Impact of Smoke Exposure on Heat Stress–Induced Growth Inhibition in Plants and Disease Mitigation

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Abstract: Plant exposure to smoke-derived bioactive compounds has been increasingly recognized for its regulatory effects on growth, stress tolerance, and defense signaling, yet its role as a dual-function intervention against both abiotic stress–induced growth inhibition and insect herbivory remains poorly defined. In this study, we investigated the effects of a controlled polyherbal fumigation system on plant growth performance and disease mitigation under stress-prone conditions. A standardized botanical smoke formulation composed of neem (Azadirachta indica), turmeric (Curcuma longa), Calotropis gigantea, Boswellia serrata, and vetiver (Chrysopogon zizanioides) was applied using defined exposure protocols across multiple experimental settings. The study integrated controlled-environment and open-field experiments to evaluate growth responses in representative crop species, alongside targeted curative and preventive assessments against severe mealybug (Pseudococcidae) infestation. Plant morphometric traits, pest progression dynamics, and post-treatment recovery were systematically monitored to assess both physiological and protective outcomes of fumigation. The results demonstrate that short-duration, low-intensity herbal smoke exposure can simultaneously alleviate stress-associated growth suppression and disrupt insect persistence without observable phytotoxic effects. Additionally, fumigation generated a transient protective zone that reduced pest establishment in untreated neighbouring plants. Collectively, these findings support botanical fumigation as a scalable, low-input strategy with potential applications in sustainable agriculture, particularly in environments where heat stress and insect pressure co-occur.

➢ ***Index Terms***

Herbal fumigation refers to the controlled combustion of plant-derived materials to generate bioactive smoke capable of modulating plant growth responses and suppressing insect pests. Smoke-mediated plant responses encompass physiological, developmental, and defensive changes induced by exposure to volatile compounds released during botanical combustion. Heat stress mitigation denotes strategies aimed at reducing temperature-induced growth inhibition through combined biochemical and microclimatic interventions. Integrated pest management (IPM) involves the suppression of insect populations using chemical-free, ecologically compatible approaches that minimize environmental impact. Mealybug control describes the disruption of phloem-feeding insect establishment, survival, and persistence via smoke-based deterrent and curative mechanisms. Plant–insect interactions refer to the dynamic responses between host plants and herbivorous insects under simultaneous abiotic and biotic stress conditions. Sustainable agriculture encompasses low-input cultivation practices designed to maintain long-term productivity, ecological balance, and resource efficiency.

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I. INTRODUCTION

The persistent use of synthetic pesticides in agriculture has raised serious concerns about environmental safety and human health, including persistent soil and water contamination and impacts on non-target biota. [1] Estimates indicate large numbers of accidental pesticide poisonings globally, with considerable morbidity and mortality in agricultural communities. [2] International policy frameworks therefore emphasize integrated pest management and reduced reliance on hazardous agrochemicals as priorities for sustainable agriculture. [3]

Integrated pest management (IPM) is a multi-pronged framework that combines cultural, biological and (where necessary) chemical tactics to suppress pest populations while minimizing environmental risk. [4] Within IPM, botanical and biopesticidal options have received renewed attention because they typically decompose rapidly, exhibit selective toxicity, and can be integrated with ecological control methods. [5]

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Ethnobotanical fumigation practices (e.g., traditional "dhoopan") have long used plant-derived materials such as neem, turmeric and Boswellia resin for environmental sanitation and insect deterrence, and controlled modern studies report measurable reductions in airborne microbial load following such fumigation. [6][7]

Plant-derived botanical constituents form the biochemical basis for fumigation efficacy: complex mixtures of terpenoids, phenolics and alkaloids released during combustion or volatilization can act as repellents, antifeedants and antimicrobials. [8] Neem (Azadirachta indica) is a widely studied botanical source whose limonoids (notably azadirachtin) exhibit antifeedant and insect-growth-regulatory activity with low environmental persistence. [9] Turmeric (Curcuma longa) yields volatile sesquiterpenes (e.g., ar-turmerone) with antimicrobial and repellent properties documented in laboratory and field assays. [10] Vetiver (Vetiveria zizanioides) root volatiles and Boswellia resins release sesquiterpenoids and monoterpenoids that contribute to prolonged fumigant persistence and broad-spectrum bioactivity. [11] [12] Calotropis gigantea contains cardenolides and other metabolites with antifeedant and insecticidal potential, though its irritant properties require controlled application. [13]

Beyond direct pest suppression, combustion-derived smoke contains biologically active butenolides (karrikins) and a suite of volatile organic compounds (VOCs) that influence plant developmental pathways. [14] Karrikins were discovered as smoke-derived germination cues and subsequently shown to act at nanomolar concentrations to enhance seed germination, seedling vigor and root architecture across diverse species. [15] The KAI2-mediated signaling pathway that perceives karrikins interfaces with canonical phytohormone networks, altering transcriptional programmes related to growth, antioxidant capacity and stress responses. [16] Experimental applications of smoke-water or purified karrikin compounds have been reported to increase chlorophyll content, antioxidant enzyme activity and seedling robustness in multiple crops. [16]

A growing body of work links smoke-derived signaling and VOC exposure to improved tolerance of abiotic stresses, including drought, salinity and thermal stress. [17] Foliar or seed treatments with smoke-derived products have, in some model and crop systems, enhanced membrane stability, antioxidant defenses and physiological resilience under elevated temperature regimes. [18][19] Such findings provide a mechanistic rationale for exploring low-intensity, repeat fumigation regimes as interventions that could simultaneously reduce pest pressure and ameliorate heat-stress–related growth inhibition via modulation of endogenous stress pathways. [18]

Sap-sucking pests such as mealybugs (Family Pseudococcidae) are especially challenging in warm climates because their waxy coverings and cryptic habits render contact insecticides less effective and promote rapid population expansion under dense cropping and high-temperature conditions. [20] Botanical extracts and essential oils have shown efficacy against several mealybug species in laboratory and controlled-environment trials, while field observations of repeated localized fumigation report reduced pest establishment and limited spread to neighbouring plants. [21] [22] Botanical fumigants therefore present a potentially useful complement to IPM tactics for managing sap-feeding pests in heat-prone agroecosystems. [21]

Despite these promising lines of evidence, important knowledge gaps remain: (i) most controlled studies focus on isolated smoke components or seed-priming rather than standardized repeated whole-plant fumigation regimes; (ii) quantitative exposure–response data for multi-component fumigant mixtures under realistic dispersion geometries are limited; (iii) field-scale studies documenting reduced pest transmission among neighbouring plants are scarce; and (iv) comprehensive combustion-chemistry profiling and human exposure risk assessments under operational fumigation conditions remain incomplete.

II. MATERIALS AND METHODS

A. Materials Used

This section describes the biological materials and fumigation components employed in the experimental evaluation of herbal smoke exposure on plant growth performance and insect pest mitigation. Selection of materials was guided by reproducibility, availability in arid and semi-arid agricultural settings, and prior evidence of bioactivity in plant–insect interaction studies. All materials were used without chemical modification.

➢ *Plant Species Selection*

Green gram (Vigna radiata) and tomato (Solanum lycopersicum) were selected as representative annual crop species based on their agronomic relevance, sensitivity to environmental stressors, and documented susceptibility to phloem-feeding insect pests. Green gram was chosen due to its rapid vegetative response and suitability for short-duration growth assessments, while tomato was selected to evaluate fumigation effects under prolonged open-sun exposure. In addition, a mature perennial plant exhibiting advanced mealybug infestation was selected for curative assessment. The infestation was characterized by dense insect colonies distributed across stems and leaves, accompanied by visible physiological stress indicators, including chlorosis, leaf deformation, and reduced turgor.

➢ *Herbal Fumigation Materials*

- *Botanical Components*

The fumigation formulation comprised dried plant-derived materials processed into fine powder to ensure uniform combustion and smoke release. They are-:

✓ *Neem (Azadirachta Indica)*

Neem has a long history of use in fumigation practices across South and Southeast Asia for pest control, environmental sanitation, and disease prevention. Combustion of neem leaves, bark, or seed-derived residues releases smoke enriched with bioactive limonoids and flavonoids, including azadirachtin, nimbin, nimbidin, and quercetin. These

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compounds exhibit broad-spectrum antimicrobial activity through disruption of microbial cell membranes and inhibition of metabolic processes, while azadirachtin and related terpenoids interfere with insect feeding behavior, reproductive cycles, and sensory perception. Previous studies have demonstrated that neem smoke significantly reduces airborne bacterial and fungal load and functions as an effective insect deterrent, supporting its use in grain preservation and vector management. The volatilization of neem-derived bioactives during controlled combustion forms the biochemical basis for its inclusion as a primary fumigant component in this study.

✓ *Turmeric (Curcuma Longa)*

Turmeric rhizome has been traditionally employed in fumigation for disinfection, respiratory support, and insect deterrence. Upon combustion, turmeric releases volatile compounds such as curcuminoids, ar-turmerone, turmerones, and zingiberene. These constituents possess well-documented antimicrobial properties, acting through membrane destabilization and inhibition of enzymatic activity in bacterial and fungal cells. In addition, several turmeric-derived volatiles function as olfactory irritants and host-cue masking agents for insects, contributing to repellence effects. Turmeric was incorporated in the fumigation formulation to enhance antimicrobial efficacy while contributing complementary insect-deterrent activity. Exposure duration was controlled to avoid excessive smoke density, consistent with established fumigation practices.

✓ *Calotropis (Calotropis Gigantea)*

Calotropis gigantea, has been widely used in traditional fumigation for wound sanitation, pest control, and household disinfection. Combustion of dried leaves and other plant tissues produces acrid smoke containing cardiac glycosides (including calotropin, uscharin, and calotoxin), along with flavonoids, triterpenoids, and proteolytic enzymes. These compounds exhibit antimicrobial activity by disrupting cellular membranes and inhibiting microbial proliferation. The smoke also functions as a potent insect deterrent, primarily through olfactory irritation and sensory disruption. Ethnobotanical records document its use in malaria control and grain protection, and it is a constituent of classical formulations such as Aparajitha dhoopana choornam. Due to the presence of bioactive cardenolides, controlled application was employed to minimize potential irritation, aligning with traditional low-dose fumigation practices.

✓ *Indian Frankincense (Boswellia Serrata)*

Resin from Boswellia serrata has been historically burned for medicinal, ritualistic, and environmental purification purposes. Combustion releases volatile monoterpenes and sesquiterpenes, including α-pinene, β-pinene, limonene, and incensole acetate. These compounds exhibit antimicrobial effects through membrane disruption and metabolic inhibition in airborne bacteria and fungi. Additionally, frankincense smoke contributes to insect deterrence via olfactory masking mechanisms. Incensole acetate has also been associated with modulatory effects on respiratory and inflammatory pathways, supporting the traditional use of frankincense in enclosed environments. In the present formulation, Boswellia resin was included to stabilize smoke composition and enhance persistence of bioactive volatiles.

✓ *Vetiver (Vetiveria Zizanioides)*

The roots of Vetiveria zizanioides (vetiver or khus) have been traditionally burned in South India for indoor air purification, pest deterrence, and grain protection. Vetiver smoke contains sesquiterpenoid compounds such as vetiverol, vetivone, khusimol, and isovalencenol, which exhibit antimicrobial activity through disruption of microbial membranes and inhibition of growth. These volatiles also act as natural insect repellents, deterring mosquitoes and flies by olfactory irritation and host-cue interference. Vetiver was incorporated into the fumigation mixture to contribute long-lasting aromatic volatiles and to enhance spatial persistence of smoke-mediated effects. Exposure levels were regulated to avoid respiratory discomfort.

- *Combustion Substrate and Apparatus*

Coconut fibre was selected as the combustion substrate due to its slow smoldering characteristics and minimal production of open flame. Combustion was conducted in a non-reactive earthen vessel to avoid metallic interference and to maintain thermal stability during smoke generation. The polyherbal mixture to be gently sprinkled over the burning Coconut fiber in a mud pot kept under the plant so that the fumes are spread to entire plant including the affected area and neighboring plants.

Table 1 Prototype Built for Experimental Evaluation

#	Local name	Scientific name	Part used
1	Neem	Azadirachta indica	Bark and seed
2	Turmeric	Curcuma longa	Rhizomes
3	Giant Milkweed	Calotropis gigantea	Whole plant
4	Indian Frankincense	Boswellia serrata	Resin
5	Vetiver	Vetiveria zizanoides	Root

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B. Experimental Configuration and Exposure Domain

➢ *Spatial Arrangement and Smoke Dispersion*

Fumigation was conducted in an open yet spatially defined environment to allow natural dispersion of smoke while maintaining consistent exposure across experimental units. Effective smoke distribution was observed within a vertical domain of approximately 6–10 ft and a horizontal radius of 6–8 ft from the fumigation source. This dispersion zone was used to define treatment boundaries for both direct exposure and proximity-based preventive assessment. Control plants were positioned outside the effective smoke dispersion domain and oriented with respect to prevailing airflow to prevent unintended exposure.

C. Growth Response Experiments

➢ *Green Gram Growth Assessment*

Green gram plants were cultivated under controlled conditions using uniform soil substrate and irrigation schedules. Plants selected for treatment and control groups were matched for initial height, leaf number, and developmental stage. Fumigation was applied once every 24 h with an exposure duration of 5 min per session over a continuous period of 14 days. Growth parameters were recorded at baseline and at regular intervals throughout the experimental duration.

➢ *Tomato Growth Assessment*

Tomato plants were grown under open-sun exposure representative of arid environmental conditions. The experimental protocol mirrored that used for green gram, with daily fumigation of 5 min per session over a 14-day period. This experiment was intended to evaluate fumigation effects under higher thermal and radiative stress, reflecting real-world agricultural scenarios.

D. Test Matrix and Procedure

➢ *Curative Pest Mitigation Experiment*

The curative experiment targeted a plant exhibiting severe mealybug infestation at the onset of the study. Herbal fumigation was applied once daily for 15 min over 10 consecutive days. Pest density, spatial distribution, and visible plant recovery were documented at baseline (Day 1), immediately after completion of the treatment period (Day 10), and during post-treatment follow-up (Day 30). Particular attention was given to reinfestation dynamics and long-term suppression following cessation of fumigation.

E. Growth and Pest Assessment Protocols

➢ *Morphometric Measurements*

Plant growth was assessed using non-destructive morphometric parameters, including shoot height, leaf length, leaf width, leaf number, and overall canopy development. Measurements were conducted using consistent reference points and measurement tools to minimize observational variability.

➢ *Pest Monitoring*

Pest presence was evaluated through visual inspection and photographic documentation. Infestation severity was assessed based on colony density, spatial coverage, and associated plant stress indicators. Observations were recorded systematically at predefined time points for all relevant experimental groups.

III. EXPERIMENTS

A. Experiment 1

Observation on the growth pattern on newly budded green gram plant under artificial grow light with the conventional drip irrigation method.

Plant 1 (P1) was exposed to the controlled poly herb fumigation for 5 minutes at an interval of 24 hours. Plant 2 (P2) was kept as the control group for the comparison.

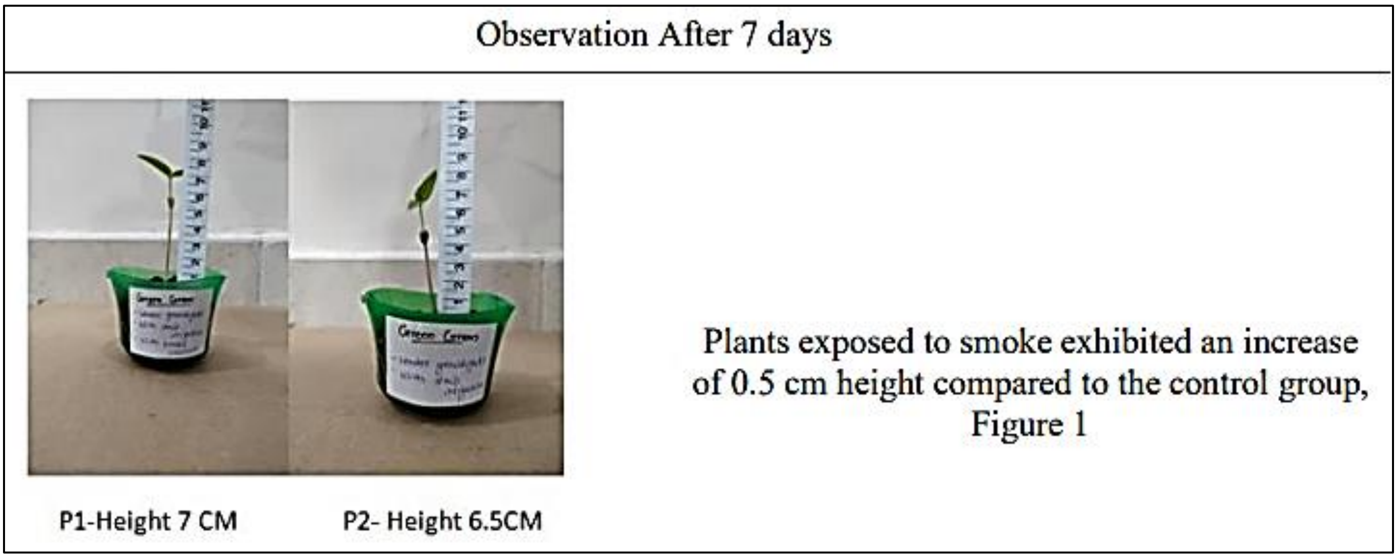

Fig 1 Observation After 7 Days

Table 2 Observation After 14 Days

Observation After 14 days			
Green gram plant	Plant Height in cm	Leaf length in cm	Leaf width in cm
Under grow light with drip irrigation and smoke exposure (P1)	13.5	3	1.5
Under grow light with drip irrigation without smoke exposure (P2)	12.5	2.7	1

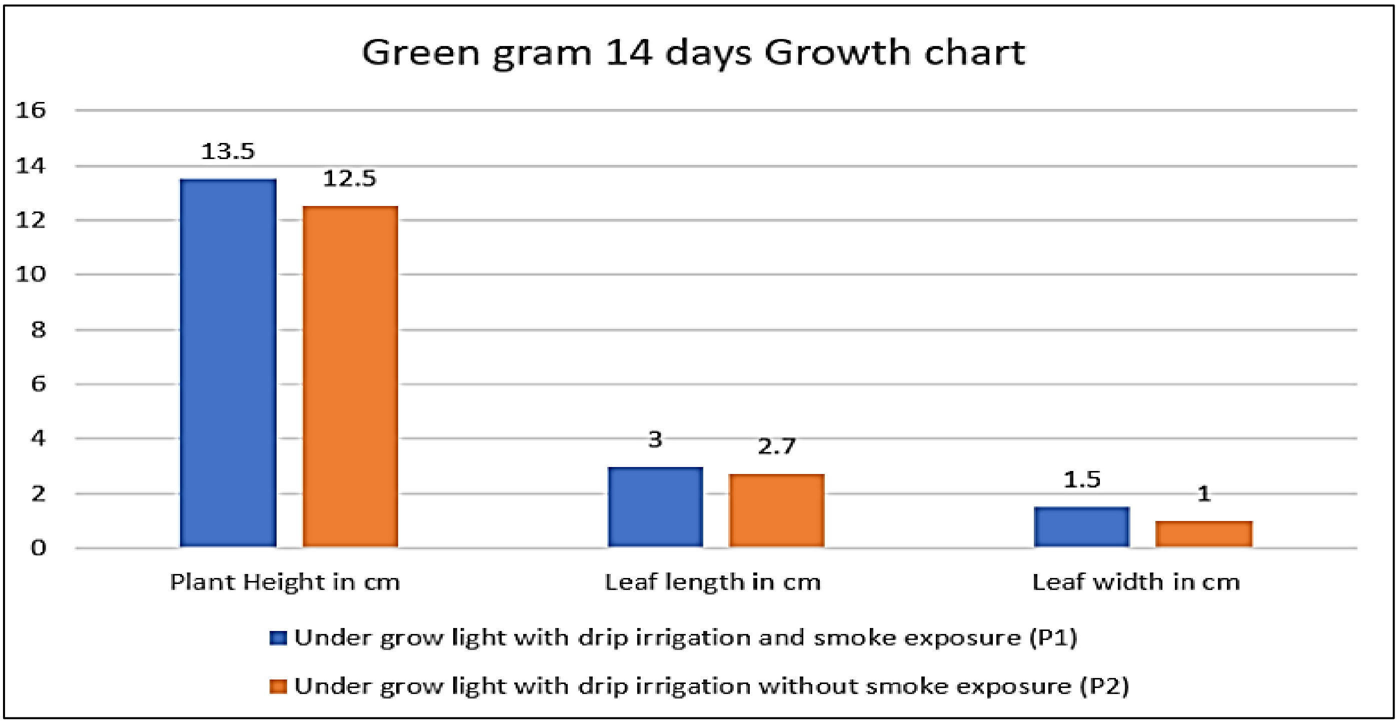

Fig 2 Green Gram 14 Days Growth Chart

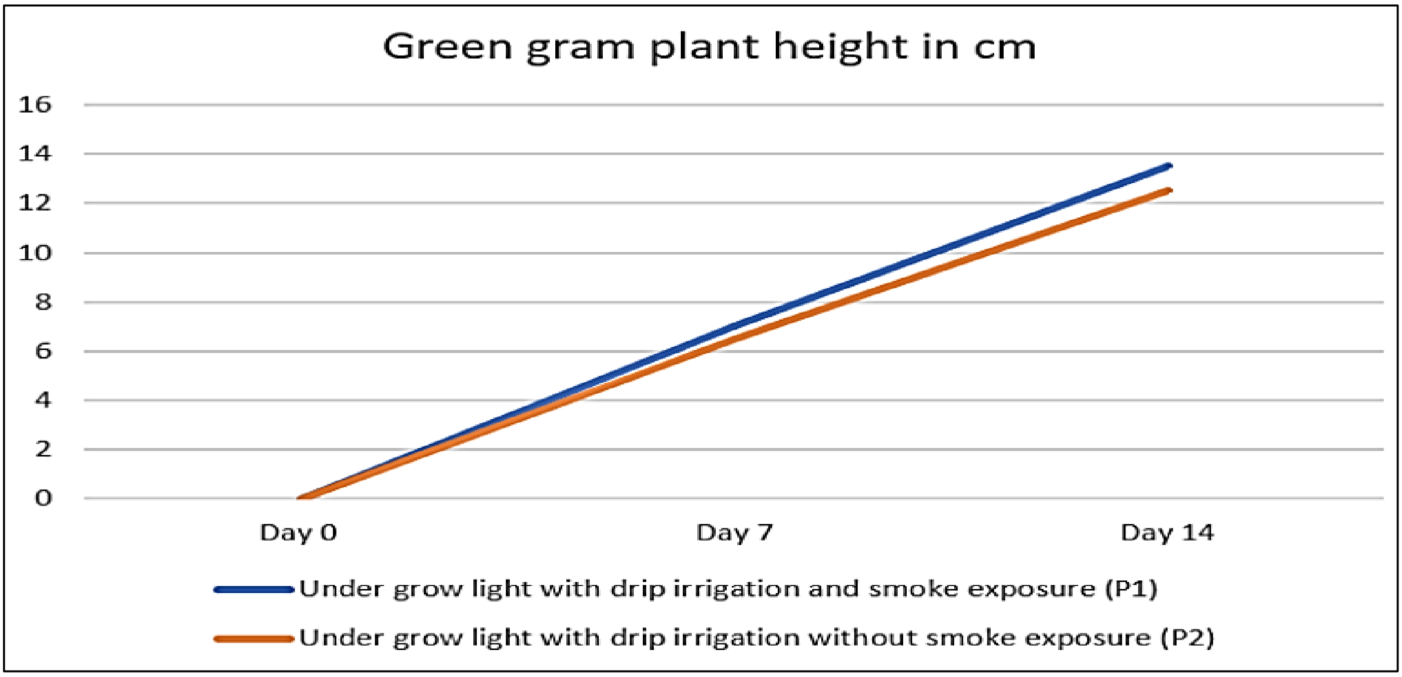

Fig 3 Green Gram Plant Height in cm

In Experiment 1, green gram plants exposed to polyherbal fumigation under controlled grow light and drip irrigation conditions showed notable improvements in growth compared to the control group. After 14 days, the fumigated plant exhibited an 8% increase in height, along with enhanced leaf length (11%) and leaf width (50%). Additionally, more pronounced root branching was observed, indicating improved nutrient uptake and overall vigor. These results suggest that herbal fumes may positively influence plant physiology, promoting healthier and more robust growth even in early developmental stages.

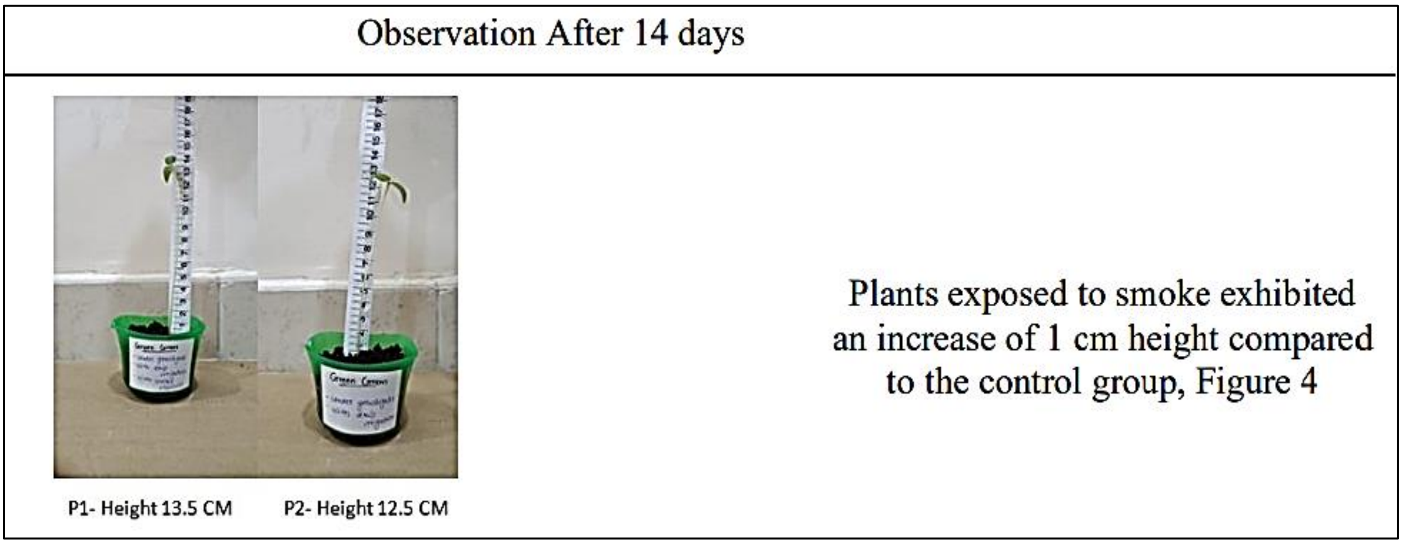

Fig 4 Observation After 14 Days

Fig 5 Plants Exposed to Smoke Exhibited an Increase of .3 cm Leaf Length Compared to the Control Group

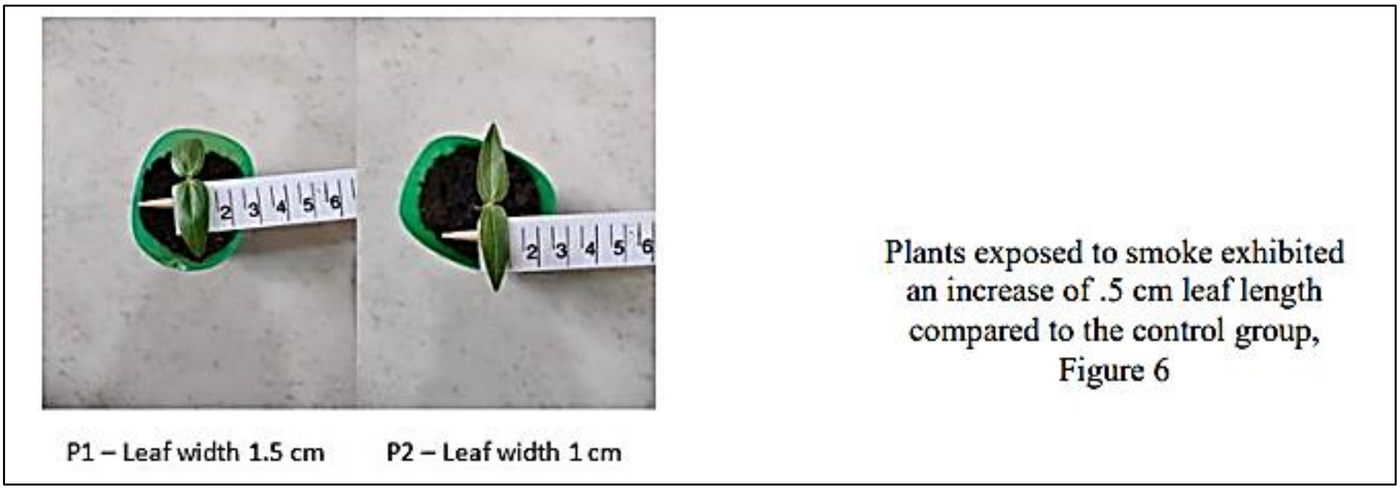

Fig 6 Plants Exposed to Smoke Exhibited an Increase of .5 cm Leaf Length Compared to the Control Group

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Plants exposed to smoke exhibited an increase in root branches compared to the control group, Figure 7

Fig 7 Plants Exposed to Smoke Exhibited an Increase in Root Branches Compared to the Control Group

B. Experiment 2

Observation on the growth pattern on newly budded tomato plant under sunlight with the conventional irrigation method. Plant 3 (P3) was exposed to the controlled poly herb fumigation for 5 minutes at an interval of 24 hours. Plant 4 (P4) was kept as the control group for the comparison.

Table 3 Observation After 14 Days

Observation After 14 days			
Tomato Plant	**Plant Height in cm**	**Leaf length in cm**	**Leaf width in cm**
Under sunlight with conventional irrigation method with smoke exposure (P3)	5.5	3.2	1.9
Under sunlight with conventional irrigation method without smoke exposure (P4)	5	2.5	1

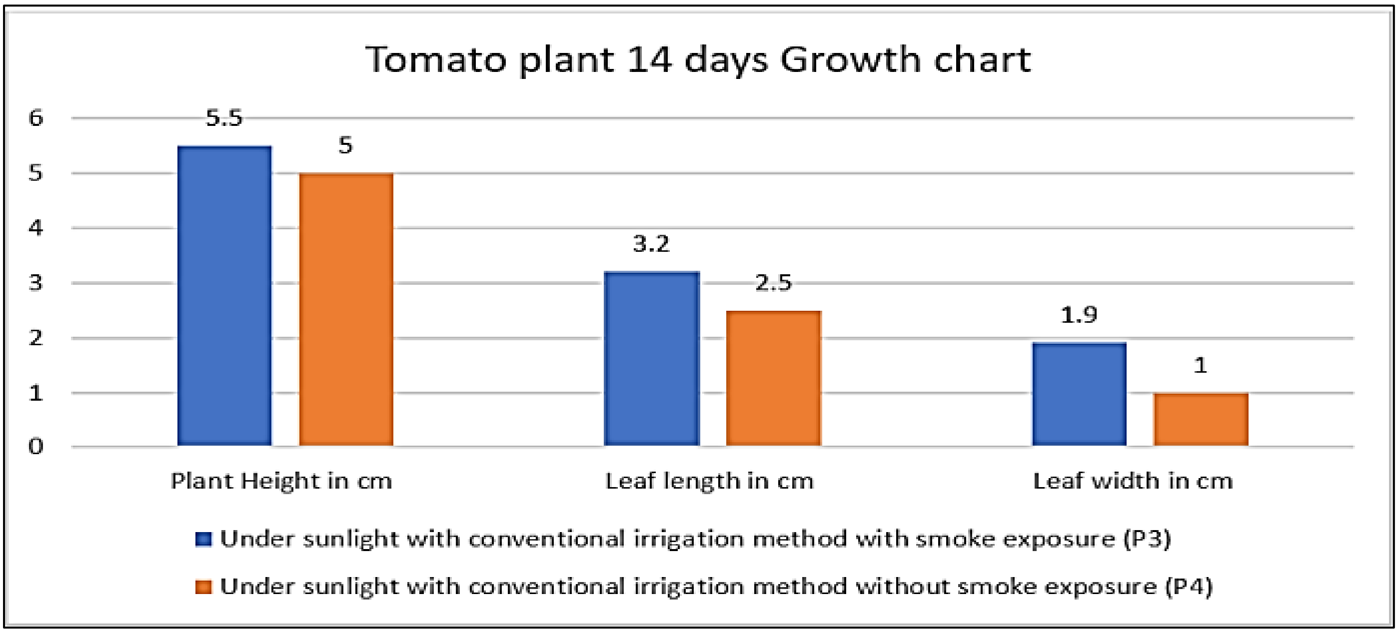

Fig 8 Tomato Plant 14 Days Growth Chart

In Experiment 2, tomato plants grown under natural sunlight and conventional irrigation showed clear growth enhancement when exposed to polyherbal fumigation. After 14 days, the fumigated plant exhibited a 10% increase in height, a 28% improvement in leaf length, and a striking 90% increase in leaf width compared to the control. Additionally, the fumigated specimen developed more leaves and showed enhanced root branching, indicating improved vitality and nutrient absorption. These findings reinforce the potential of herbal fumes as stimulants for healthier plant development in open-field conditions.

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Fig 9 Plants Exposed to Smoke Exhibited More Leaf Growth Compared to the Control Group

Fig 10 Plants Exposed to Smoke Exhibited an Increase of 0.5 cm Height Compared to the Control Group

Fig 11 Plants Exposed to Smoke Exhibited an Increase in Root Branches Compared to the Control Group

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C. Experiment 3

Experiment 3 is to observe the effectiveness of poly herbal fumes in leaf mealybug. A severely leaf mealybug–infested Indian hog plum plant was subjected to daily polyherbal fumigation for 15 minutes over a 10-day period. The treatment led to a remarkable reduction in pest infestation, with visible signs of recovery by the end of the exposure cycle. Notably, 30 days after fumigation ceased, the plant exhibited healthy regrowth with no recurrence of infection, indicating both curative and sustained protective effects. These results highlight the therapeutic potential of herbal fumes in restoring plant vitality and suppressing persistent mealybug infestations without chemical intervention.

Day 1 Before fumigation. Figure 12

Fig 12 Day 1 Before Fumigation

Fumigation Process. Figure 13

Fig 13 Fumigation Process

Observation after 10 days exposure of the fumes. Figure 14

Fig 14 Observation After 10 Days Exposure of the Fumes

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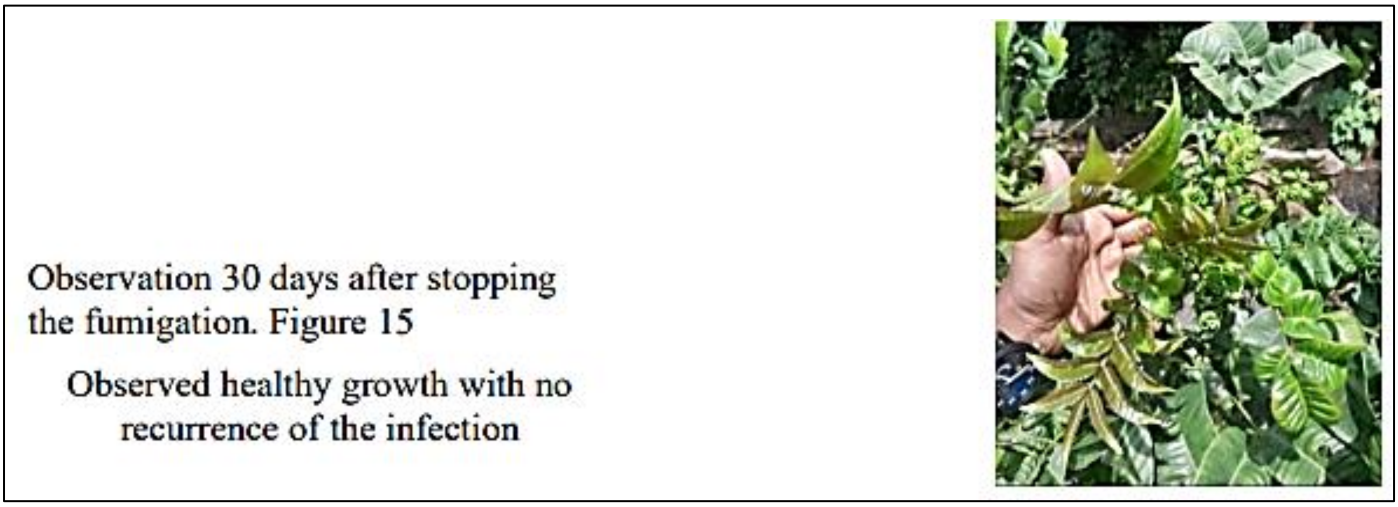

Fig 15 Observation 30 Days After Stopping the Fumigation

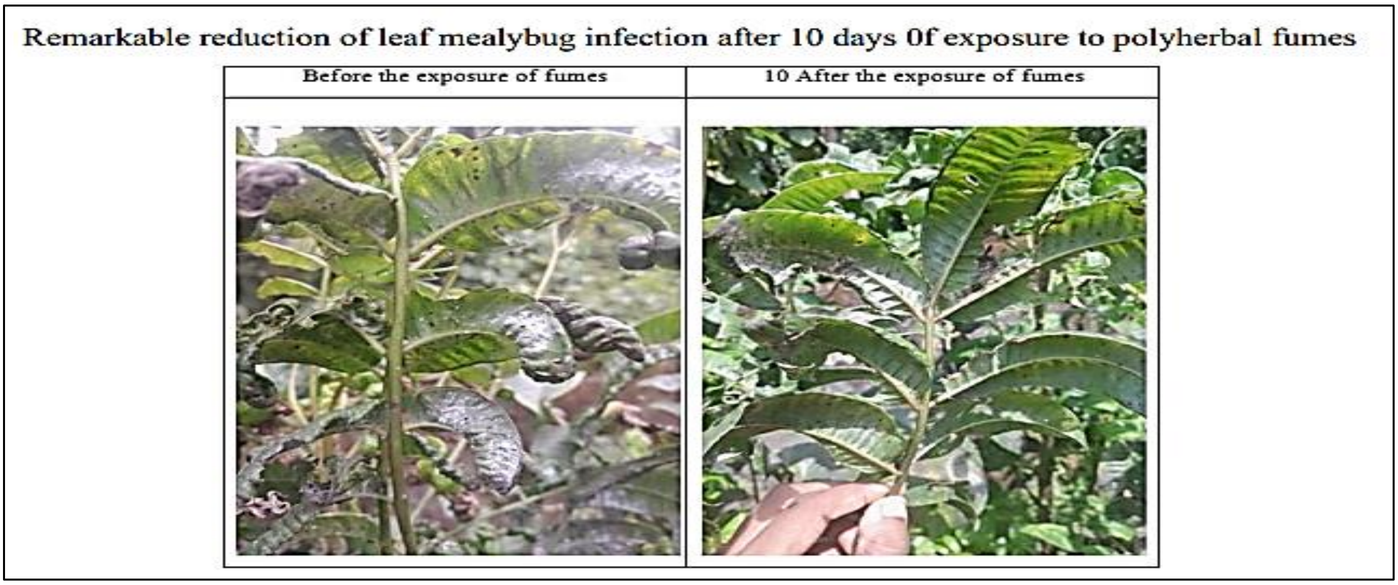

Fig 16 Remarkable Reduction of Leaf Mealybug Infection After 10 Days of Exposure to Polyherbal Fumes

D. Experiment 4

In Experiment 4, the preventive potential of polyherbal fumigation was assessed by monitoring healthy plants surrounding a mealybug-infected specimen during a 10-day fumigation period. Remarkably, no signs of infestation were observed in the neighboring plants throughout the exposure cycle, as confirmed by visual inspections on Day 1 and Day 10. This suggests that the herbal fumes created a protective barrier, effectively deterring pest transmission. The outcome underscores the role of botanical fumigation not only in treatment but also in proactive pest management, offering a promising, eco-friendly strategy for safeguarding plant health in vulnerable agroecosystems.

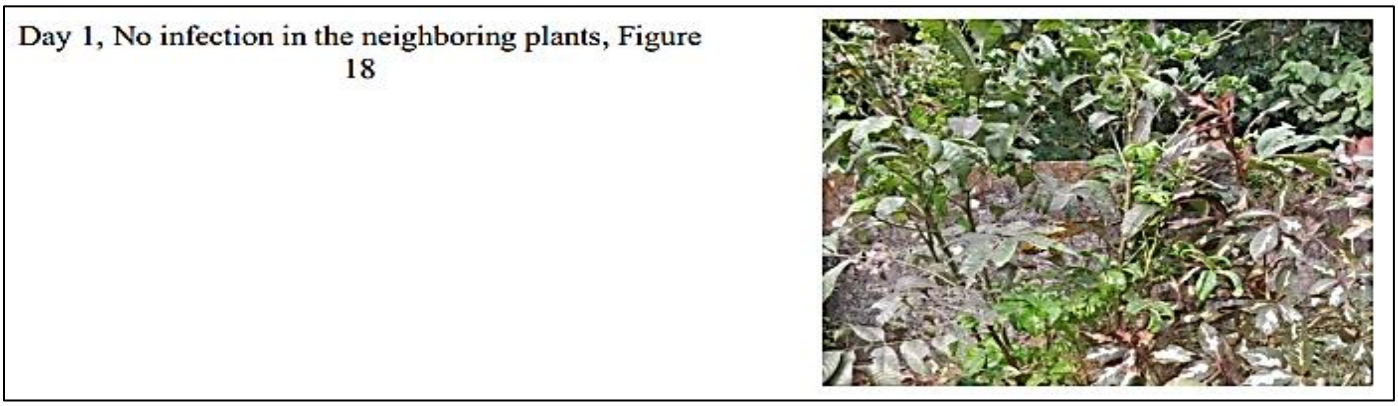

Fig 17 Day 1, No Infection in the Neighboring Plants

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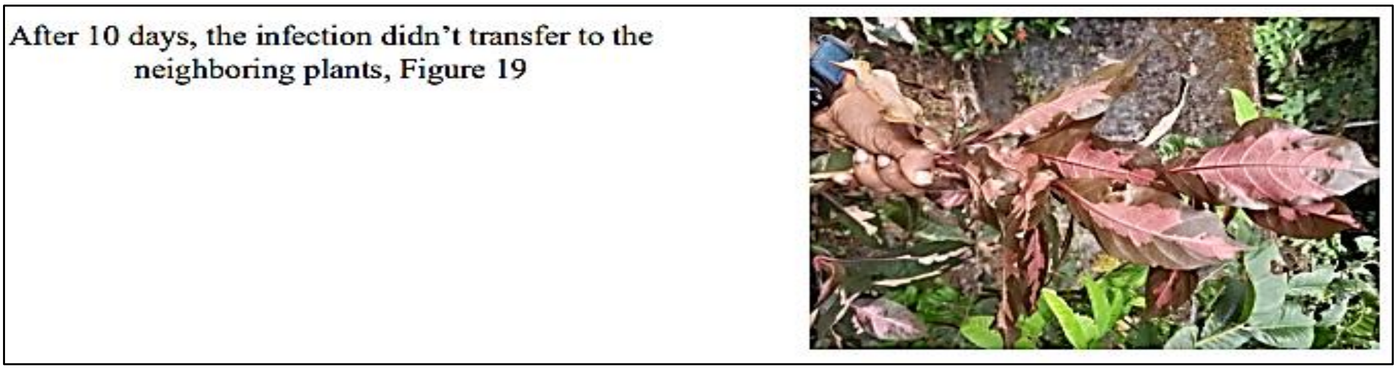

Fig 18 After 10 Days, the Infection didn't Transfer to the Neighboring Plants

IV. RESULT ANALYSIS

The experimental results demonstrate that controlled polyherbal fumigation exerts a measurable influence on both plant growth performance and pest suppression under varied environmental conditions. Across all experiments, fumigated plants consistently outperformed non-fumigated controls in key growth metrics, while pest pressure was substantially reduced without chemical intervention.

In Experiment 1, green gram plants exposed to polyherbal fumes under artificial lighting and drip irrigation exhibited improved vegetative growth relative to the control. A mean height increase of 8% was recorded after 14 days, accompanied by enhancements in leaf length (11%) and leaf width (50%). The increased leaf surface area indicates improved photosynthetic capacity, while enhanced root branching suggests better resource acquisition efficiency. These outcomes imply that herbal smoke exposure may partially mitigate growth constraints associated with controlled or thermally constrained environments by improving physiological efficiency rather than altering developmental pathways.

Experiment 2, conducted under natural sunlight and conventional irrigation, reinforced these findings under open environmental conditions. Fumigated tomato plants showed a 10% increase in height, a 28% increase in leaf length, and a pronounced 90% increase in leaf width compared to non-exposed plants. The magnitude of leaf expansion observed under field-like conditions indicates that the growth-promoting effects of polyherbal fumigation are not restricted to artificial environments and may scale under ambient thermal loads. Enhanced root branching and increased leaf number further suggest improved tolerance to environmental stressors, including heat exposure.

In Experiment 3, polyherbal fumigation proved highly effective in suppressing severe leaf mealybug infestation. Visible pest density declined markedly within 10 days of treatment, with no observable reinfestation during a 30-day post-treatment monitoring period. The sustained recovery of the treated Indian hog plum plant indicates that fumigation achieved not only short-term pest suppression but also longer-term stabilization of plant health. This outcome is particularly significant given the wax-coated morphology of mealybugs, which often reduces the effectiveness of contact-based chemical pesticides.

Experiment 4 evaluated the preventive capacity of polyherbal fumes. Healthy plants located adjacent to the treated, previously infested specimen remained pest-free throughout the fumigation cycle. This observation suggests that the herbal smoke created a transient deterrent zone that inhibited pest migration, indicating potential application at a system level rather than solely as a curative treatment. Such a spatial protective effect aligns with sustainable pest management strategies that emphasize prevention over repeated intervention.

Collectively, the results indicate that polyherbal fumigation functions as a dual-action intervention: reducing pest pressure while supporting plant growth under conditions associated with thermal and environmental stress. The consistency of outcomes across controlled and natural settings strengthens the reliability of the observed effects.

V. FURTHER DISCUSSION

A. *Synthesis of Principal Findings*

The experiments demonstrate two reproducible outcomes: (i) short, repeated, low-intensity polyherbal fumigation delivered daily produced consistent improvements in early vegetative metrics in both a controlled green gram trial and an open-sun tomato trial (8–10% height gains; larger proportional increases in leaf dimensions and apparent root branching), and (ii) the same fumigation regimen produced rapid curative effects against a severe leaf-mealybug infestation (marked reduction within 10 days and no observable recurrence at 30 days), while also generating a measurable preventive effect on neighbouring plants. These dual outcomes — growth promotion under routine thermal exposure and robust pest suppression — position controlled herbal smoke as a multifunctional, low-input intervention for constrained agroecosystems.

B. *Mechanistic Interpretation (Observed Data → Plausible Mechanisms)*

It is important to keep mechanistic claims proportional to the evidence. The present dataset demonstrates phenotypic outcomes; mechanistic explanations below are therefore offered as plausible, literature-grounded hypotheses that require direct testing.

➢ *Pest Suppression Mechanisms (Strongly Supported by Outcome)*

The rapid decline of mealybug density following 10 days of 15-min daily fumigation is consistent with at least two non-exclusive mechanisms: (a) direct toxic/antifeedant effects of volatile constituents (e.g., neem limonoids, Calotropis glycosides, terpenoids from frankincense and vetiver) that can penetrate or interfere with insect physiology and behaviour; and (b) olfactory masking or irritancy that disrupts host-finding, feeding, or oviposition. The sustained absence of reinfestation suggests either residual deterrence in the treated microenvironment or a disruption of population recovery dynamics (reduced reproduction or increased mortality).

➢ *Growth-Promotion and Heat-Stress Mitigation (Hypothesis-Driven, Indirect Evidence)*

The observed increases in leaf area and root branching under both controlled and open-sun treatments suggest reductions in the functional constraints that typically accompany heat stress (reduced cell expansion, stomatal closure, oxidative damage). Two non-mutually exclusive hypotheses can account for these observations:

- Signal-mediated physiological priming: combustion of botanical materials releases smoke-derived signaling molecules (including but not limited to karrikin-like compounds and specific VOCs) that at low concentrations can modulate growth regulators and priming pathways. Karrikin family compounds and smoke water are known to influence germination and seedling vigor; analogous signaling may enhance antioxidant capacity or modulate hormonal balances (e.g., maintain favorable stomatal conductance and reduce ABA-driven stomatal closure under transient heat), thereby permitting continued growth under thermal load.

- Microclimate and surface chemistry modification: repeated low-intensity fumigation may alter the immediate canopy microenvironment (transient alteration of boundary-layer chemistry or small changes in radiative/evaporative microconditions) and/or deposit thin layers of plant-derived organics on leaf surfaces that modify cuticular properties or evapotranspiration dynamics. Such changes could indirectly improve water-use efficiency or reduce transpiration spikes during heat events.

Both hypotheses are plausible but remain speculative until direct physiological, biochemical, and microclimate data are acquired.

C. Scientific and Practical Implications

➢ *Integrated, Dual-Function Intervention:*

If mechanisms above are confirmed, polyherbal fumigation could be deployed as a dual-purpose management tool; combining preventive/curative pest control with mitigation of moderate heat stress; thereby reducing dependence on synthetic pesticides and active cooling or shade infrastructure in resource-limited settings.

➢ *Scalability and Appropriateness:*

The technique uses locally available biomass and simple apparatus (mud pot + coconut fiber) and therefore has potential for low-cost adoption by smallholders. However, scaling beyond the micro plot requires careful evaluation of smoke dispersion, non-target effects, labour inputs, and cumulative particulate emissions.

- Resistance management advantage: Multi-constituent fumigation confers a lower resistance risk than single-mode synthetic pesticides, because pests would have to adapt to multiple concurrent chemical and sensory pressures.

VI. LIMITATIONS

While the results of this study are promising, several limitations must be acknowledged to ensure accurate interpretation and responsible application of the findings.

First, the experiments were conducted on a limited number of plant species and under controlled or semi-controlled conditions. Although green gram, tomato, and Indian hog plum represent diverse plant types, the responses observed cannot be assumed to apply universally across all crops or ecological contexts. Different species may vary in their sensitivity to smoke exposure and environmental stress.

Second, the study focused primarily on visible growth parameters and pest presence rather than detailed physiological measurements. Parameters such as leaf temperature, photosynthetic efficiency, transpiration rate, or oxidative stress indicators were not quantified. As a result, conclusions regarding heat stress mitigation are based on growth outcomes rather than direct measurement of stress-response pathways.

Third, pest assessment relied on visual observation and photographic documentation rather than quantitative pest population counts. While this approach is suitable for exploratory and applied research, future studies would benefit from standardized pest density measurements to improve precision and reproducibility.

Despite these limitations, the study provides a strong experimental foundation and generates testable hypotheses for future research. Addressing these constraints through expanded trials, physiological measurements, and field-scale validation will help refine the application of polyherbal fumigation as a sustainable agricultural strategy.

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