRE cultivar exhibited a stronger, more coherent inhibition pattern with R^2 = 0.2227, suggesting moderate sensitivity and a measurable reduction in root length near the donor. The MR220 CL2 variety displayed a relatively stronger regression (R^2 = 0.3428), implying that the modern cultivar was more consistently affected by *L. camara*-derived compounds, though its overall reduction remained moderate compared with *C. nardus* exposure.

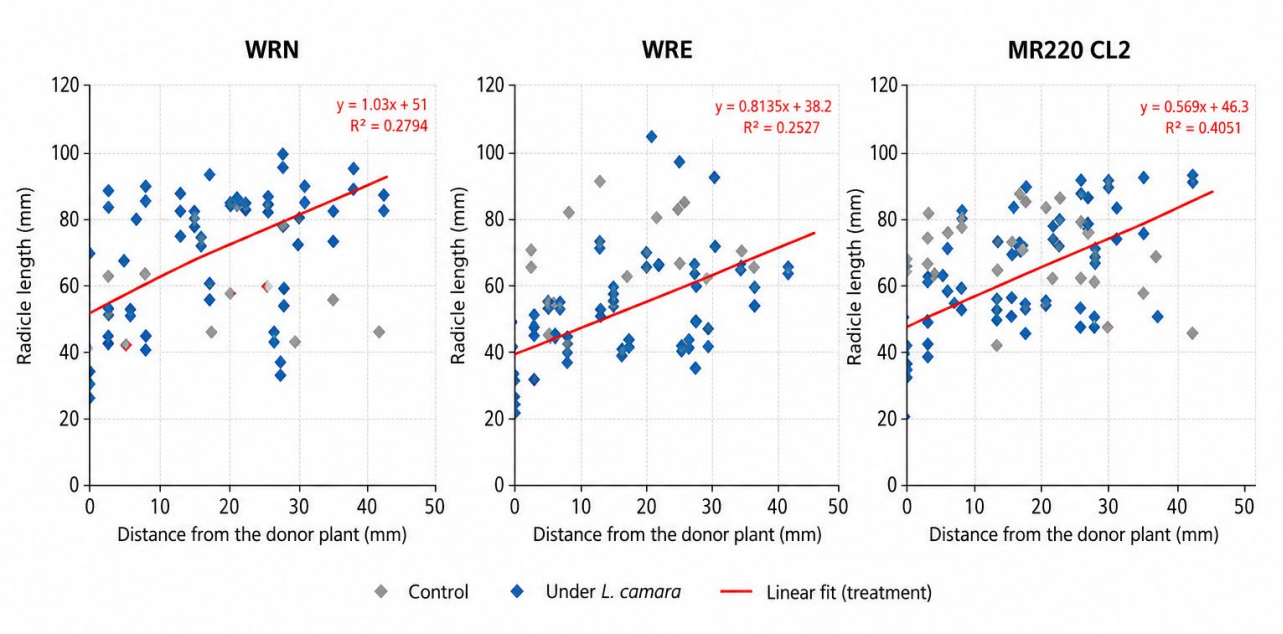


Figure 7: Radicle elongation responses of WRN, WRE, and MR220 CL2 rice seedlings grown at increasing distances from the donor plant *Lantana camara* under the plant-box assay. Linear regression analysis illustrates the relationship between donor proximity and radicle growth response.

Chemical Composition of *Cymbopogon nardus* Extracts

Based on the notable growth suppression observed in the plant-box bioassay, *C. nardus* was

subjected to further chemical examination to explore the possible compounds associated with its inhibitory effect. Although the precise mechanisms underlying its allelopathic influence remain uncertain, the consistent reduction in radicle elongation among the test cultivars indicated that the species may release bioactive metabolites into the growth medium. To gain preliminary insight into its chemical profile, both aqueous and methanolic extracts were analysed using GC–MS, with the aim of identifying constituents that could contribute to the observed biological responses.

The GC–MS analysis revealed distinct differences in the chemical composition of the aqueous and methanolic extracts of *Cymbopogon nardus*, reflecting the contrasting polarity and volatility of the two solvent systems (Table 3). The aqueous extract primarily consisted of long-chain fatty acid methyl esters and related lipid derivatives, which are semivolatile and weakly polar in nature. The most abundant compound detected was 9,12-octadecadienoic acid, methyl ester (36.7%), followed by methyl stearate (17.1%), 9-octadecenoic acid, methyl ester (15.6%), and hexadecanoic acid, methyl ester (14.3%). In smaller quantities, several saturated and unsaturated fatty acids, including geranic acid, n-hexadecanoic acid, and octadecanoic acid, were also identified. The presence of these fatty acid esters indicates that the aqueous extract contains stable, water-dispersible compounds derived from the partial hydrolysis and esterification of plant lipids.

In contrast, the methanolic extract exhibited a richer and more complex volatile profile dominated by terpenoid compounds. Geraniol was the most prominent constituent (23.2%), followed by citral, consisting of its neral and geranial isomers (7.4%). Other notable components included 2,6-octadienal, 3,7-dimethyl- (E) (6.2%) and 2,6-octadien-1-ol, 3,7-dimethyl- (Z) (5.0%), together with minor quantities of caryophyllene, geranyl acetate, citronellol, eugenol, and phytol. These compounds are primarily volatile monoterpenes and sesquiterpenes, which contribute to the distinctive aroma of *C. nardus* and represent the non-polar, low-molecular-weight fraction of its secondary metabolites. Overall, the methanolic extract was characterized by volatile and non-polar constituents, while the aqueous extract contained semivolatile, weakly polar compounds. The contrasting chemical profiles suggest that *C. nardus* produces both volatile and soluble metabolites, which may play complementary roles in its allelopathic activity.

Table 3: Major chemical constituents identified from the aqueous and methanolic extracts of *Cymbopogon nardus* by GC–MS analysis, including chemical classification and volatility characteristics.

No.	Compound Name	Extract Type	Chemical Class	Volatility / Polarity	Retention Time (min)	Relative abundance (%)
1	Geraniol	Methanolic	Monoterpenoid alcohol	Volatile, non-polar	14.79	23.2
2	Citral (neral + geranial)	Methanolic	Monoterpenoid aldehyde	Volatile, non-polar	14.34	7.4
3	2,6-Octadienal, 3,7-dimethyl-, (E)-	Methanolic	Aldehyde	Volatile, non-polar	15.07	6.2
4	2,6-Octadien-1-ol, 3,7-dimethyl-, (Z)-	Methanolic	Monoterpenoid alcohol	Volatile, non-polar	14.22	5.0
5	Caryophyllene	Methanolic	Sesquiterpene hydrocarbon	Volatile, non-polar	18.36	1.4
6	Geranyl acetate	Methanolic	Monoterpenoid ester	Volatile, non-polar	17.40	1.1
7	Citronellol	Methanolic	Monoterpenoid alcohol	Volatile, non-polar	23.80	0.9
8	9,12-Octadecadienoic acid, methyl ester (E,E)	Aqueous	Fatty acid ester	Semivolatile, weakly polar	25.81	36.7
9	Methyl stearate	Aqueous	Fatty acid ester	Semivolatile, weakly polar	26.36	17.1
10	9-Octadecenoic acid (Z)-, methyl ester	Aqueous	Fatty acid ester	Semivolatile, weakly polar	25.93	15.6
11	Hexadecanoic acid, methyl ester	Aqueous	Fatty acid ester	Semivolatile, weakly polar	22.46	14.3
12	Geranic acid	Aqueous	Monoterpenoid acid	Low volatility, polar	10.76	2.1
13	n-Hexadecanoic acid	Aqueous	Saturated fatty acid	Non-volatile, polar	23.44	1.9
14	Octadecanoic acid	Aqueous	Saturated fatty acid	Non-volatile, polar	26.96	1.7
15	Eugenol	Methanolic	Phenolic monoterpenoid	Volatile, moderately polar	16.97	0.6

No.	Compound Name	Extract Type	Chemical Class	Volatility / Polarity	Retention Time (min)	Relative abundance (%)
16	Phytol	Methanolic	Diterpenoid alcohol	Low volatility, non-polar	30.75	0.17

Note: Relative abundance values are expressed as percentages of total chromatographic peak area detected within each extract type.

DISCUSSION

Across all bioassays conducted in the present study, *Cymbopogon nardus* consistently exerted stronger inhibitory effects than *Lantana camara*, indicating that the phytotoxic activity of the donor species was strongly influenced by both chemical composition and exposure pathway. The stronger suppression produced by *C. nardus* in the volatilisation assay suggests that volatile allelochemicals play an important role in its inhibitory mechanism, particularly at shorter distances where compound concentration and exposure intensity are likely to be greatest. In contrast, the comparatively weaker responses observed in *L. camara* imply that its volatile constituents were either less phytotoxic or less effective in maintaining inhibitory concentrations within the exposure system. A similar trend was observed in the foliage leachate and plant-box assays, where *C. nardus* maintained stronger suppression across both soluble and root-mediated exposure pathways. The greater reduction in radicle elongation observed in WRN and WRE compared with MR220 CL2 further suggests that the allelopathic effects of *C. nardus* were not uniformly expressed across all rice genotypes. Instead, the stronger sensitivity displayed by the weedy rice variants indicates the possibility of genotype-dependent responses to allelochemical exposure. This pattern is important because it suggests that allelopathic interactions in rice systems may depend not only on the donor species, but also on the physiological characteristics of the recipient genotype. The clearer distance-dependent inhibition pattern and higher coefficients of determination recorded for *C. nardus* also indicate that its released compounds were more consistently associated with suppression gradients in the growth medium. Such responses support previous findings that essential-oil-rich species may influence neighbouring plants through both volatile and non-volatile pathways, with the magnitude of inhibition depending on compound diffusion, proximity, and target-species sensitivity (Zheljazkov et al., 2021; Tütenocaklı et al., 2022). Therefore, the stronger and more consistent responses produced by *C. nardus* across multiple bioassays suggest that the species possesses a more stable and biologically active allelopathic profile than *L. camara* under the experimental conditions evaluated in this study.

The GC–MS analysis helps explain the stronger allelopathic activity shown by *C. nardus*

throughout the volatilisation, sandwich, and plant-box assays. The methanolic extract was mainly dominated by volatile monoterpenes, particularly geraniol, citral (neral and geranial), and related C10 aldehydes and alcohols, together with smaller amounts of sesquiterpenes such as caryophyllene and geranyl acetate. These compounds are commonly recognised as biologically active constituents found in aromatic plants and essential oils (Chen et al., 2022). Their dominance in the methanolic fraction suggests that volatile terpenoids may play an important role in the rapid phytotoxic responses observed in the present study. The inhibitory effects observed in this study are also consistent with previous reports describing the phytotoxic and allelopathic behaviour of terpenoid-rich *Cymbopogon* species. Kaur et al. (2021) similarly reported that *C. nardus* leaves are dominated by citronellol, citronellal, and geraniol, indicating that these metabolites form major components of the species' secondary chemistry. Geraniol has also been associated with inhibitory effects on seed germination and seedling growth under increasing exposure concentrations (Tütenocaklı et al., 2022). In addition, citral and citronellol, both major constituents of *Cymbopogon* oils, have demonstrated inhibitory effects on the early growth of cress and barnyard grass (Li et al., 2005). Therefore, the stronger inhibitory effects produced by *C. nardus* compared with *L. camara* may not be due to a single compound alone, but rather the combined activity of several volatile terpenoids acting together across different exposure pathways evaluated in this study.

Previous studies have demonstrated that *C. nardus* possesses measurable allelopathic activity; however, the present findings suggest that its inhibitory effects may involve multiple exposure pathways operating simultaneously rather than a single isolated mechanism. Suwitchayanon et al. (2013) reported that aqueous methanol extracts of *C. nardus* suppressed root and shoot elongation in lettuce, cress, and ryegrass seedlings in a concentration-dependent manner, indicating that the species contains biologically active metabolites capable of interfering with early plant development. Their observation that both leaf and root extracts were inhibitory further suggests that the allelopathic activity of *C. nardus* is distributed across multiple plant tissues. This may explain why the species consistently maintained inhibitory activity across the volatilisation, foliage leachate, and root exudation assays conducted in the present study.

The GC–MS analysis further indicates that the inhibitory behaviour of *C. nardus* may be associated with chemically distinct fractions that function differently within the surrounding environment. Unlike the methanolic fraction, which was dominated by volatile monoterpenes, the aqueous extract contained mainly long-chain fatty acid methyl esters such as 9,12-octadecadienoic acid methyl ester, methyl stearate, and hexadecanoic acid methyl ester. Due to their comparatively lower volatility and semivolatile behaviour, these compounds may

persist longer within the growth medium and diffuse more gradually through water-based pathways (Zaratti et al., 2024). Consequently, the progressive distance-dependent suppression observed in the plant-box assay may not simply reflect concentration effects alone, but also the mobility and persistence of these metabolites within the rhizosphere environment. Similar fatty acid derivatives have previously been associated with membrane disruption, metabolic imbalance, and inhibitory effects on root growth (Anwar et al., 2021; Puig et al., 2021), supporting the interpretation that the aqueous fraction contributed substantially to the sustained suppression patterns observed in this study.

In contrast, *L. camara* displayed weaker and less consistent inhibition across all exposure modes, suggesting that its allelopathic activity may be more dependent on environmental conditions, exposure concentration, and recipient-species sensitivity. Although the species is known to contain phenolic acids, sesquiterpenes, and triterpenoids such as lantadene A and lantanolic acid, the present findings indicate that these compounds did not generate suppression patterns comparable to those produced by *C. nardus*. Kato-Noguchi and Kurniadie (2021) similarly emphasised that the allelopathic effects of *L. camara* can vary considerably depending on extraction conditions, exposure level, and target-species sensitivity. Comparable observations were also reported by Alemayehu et al. (2024), who found that the inhibitory effects of *L. camara* leaf extracts diminished progressively with dilution and distance from the exposure source. These findings suggest that the allelopathic activity of *L. camara* may be less stable or less persistent within the growth environment compared with *C. nardus*. Although direct GC–MS profiling was not conducted for *L. camara* in the present study, the comparatively weaker and less consistent inhibitory responses observed across the bioassays suggest that its allelochemical composition and environmental behaviour may differ substantially from those of *C. nardus*. Future comparative chemical profiling would therefore be valuable for clarifying the specific metabolites and interaction pathways associated with *L. camara* allelopathy.

The spatial inhibition patterns observed in the plant-box assay further indicate that proximity plays an important role in determining allelopathic intensity. The stronger suppression recorded near the donor roots supports the idea that allelochemical concentration decreases progressively with distance from the release source. Similar diffusion behaviour has been reported in rhizosphere studies using isotopically labelled allelochemicals, where biologically active compounds accumulated most strongly within the immediate vicinity of donor roots before declining sharply across surrounding substrates (Hua et al., 2023; Wang et al., 2021). Therefore, the steeper inhibition gradients observed for *C. nardus* may reflect not only stronger phytotoxicity, but also a more effective diffusion and persistence profile within the local root

environment.

The combined chemical and biological evidence suggest that *C. nardus* expresses a more integrated allelopathic mechanism than *L. camara*, involving both volatile- and water-mediated suppression pathways. The stronger inhibitory responses recorded in WRN and WRE compared with MR220 CL2 further indicate that the phytotoxic effects of *C. nardus* were not uniformly expressed across all rice genotypes. Rather than functioning as a broad non-selective toxin, the species may exert genotype-dependent allelopathic effects under controlled exposure conditions. Although the lower sensitivity of MR220 CL2 may partly reflect physiological differences associated with its Clearfield background, the present data remain insufficient to directly associate this response with imidazolinone tolerance mechanisms. Nevertheless, the consistent suppression patterns observed across multiple assays indicate that *C. nardus* possesses a more stable and biologically active allelopathic profile than *L. camara*, making the species particularly relevant for future studies investigating plant-derived weed suppression and allelochemical interactions in rice production systems.

From an applied perspective, the present findings suggest that *C. nardus* may possess practical relevance in rice-production environments through multiple exposure pathways. Because the species exhibited strong volatile-mediated inhibition in the dish-pack assay, its cultivation along paddy bunds or surrounding field margins may potentially contribute to localized suppression of nearby weedy rice emergence through continuous release of volatile compounds. In addition, the inhibitory effects observed in the foliage leachate and plant-box assays indicate that water-mediated applications, such as aqueous mulch incorporation or plant-based extract treatments prior to sowing, may also warrant further investigation. Similar approaches involving allelopathic crop residues and plant-derived phytotoxic compounds have previously been discussed within sustainable weed-management systems (Scavo & Mauromicale, 2021). However, the present study was conducted entirely under controlled laboratory conditions, and the persistence, diffusion behaviour, crop selectivity, and environmental stability of these allelochemicals under field conditions remain uncertain (Bhowmik, 2022). Therefore, further field-scale studies are still necessary before practical agronomic applications can be evaluated reliably.

CONCLUSION

The findings of the present study indicate that allelopathic interactions in aromatic plants may depend not only on the presence of phytotoxic compounds, but also on the diversity of metabolite classes and their modes of environmental transfer. The stronger and more

consistent responses associated with *C. nardus* suggest that the species possesses a more stable allelopathic profile than *L. camara*, particularly under conditions involving volatile exposure and rhizosphere-mediated interactions. This distinction is important because it demonstrates that not all aromatic plants express comparable inhibitory behaviour despite both containing biologically active secondary metabolites. The chemical differences identified between the methanolic, and aqueous extracts further imply that volatile and soluble compounds may contribute differently to allelopathic performance within the surrounding growth environment. Rather than functioning through a single dominant mechanism, the inhibitory activity of *C. nardus* appears to involve multiple forms of chemical interaction operating simultaneously across different exposure pathways. The stronger responses recorded in the weedy rice variants compared with MR220 CL2 also suggest that allelopathic sensitivity may vary according to recipient genotype, highlighting the importance of considering genotype-specific responses in future allelopathy research involving rice systems. The present study contributes additional evidence that aromatic plant species can differ substantially in both the consistency and expression of their allelopathic effects. Further investigation under field conditions remains necessary to determine how environmental factors, metabolite persistence, and crop selectivity influence the practical significance of these interactions in sustainable weed-management systems.

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AUTHORS' CONTRIBUTIONS

Muhamad Safwan Ishak: Conseptualisation, writing – initial draft, review and editing, data collection, data analysis, methodology, visualisation
Khairiatul Mardiana Jansar: Supervision, funding acquisition, data collection, methodology, project administration
Noraziyah Abd Aziz Shamsudin: Supervision, data collection, data analysis
Nornasuha Yusoff: Visualisation, writing – review and editing, validation

REFERENCES

Alemayehu Y, Chimdesa M and Yusuf Z. (2024). Allelopathic effects of *Lantana camara* L. leaf aqueous extracts on germination and seedling growth of *Capsicum annuum* L. and *Daucus carota* L. *Scientifica* 2024(1): 9557081.

Anwar S, Naseem S, Karimi S, Asi M R, Akrem A and Ali Z. (2021). Bioherbicidal activity and metabolic profiling of potent allelopathic plant fractions against major weeds of wheat — way forward to lower the risk of synthetic herbicides. *Frontiers in Plant Science* 12: 632390.

Bhadoria P B S. (2011). Allelopathy: A natural way towards weed management. *American Journal of Experimental Agriculture* 1(1): 7–20.

Bhowmik, P. C. (2022). Bioavailability of Allelochemicals in Soil Environment Under Climate Change: Challenges and Perspectives. *Indian Journal of Weed Science*, *54*(4), 389–396. https://doi.org/10.5958/0974-8164.2022.00070.3

Chen W, Viljoen A M and Vermaak I. (2022). Geraniol: A review update on its pharmacological and biological activities. *Frontiers in Pharmacology* 13: 939098.

Duke S O, Twitty A, Baker C, Sands D, Boddy L, Travaini M L, Sosa G, Polidore A L, Jhala A J, Kloeber J M and Jacq X. (2024). New approaches to herbicide and bioherbicide discovery. *Weed Science* 72(5): 444–464.

Engku A K, Norida M, Juraimi A S, Rafii M Y, Abdullah S N A and Alam M A. (2016). Gene flow from Clearfield® rice to weedy rice under field conditions. *Plant, Soil and Environment* 62(1): 16–22.

Fujii Y, Furukawa M, Hayakawa Y, Sugawara K and Shibuya T. (1991). Survey of Japanese medicinal plants for the detection of allelopathic properties. *Weed Research (Japan)* 36: 36– 42.

Fujii Y, Matsuyama M, Hiradate S and Shimozawa H. (2005). Dish pack method: A new bioassay for volatile allelopathy. In: Harper J D I, An M, Wu H and Kent J H (eds.). *Proceedings of the 4th World Congress on Allelopathy: Establishing the Scientific Base*. Wagga Wagga, New South Wales, Australia. pp. 493–497.

Fujii Y, Parves S, Parves M, Ohmae Y and Lida O. (2003). Screening of 239 medicinal plant species for allelopathic activity using the sandwich method. *Weed Biology and Management* 3(4): 233–241.

Fujii Y, Pariasca D, Shibuya T, Yasuda T, Kahn B and Waller G R. (2007). Plant-box method: A specific bioassay to evaluate allelopathy through root exudates. In: Fujii Y and Hiradate S (eds.). *Allelopathy: New Concepts and Methodology*. Enfield: Science Publishers. pp. 39–56.

Gindri D M, Coelho C M M and Uarotta V G. (2020). Physiological and biochemical effects of *Lantana camara* L. allelochemicals on the seed germination of *Avena sativa* L. *Pesquisa Agropecuária Tropical* 50: e62546.

Hossain M K and Alam M Z. (2018). Allelopathic potential of medicinal and aromatic plants in weed suppression: A review. *South African Journal of Botany* 117: 150–164.

Hua Z, Xie Q, Li Y, He M, Wang Y, Wu H and Zhang Z. (2023). Effects of 13C isotope-labeled allelochemicals on the growth of the invasive plant *Alternanthera philoxeroides*. *Scientific Reports* 13(1): 13756.

Huang Y. (2024). Cultural weed management strategies in rice cultivation: Reducing the infestation of weedy rice. *Field Crop* 7.

Joy P P, Thomas J, Mathew S, Jose G and Joseph J. (2001). Aromatic plants. In: Bose T K, Kabir J, Das P and Joy P P (eds.). *Tropical Horticulture*. Vol. 2. Calcutta: Naya Prakash. pp. 633–733.

Kato-Noguchi H and Kurniadie D. (2021). Allelopathy of *Lantana camara* as an invasive plant. *Plants* 10(5): 1028.

Khan M, Mahmood A and Alkhathlan H Z. (2016). Characterization of leaves and flowers volatile constituents of *Lantana camara* growing in the central region of Saudi Arabia. *Arabian Journal of Chemistry* 9(6): 764–774.

Lei Y, Fu P, Jun X and Cheng P. (2019). Pharmacological properties of geraniol – a review. *Planta Medica* 85(1): 48–55.

Li H, Huang J, Zhang X, Chen Y, Yang J and Hei L. (2005). Allelopathic effects of *Cymbopogon citratus* volatile and its chemical components. *Ying Yong Sheng Tai Xue Bao = The Journal of Applied Ecology* 16(4): 763–767.

Liang, X., Zhao, C., Liu, K., Wang, W., Huo, Z., Song, X., & Qiang, S. (2025). Advances in Research on the Biological Characteristics of Weedy Rice. *Plants*, *14*(20), 3188. https://doi.org/10.3390/plants14203188

Mahmod I F, Syed Bakar S N, Mispan M S, Supandi F, Mohamed Z and Saiman M Z. (2024). Weedy rice infestation in Malaysia: What do we know and where do we go? *Agriculture* 14(8): 1307.

Maurya P, Mazeed A, Kumar D, Ahmad I Z and Suryavanshi P. (2022). Medicinal and aromatic plants as an emerging source of bioherbicides. *Current Science* 122(258): 258–266.

Mispan M S, Bzoor M, Mahmod I, Md-Akhir A H and Zulrushdi A. (2019). Managing weedy rice (*Oryza sativa* L.) in Malaysia: Challenges and ways forward. *Journal of Research in Weed Science* 2(2): 149–167.

Mushtaq W, Siddiqui M B and Hakeem K R. (2020). *Allelopathy: Potential for Green Agriculture.* Cham, Switzerland: Springer.

Puig C G, Valencia-Gredilla F, Pardo-Muras M, Souto X C, Recasens J and Pedrol N. (2021). Predictive phytotoxic value of water-soluble allelochemicals in plant extracts for choosing a cover crop or mulch for specific weed control. *Italian Journal of Agronomy* 16(4): 1872.

Saxena R, Tomar R and Kumar M. (2016). Allelopathy: A green approach for weed management and crop production. *International Journal of Current Research in Bioscience and Plant Biology* 3(4): 43–50.

Scavo A and Mauromicale G. (2021). Crop allelopathy for sustainable weed management in agroecosystems: Knowing the present with a view to the future. *Agronomy* 11(11): 2104.

Suwitchayanon P and Kato-Noguchi H. (2014). Allelopathic activity of leaves, stalks and roots of *Cymbopogon nardus. Emirates Journal of Food and Agriculture* 26(5): 436–441.

Suwitchayanon P, Pucklai P and Kato-Noguchi H. (2013). Allelopathic activity of *Cymbopogon nardus* (Poaceae): A preliminary study. *Journal of Plant Studies* 2(2): 1–6.

Tütenocaklı T Ü, Coşkun Y A, Taş İ, Oral A and Türker G. (2022). Allelopathic effects of some essential oil components on germination and seedling growth of wheat. *Current Trends in Natural Sciences* 11(21): 55–62.

Wang N Q, Kong C H, Wang P and Meiners S J. (2021). Root exudate signals in plant–plant interactions. *Plant, Cell & Environment* 44(4): 1044–1058.

Zaratti, C., Marinelli, L., Colasanti, I. A., Barbaccia, F. I., Aureli, H., Prestileo, F., de Caro, T., la Russa, M. F., & Macchia, A. (2024). Evaluation of Fatty Acid Methyl Esters (FAME) as a Green Alternative to Common Solvents in Conservation Treatments. *Applied Sciences*, *14*(5), 1970. https://doi.org/10.3390/app14051970

Zheljazkov V D, Jeliazkova E A and Astatkie T. (2021). Allelopathic effects of essential oils on seed germination of barley and wheat. *Plants* 10(12): 2728.

Zouaoui N, Chenchouni H, Bouguerra A, Massouras T and Barkat M. (2020). Characterization of volatile organic compounds from six aromatic and medicinal plant species growing wild in North African drylands. *NFS Journal* 18: 19–28.