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Root Zone Manipulation: Integrating Rooting Volume and Growing-Medium Composition for Biomass Productivity and Essential Oil Quality of *Cymbopogon nardus*

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Cymbopogon Nardus; Root-Zone Management; Sack Cultivation; Tillering; Postharvest Storage.

ABSTRACT

Citronella grass (*Cymbopogon nardus*) is a promising aromatic non-timber forest product; however, the contributions of root-zone conditions and postharvest handling to crop performance require separate evaluation. This study assessed the effects of growing-medium composition and nominal sack capacity on citronella grass growth over 12 weeks and separately examined the effects of storage duration on essential oil obtained through a standardized two-hour distillation process. The cultivation experiment employed a randomized complete block design with two growing media (topsoil alone and a 3:1:1 mixture of topsoil, rice husks, and manure) and three nominal sack capacities (10, 25, and 50 kg). Growing-medium composition and sack capacity significantly affected final vegetative growth characteristics and root length, with significant interaction effects observed for tiller number ($p = 0.0177$) and root length ($p = 0.0316$). The P1J3 treatment, consisting of the growing-medium mixture in 50-kg-capacity sacks, produced the highest mean leaf number (96.50 ± 23.44 leaves per sack), tiller number (29.25 ± 1.89 tillers per sack), and root length (46.00 ± 2.45 cm). The highest estimated total dry biomass was also recorded under P1J3 (432.32 ± 147.78 g per sack), although biomass estimates depended on predetermined organ proportions and moisture fractions. In the separate postharvest assessment, the highest reported essential oil yield was 0.1083% after nine days of storage. Storage duration did not significantly affect the measured oil moisture content ($p = 0.0632$) or relative density ($p = 0.5586$), whereas sensory evaluation scores differed significantly across storage periods ($p = 0.0004$), reaching their highest mean after 18 days (3.27 ± 0.87). These findings identified P1J3 as a promising cultivation treatment for improving vegetative growth and estimated biomass productivity, while indicating that optimal storage durations differed between essential oil recovery and sensory acceptability.

INTRODUCTION

Cymbopogon nardus (L.) Rendle is an economically important aromatic grass cultivated for citronella essential oil, which is widely used in fragrances, cosmetics, pharmaceutical formulations, and insect-repellent products (Caballero-Gallardo et al., 2023). Its commercial value depends not only on the quantity of harvested plant biomass but also on the yield and quality of the extracted essential oil. Citronellal, citronellol, and geraniol are among the major volatile compounds contributing to the industrial value of citronella oil. Consequently, cultivation practices

aimed at improving plant growth should also be considered in relation to essential oil recovery and quality characteristics. Previous studies have demonstrated that fertilizer application, harvesting intervals, and rhizosphere management influence plant growth and essential oil production in C. nardus (Danata et al., 2025; Idris et al., 2024; Rahma et al., 2026). These findings underscore the importance of effective cultivation management in citronella production, although vegetative growth and essential oil characteristics represent distinct dimensions of crop productivity.

Root-zone conditions influence plant growth by regulating root development, water and nutrient uptake, and biomass allocation. Rooting volume is particularly important in container-based cultivation because the space available for root expansion depends on container dimensions and substrate volume. In a meta-analysis of 65 studies, Poorter, Bühler, et al. (2012) reported that doubling container volume increased plant biomass by an average of 43%. Root-volume restriction may also alter plant physiological responses and biomass partitioning, even when water and nutrient limitations are controlled (Wen et al., 2026). These findings suggest that container size can influence plant performance beyond merely providing physical space for root development. However, the responses of C. nardus to variations in rooting volume, particularly in combination with different growing-medium compositions, remain insufficiently understood.

Growing-medium composition also influences plant growth by modifying the physical and chemical properties of the root environment. Manure supplies organic matter and essential plant nutrients, whereas rice husks can improve substrate porosity, aeration, and drainage. Combining these materials with topsoil may therefore enhance root development and nutrient availability, particularly under container-restricted growing conditions. Previous research on C. nardus has demonstrated that fertilizer application and harvesting management affect plant productivity and essential oil characteristics (Idris et al., 2024). Danata et al. (2025) further investigated the roles of magnesium supplementation and rhizosphere microorganisms in citronella growth and essential oil biosynthesis, while Rahma et al. (2026) examined the combined effects of mycorrhizal inoculation and potassium fertilization under shaded conditions. Although these studies highlight the importance of nutrient management in citronella cultivation, limited research has examined the interaction between growing-medium composition and container capacity in determining vegetative growth and root development in sack-based cultivation systems.

The importance of these cultivation practices extends to the development of non-timber forest products (NTFPs) within agroforestry systems. The Kawasan Hutan dengan Tujuan Khusus (KHDTK) Pujon Hill, a Special Purpose Forest Area associated with Universitas Muhammadiyah Malang in East Java, Indonesia, has served as a site for agroforestry development and the diversification of forest-based commodities. The surrounding upland landscape includes agricultural areas dominated by seasonal crops, particularly vegetables, where intensive cultivation on sloping terrain may increase the risks of soil erosion and land degradation. In response to these challenges, citronella grass (C. nardus) and lemongrass (Cymbopogon citratus) have been promoted as potential aromatic NTFPs capable of supporting livelihood diversification and value-added production. Previous studies conducted in the Pujon landscape have examined the contributions of agroforestry practices to forest sustainability and local livelihoods (Triwanto,

2022; Waskitho et al., 2026), while citronella cultivation and essential oil processing activities at Pujon Hill have also been documented (Hilmi et al., 2025). Improving the cultivation and processing performance of aromatic plants in this production setting could support the diversification of forest-based commodities and generate additional economic opportunities for local communities. However, their potential contribution to mitigating land degradation requires further environmental assessment.

Container-based cultivation provides an opportunity to manipulate rooting volume and growing-medium composition under relatively controlled management conditions. However, the effects of these factors may be interdependent. Larger containers provide greater space for root development and may increase the availability of water and nutrients, while growing media containing topsoil, rice husks, and manure modify the substrate properties that regulate root growth and nutrient uptake. Interactions between these factors may consequently produce different vegetative growth responses across cultivation treatments. In addition, essential oil recovery and quality may be influenced by postharvest handling practices, particularly storage duration and distillation conditions, which can affect extraction efficiency and the physicochemical characteristics of the recovered oil (Ahmad et al., 2025; Blank et al., 2007; Mae et al., 2026). Although previous studies have investigated cultivation management and essential oil extraction, relatively limited attention has been given to examining these processes within a sequential production framework. Evaluating cultivation performance and postharvest processing separately within the same production context may provide a more comprehensive understanding of the factors influencing citronella biomass productivity and essential oil characteristics without assuming a direct causal relationship between the two experimental stages.

Accordingly, this study aimed to investigate the effects of nominal sack capacity and growing-medium composition on the vegetative growth and root development of C. nardus cultivated at KHDTK Pujon Hill, East Java, Indonesia. The cultivation experiment evaluated plant growth responses to identify the most promising treatment combination, while a separate postharvest experiment examined the effects of storage duration on essential oil recovery, selected physicochemical properties, and sensory characteristics under a standardized distillation procedure. Both experimental stages were analyzed independently according to their respective treatment factors, enabling the differentiation of cultivation-related responses from postharvest processing outcomes. The study contributes experimental evidence regarding the combined effects of growing-medium composition and container capacity on citronella growth, alongside an independent assessment of storage-related variations in essential oil characteristics. From a practical perspective, the findings may support the selection of cultivation and postharvest management practices for local citronella producers. From an academic perspective, the study advances understanding of root-zone management and essential oil processing within the broader context of sustainable aromatic NTFP production in agroforestry systems.

METHOD

Study Area and Research Framework

The study was conducted at the Kawasan Hutan dengan Tujuan Khusus (KHDTK) Pujon Hill, a Special Purpose Forest Area managed by Universitas Muhammadiyah Malang in East Java, Indonesia. The investigation comprised two independently analyzed stages: a cultivation experiment examining the effects of growing-medium composition and container capacity, and a postharvest experiment assessing the effects of storage duration and distillation time.

The cultivation experiment employed a two-factor randomized complete block design (RCBD). The first factor was growing-medium composition, consisting of topsoil alone (P0) and a 3:1:1 mixture of topsoil, rice husks, and manure (P1). The second factor was nominal sack capacity, comprising 10 kg (J1), 25 kg (J2), and 50 kg (J3). Six treatment combinations were arranged in four blocks, resulting in 24 independent experimental units. Each sack constituted one experimental unit and contained three healthy, relatively uniform vegetative propagules of *Cymbopogon nardus*, which were trimmed before planting. The experimental sacks were maintained under field conditions at the KHDTK Pujon Hill cultivation site, and plant growth was monitored weekly for 12 weeks.

Growth and Biomass Assessment

a. Vegetative Growth and Root

Leaf number and tiller number were recorded by direct counting. Leaf length and basal stem were measured with a caliper. Root length was recorded at final harvest. These variables characterize vegetative vigor and belowground development in the context of cultivar performance and container constraints (Idris et al., 2024; Poorter, Bühler, et al., 2012). Final-week values were used for independent-unit factorial comparisons, whereas the weekly record was retained to describe growth trajectories.

b. Dry Biomass Assessment

Fresh biomass was assessed at leaves, stems (constitute aboveground biomass) and roots (constitute belowground biomass). Then it dried to constant mass to obtain dry weights, in accordance with biomass allocation and root-trait measurement principles (Freschet et al., 2021; Poorter, Niklas, et al., 2012). Total dry biomass per sack (g) is the sum of aboveground and belowground dry weights.

$$\text{Dry biomass content (\%)} = [\text{Dry weight (g)} / \text{fresh weight (g)}] \times 100$$

Based on the observed week-12 vegetative indicators, the highest descriptive for leaf number, tiller number, leaf length, basal stem diameter and dry biomass content would be choose as material at the postharvest experiment.

Biomass-to-Rooting-Volume Ratio (BVR)

The biomass-to-rooting-volume ratio (BVR) was used to evaluate dry biomass accumulation relative to the available rooting space under different container sizes and growing-medium compositions Poorter, Bühler, et al. (2012). Total dry biomass was calculated as the sum of aboveground and belowground dry mass, including all plants established within each experimental sack:

$$\text{BVR (g L}^{-1}\text{)} = \text{Total plant dry biomass (g)} / \text{Actual rooting volume (L)}$$

where total plant dry biomass represents the combined dry mass of leaves, stems, and roots within each experimental unit, and rooting volume represents the actual volume of growing medium expressed in liters.

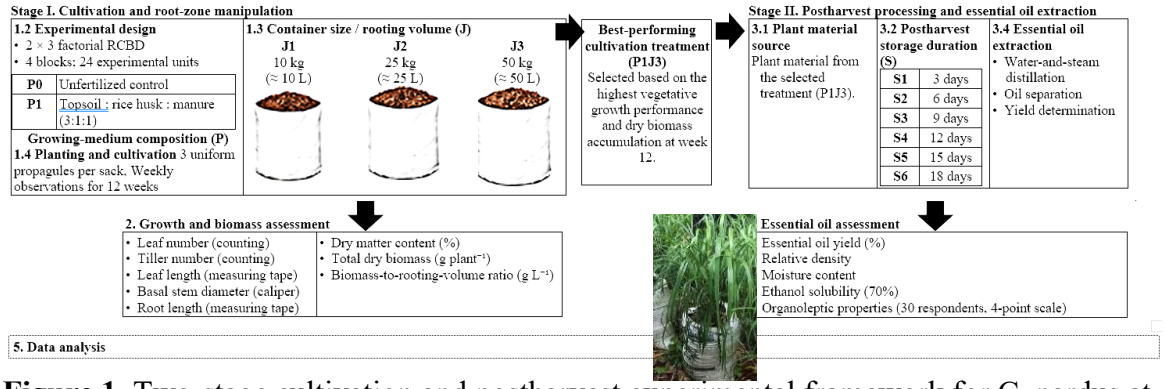


Figure 1. Two-stage cultivation and postharvest experimental framework for C. nardus at KHDTK Pujon Hill. Dry biomass and correlation assessments are conditional on verified gravimetric records; the connection between historical cultivation and oil processing samples requires provenance verification.

Postharvest: Essential Oil Distillation and Oil Yield

The postharvest study examined six storage periods (3, 6, 9, 12, 15, and 18 days) and two distillation durations (2 and 3 h), generating 12 combinations. Oil was recovered by steam distillation, with vapor passing through plant material, followed by condensation and oil–water separation. Storage and extraction time are plausible influences on oil recovery and characteristics, and have been evaluated in prior essential-oil processing studies (Ahmad et al., 2025; Božović et al., 2017). Oil yield (%) was calculated as recovered oil mass by fresh material.

$$\text{Essential oil yield (\%)} = [\text{Recovered oil mass (g)} / \text{Distilled leaf mass (g)}] \times 100$$

Oil characteristics

The oil was characterized through relative density, measured oil moisture, solubility in 70% ethanol. Such physical and processing responses are relevant measures of citronella oil characteristics (Ahmad et al., 2025; Sukandar et al., 2022).

Statistical Analysis

Data from the cultivation experiment were analyzed using two-way factorial analysis of variance (ANOVA) within a randomized complete block design (RCBD). The analysis included vegetative growth parameters, total dry biomass, dry matter content, and biomass-to-rooting-volume ratio (BVR). Model assumptions were evaluated through residual diagnostics, including assessments of normality and homogeneity of variance. Significant treatment effects were further examined using Tukey's honestly significant difference (HSD) test at a significance level of 5% ($p < 0.05$).

Weekly vegetative growth measurements were evaluated using linear mixed-effects models to account for repeated observations within experimental units. Growing-medium composition, container size, observation time, and their interactions were included as fixed effects. The relationship between rooting space and biomass accumulation was further examined using correlation and regression analyses. Pearson's correlation coefficient was applied to continuous rooting-volume and dry-biomass measurements when the assumptions of linear association were satisfied; otherwise, Spearman's rank correlation coefficient was used.

The postharvest experiment was analyzed separately using one-way ANOVA, with storage duration (S). The analysis was applied to essential oil yield and quantitative physicochemical characteristics. Significant differences among treatment combinations were evaluated using Tukey's HSD test ($p < 0.05$). Ordinal organoleptic scores were analyzed separately using methods appropriate for ordered categorical responses. The results from the cultivation and postharvest experiments were interpreted independently according to their respective treatment structures, while their combined implications were discussed within the sequential citronella production framework.

RESULTS AND DISCUSSION

The cultivation treatment structure affected measured citronella growth at the end of 12 weeks, whereas the postharvest data showed variation in essential-oil recovery and selected product characteristics.

Vegetative Growth Responses to Root-Zone Manipulation

Leaf and tiller production, basal stem diameter, and leaf length increased over the 12-week observation period under all cultivation combinations. At week 12, growing-medium composition and nominal sack capacity each gave significant main effects on the four vegetative indicators ($p < 0.05$). Their interaction was significant for tiller number ($P \times J$, $p = 0.0177$), but not for leaf number ($p = 0.2046$), basal diameter ($p = 0.3424$), or leaf length ($p = 0.2826$).

Table 1. Effects of growing-medium composition and nominal sack capacity on vegetative growth of *Cymbopogon nardus* at week 12. Values are mean ± SD (n = 4 sacks).

Treatment	Leaf number (leaves sack^{-1})	Tiller number (tillers sack^{-1})	Basal diameter (recorded unit*)	Leaf length (cm)
P0J1	68.00 ± 4.40	19.25 ± 1.71	9.81 ± 0.31	103.25 ± 3.20
P0J2	73.00 ± 4.55	24.75 ± 2.50	11.13 ± 0.28	112.00 ± 9.56
P0J3	74.00 ± 5.42	21.00 ± 4.76	10.91 ± 0.25	114.25 ± 3.30
P1J1	73.25 ± 5.32	20.00 ± 2.71	10.43 ± 0.32	113.50 ± 10.66
P1J2	82.25 ± 7.37	24.00 ± 4.32	11.92 ± 1.22	121.00 ± 6.32
P1J3	96.50 ± 23.44	29.25 ± 1.89	12.41 ± 0.51	137.50 ± 19.64
Grand mean ± SD	77.83 ± 13.51	23.04 ± 4.50	11.10 ± 1.03	116.92 ± 14.20
Overall ANOVA (p)	0.0101	0.0022	0.0003	0.0032
Medium P (p)	0.0067	0.0374	0.0015	0.0024
Sack size J (p)	0.0270	0.0040	0.0002	0.0080
P × J (p)	0.2046	0.0177	0.3424	0.2826

Note. Values sharing at least one letter within each response column are not significantly different by Tukey HSD ($p < 0.05$). P0 = unamended control; P1 = topsoil:rice husk:manure (3:1:1); J1/J2/J3 = nominal 10/25/50-kg sack capacity. The original diameter sheet contains inconsistent cm/mm headings; measurement units must be confirmed before submission.

At the end of period (12 week), leaf number ranged from 68.00 ± 4.40 leaves sack^{-1} for P0J1 to 96.50 ± 23.44 for P1J3 (mean 77.83 ± 13.51). Tiller number ranged from 19.25 ± 1.71 to 29.25 ± 1.89 tillers sack^{-1} (mean 23.04 ± 4.50); basal stem diameter ranged from 9.81 ± 0.31 to 12.41 ± 0.51 in the recorded field unit (mean 11.10 ± 1.03); and leaf length ranged from 103.25 ± 3.20 to 137.50 ± 19.64 cm (mean 116.92 ± 14.20 cm). P1J3 consistently showed the highest mean values, respectively (Table 1).

The same-species comparison by Kartini et al. (2023) recorded 106.97–110.69 leaves and 29.86–31.22 tillers per planting hole at 84 days after planting under contrasting manure treatments; reported basal stem diameters were approximately 1.15–1.17 cm. The present grand means were lower for leaves and tillers, but comparable in numerical magnitude for basal diameter if the recorded unit is confirmed as millimeters. Susilowati and Syukur (2022) documented substantial differences in leaf length among ten C. nardus accessions, consistent with genotype-dependent morphological variation. Direct comparisons should remain cautious because experimental unit, starting propagule density, age, and environment differ between studies.

P1J3, comprising amended medium in the nominal 50-kg sack, showed the highest means of all four vegetative traits. Relative to the unamended treatment at the same nominal capacity (P0J3), P1J3 showed 30.4% more leaves, 39.3% more tillers, 13.8% greater recorded basal diameter, and 20.4% longer leaves. However, Tukey HSD did not distinguish P1J3 from P1J2 for any vegetative trait. Accordingly, the 50-kg amended treatment may be described as numerically highest-performing, but not demonstrably superior to the 25-kg amended treatment for the observed aboveground endpoints.

Larger containers may allow greater root expansion and exploration of the medium, potentially improving access to nutrients and water. Poorter, Bühler, et al. (2012) demonstrated substantial container-size effects on plant growth; Sillo et al. (2025) identified changes in root architecture and resource acquisition in response to soil volume; and Wen et al. (2026) showed that root restriction can alter leaf development through source–sink processes. Rice husk and manure may additionally affect substrate aeration, moisture and nutrient availability. From an operational standpoint, P1J2 and P1J3 shows that an intermediate container size deserves further consideration where substrate use, when handling and harvesting efficiency are priorities.

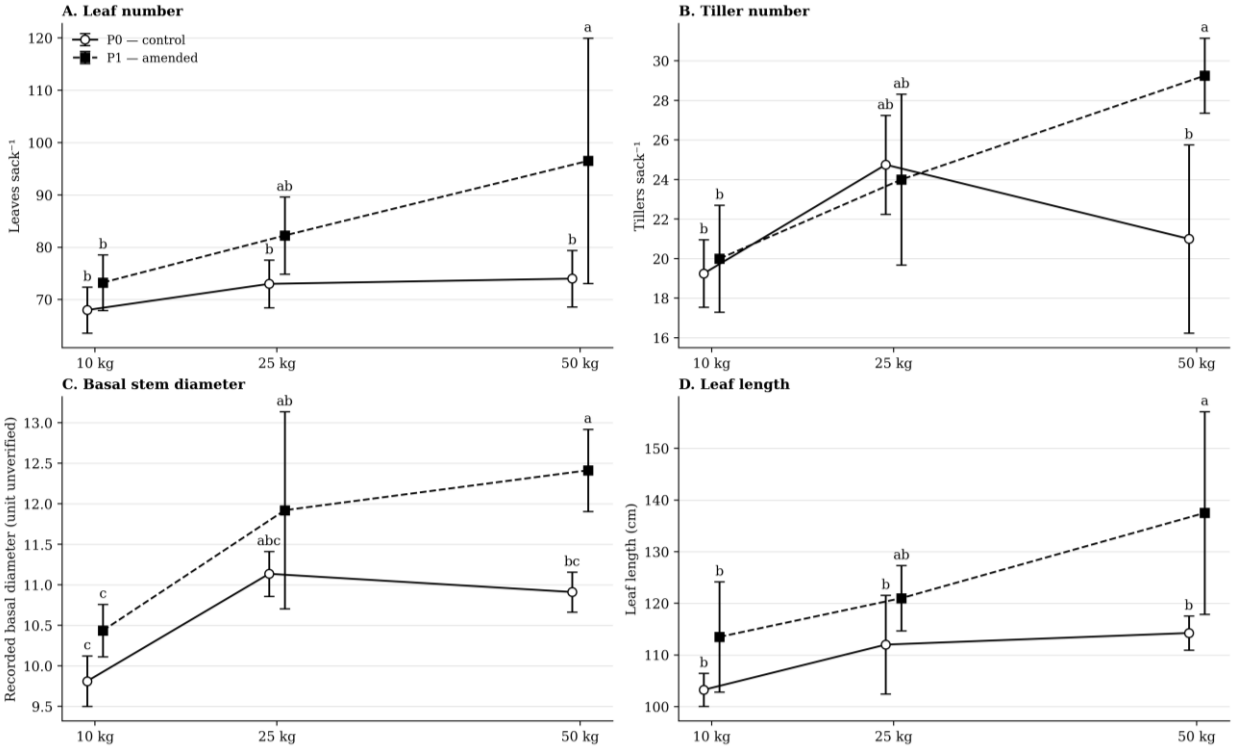


Figure 2. Week-12 vegetative responses of C. nardus by medium (P0 = open circles/solid lines; P1 = filled squares/dashed lines) and nominal sack capacity. Points show treatment means ± SD (n = 4); letters denote Tukey HSD groupings within each trait. Recorded basal-diameter unit requires confirmation

Temporal Dynamics of Citronella Growth

Across all six cultivation combinations, leaf and tiller counts rose throughout the 12-week observation period (Figure 2B). The temporal changes at vegetative development shows significantly different among treatments.

Table 2. Temporal changes in leaf and tiller numbers during the 12-week cultivation period. Values are treatment means of four experimental sacks; increases are descriptive differences, not repeated-measures significance tests.

Treatment	Leaves Week 1 (count sack⁻¹)	Leaves Week 12 (count sack⁻¹)	Leaf increase (count sack⁻¹)	Tillers Week 1 (count sack⁻¹)	Tillers Week 12 (count sack⁻¹)	Tiller increase (count sack⁻¹)
P0J1	7.50	68.00	60.50	0.00	19.25	19.25
P0J2	8.25	73.00	64.75	0.50	24.75	24.25
P0J3	8.75	74.00	65.25	0.50	21.00	20.50
P1J1	7.75	73.25	65.50	0.00	20.00	20.00
P1J2	8.75	82.25	73.50	0.50	24.00	23.50
P1J3	10.00	96.50	86.50	0.75	29.25	28.50

note. Values sharing at least one letter within each response column are not significantly different by Tukey HSD ($p < 0.05$). P0 = unamended control; P1 = topsoil:rice husk:manure (3:1:1); J1/J2/J3 = nominal 10/25/50-kg sack capacity. The original diameter sheet contains inconsistent cm/mm headings; measurement units must be confirmed before submission

Among combinations, P1J3 rose from 10.00 leaves at week 1 to 96.50 at week 12, while its tiller count increased from 0.75 to 29.25 per sack. It's proved that the accumulation of vegetative growth occurs in larger sized sacks. The differences in growth can be associated with the capacity of plants to regulate the rooting environment. Wheeldon et al. (2021) demonstrated that wheat plants, which belong to the same Poaceae family as C. nardus, adjusted tiller production according to substrate volume, even before detectable nutrient or water limitations occurred. Their findings suggest that plants may respond proactively to available substrate space and root density rather than solely to resource depletion. Similarly, Wen et al. (2026) demonstrated that restricted rooting volume could suppress vegetative development through reduced leaf-area expansion and source–sink.

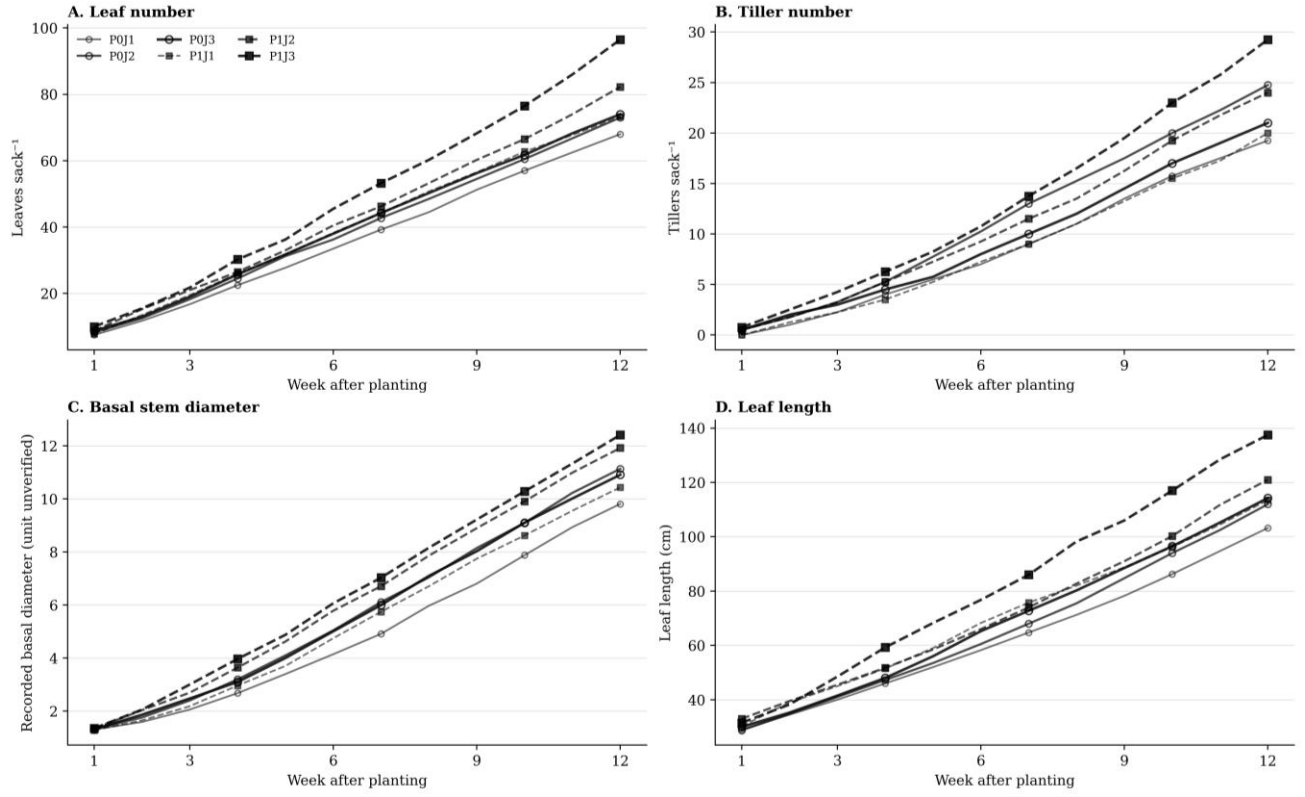


Figure 3. Descriptive weekly trajectories for leaf number, tiller number, recorded basal stem diameter, and leaf length. Each line represents the mean of four sacks within one treatment; hollow circles and solid lines represent P0, filled squares and dashed lines represent P1. Lines are visually distinguished by their symbol and stroke patterns; no significance of time interactions is asserted.

The effects of container size may also have been modified by growing-medium composition. The existing of rice husk and manure into topsoil potentially increased substrate physical

properties and nutrient availability, creating conditions favorable for root expansion and growing. Larasati et al. (2022) demonstrated that organic manure management influenced dry matter accumulation and plant nutrient status in C. nardus, supporting the relevance of substrate nutrition to citronella growth. In the present study, this interpretation is consistent with significant main effects of growing-medium composition and sack size on leaf and tiller numbers, together with a significant interaction between these factors for tiller production ($p = 0.0177$).

The greater sack capacity did not consistently produce higher tiller numbers across both growing media, and P1J3 did not differ significantly from P1J2 in final leaf or tiller number. Therefore, the temporal observations support the conclusion that P1J3 showed the greatest cumulative vegetative development. The study suggest that appropriate coordination of container size and growing-medium composition may sustain citronella growth during early establishment.

Root Development, Dry Biomass Accumulation, and Cultivation Performance

Root length was significantly affected by growing-medium composition ($p = 0.0007$), nominal sack capacity ($p < 0.001$), and their interaction ($p = 0.0316$) (Table 3). The shortest mean roots occurred under P0J1 (36.00 ± 1.83 cm) and the longest under P1J3 (46.00 ± 2.45 cm), with a mean of 39.33 ± 3.71 cm. P1J3 was significantly different from all other treatments.

Table 3. Root development and biomass of C. nardus at week 12

Treatment	Root length (cm)	Root fresh (g sack^{-1})	Root dry (g sack^{-1})	Total fresh (g sack^{-1})	Total dry (g sack^{-1})	moisture (%)	BVR (g L^{-1})
P0J1	36.00 ± 1.83 (c)	186.73 ± 13.83	74.69 ± 5.53	700.24 ± 51.86	226.41 ± 16.77	65.71 ± 0.45	8.58 ± 0.48
P0J2	37.25 ± 0.50 (bc)	218.17 ± 31.56	87.27 ± 12.62	818.12 ± 118.36	264.53 ± 38.27	66.06 ± 0.62	4.11 ± 0.47
P0J3	40.75 ± 0.96 (b)	225.17 ± 22.32	90.07 ± 8.93	844.40 ± 83.70	273.02 ± 27.06	65.16 ± 1.25	2.03 ± 0.13
P1J1	37.00 ± 2.16 (c)	221.16 ± 26.13	88.46 ± 10.45	829.34 ± 97.98	268.15 ± 31.68	65.07 ± 0.76	9.80 ± 0.95
P1J2	39.00 ± 0.82 (bc)	265.30 ± 34.67	106.12 ± 13.87	994.86 ± 129.99	321.67 ± 42.03	64.98 ± 1.29	4.70 ± 0.34
P1J3	46.00 ± 2.45 (a)	356.55 ± 121.88	142.62 ± 48.75	1,337.08 ± 457.04	432.32 ± 147.78	64.68 ± 1.46	3.11 ± 0.78
mean	**39.33**	**245.51**	**98.21**	**920.67**	**297.68**	65.28	5.39
ANOVA							
Medium P (p)	0.0007	0.0028	0.0028	0.0028	0.0028	0.0276	0.0004
Sack size J (p)	<0.0001	0.0098	0.0098	0.0098	0.0098	0.2661	<0.001
P × J (p)	0.0316	0.1306	0.1306	0.1306	0.1306	0.7060	0.4714

note. Observed root-length means sharing a superscript letter in parentheses are not significantly different by Tukey HSD ($\alpha = 0.05$; $n = 4$ sacks per treatment).

The biomass dataset exhibited a corresponding increase across cultivation treatments. Total fresh biomass ranged from 700.24 ± 51.86 g sack^{-1} under P0J1 to 1,337.08 ± 457.04 g sack^{-1} under P1J3, whereas total dry biomass ranged from 226.41 ± 16.77 to 432.32 ± 147.78 g sack^{-1}. Consequently, P1J3 showed greater total biomass than P0J1. This treatment also produced the highest leaf number (96.50 leaves sack^{-1}) and tiller number (29.25 tillers sack^{-1}), suggesting a favorable association between root development and vegetative biomass production.

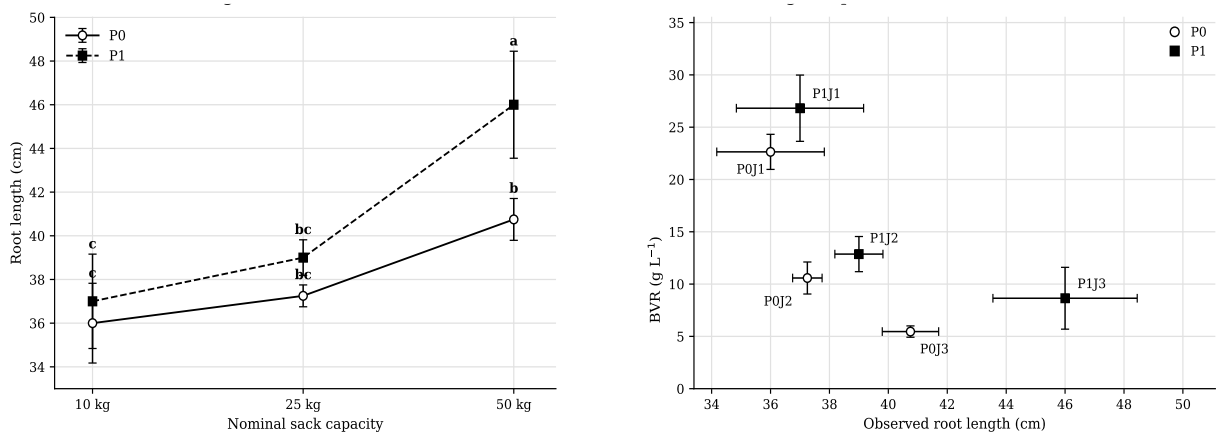


Figure 4. Observed root length and an illustrative biomass-to-rooting-volume scenario. (A) Treatment means ± SD for measured root length, with Tukey HSD letters (n = 4). (B) Root length versus BVR; hollow circles = P0 and filled squares = P1.

The relationship between root length and biomass-to-volume ratio (BVR) revealed contrasting responses to increasing rooting-medium volume in *Cymbopogon nardus* (Figure 3B). The P1J3 treatment exhibited the greatest root length (46.00 ± 2.45 cm) and total dry biomass (432.32 ± 147.78 g sack^{-1}), whereas P1J1 showed the highest BVR (26.82 g L^{-1}) despite having shorter roots (37.00 ± 2.16 cm). As rooting-medium volume increased from 10 to 50 L, BVR declined from 22.64 to 5.46 g L^{-1} under P0 and from 26.82 to 8.65 g L^{-1} under P1. It can be interpreted through plant physiological responses to substrate availability. Poorter, Bühler, et al. (2012) demonstrated that rooting volume substantially influences plant growth, particularly through its effects on photosynthetic performance. Similarly, Wheeldon et al. (2021) demonstrated that wheat plants can regulate shoot development and tillering in response to substrate volume and root density. These findings provide a physiological basis for the greater vegetative development observed under P1J3. The incorporation of rice husk and manure may also have modified the root-zone environment, potentially influencing aeration, moisture availability, and nutrient supply. But greater available rooting space may reduce physical barriers to elongation and permit more extensive access of substrate resources. Organic amendments may additionally modify substrate structure and water or nutrient availability, potentially supporting longer roots and subsequent organ production (Poorter, Bühler, et al., 2012; Sillo et al., 2025; Wen et al., 2026). However, substrate porosity, nutrient status, root function and biomass allocation are required to establish these mechanisms.

Importantly, the observed increase in vegetative biomass may have practical implications for essential oil production. Ranaweera and Thilakaratne (1992) reported strong positive correlations between essential oil yield and tiller number, as well as dry matter production (r = 0.89), in *Cymbopogon nardus*. Their findings demonstrate that improved nutrient management can simultaneously promote tillering, biomass accumulation, and essential oil production. Supporting evidence was reported by Kakaraparthi et al. (2014) in *Cymbopogon winterianus*, where increases in tiller number, leaf number, fresh biomass, and dry biomass during plant development were accompanied by greater essential oil production per plant. These findings suggest that the increased vegetative development observed under P1J3 may enhance the amount of harvestable material available for oil extraction.

Greater biomass accumulation under P1J3 should be interpreted as an opportunity to increase total essential oil production rather than direct evidence of enhanced essential oil concentration or extraction yield. The potential relationship between biomass accumulation and essential oil production is particularly relevant to the clump-forming growth habit of Cymbopogon. The development of additional tillers contributes to the formation of new leaves, increasing the quantity of photosynthetically active and potentially oil-bearing tissues. Luthra et al. (1991) demonstrated that leaf development influenced monoterpene accumulation in *C. winterianus*.

Further improvement of citronella productivity may be achieved by optimizing nutrient management and cultivation conditions. Syakir and Gusmaini (2015) demonstrated that nitrogen application increased vegetative growth, herbage production, and essential oil characteristics in C. nardus. More recently, Rahma et al. (2026) reported that mycorrhizal inoculation combined with potassium fertilization increased total dry biomass and essential oil performance under shaded conditions. These findings suggest that the cultivation advantages observed under P1J3 could be further investigated through improved nutrient supply, beneficial microbial associations, and appropriate light management.

Effects of Postharvest Storage on Essential Oil Yield and Physicochemical Characteristics

P1J3 was used as material because it produced the highest mean growth responses. Six storage periods (S1–S6: 3–18 days).

Table 4. Essential oil recovery and physicochemical and sensory characteristics of *Cymbopogon nardus* oil obtained after different postharvest storage periods under a fixed two-hour distillation.

Storage (days)	Oil recovery (%)	Apparent oil moisture (%)	Relative density	Solubility in 70% ethanol (1:x)	Sensory score (1–4)
3	0.079000	24.55 ± 2.14	0.876 ± 0.009	1:3.3	2.47 ± 1.01
6	0.063000	24.18 ± 0.75	0.774 ± 0.191	1:5.3	2.37 ± 0.81
9	0.108286	16.85 ± 4.75	0.694 ± 0.311	1:2.5	2.33 ± 0.92
12	0.083429	23.89 ± 3.13	0.884 ± 0.003	1:3.5	2.30 ± 0.95
15	0.091000	18.90 ± 4.58	0.869 ± 0.002	1:3.8	2.73 ± 1.05
18	0.078286	20.74 ± 2.43	0.876 ± 0.000	1:4.1	3.27 ± 0.87
One-way ANOVA (p)	NE	0.0632	0.5586	NE	0.0004*

Notes. Oil recovery values are single reported values per storage period; independent 2-hour distillation replicates are not identifiable, so NE = not estimable. Apparent moisture and relative density are mean ± SD (n = 3 observations per storage duration). Sensory scores are mean ± SD of 30 panelists who assessed all six samples.

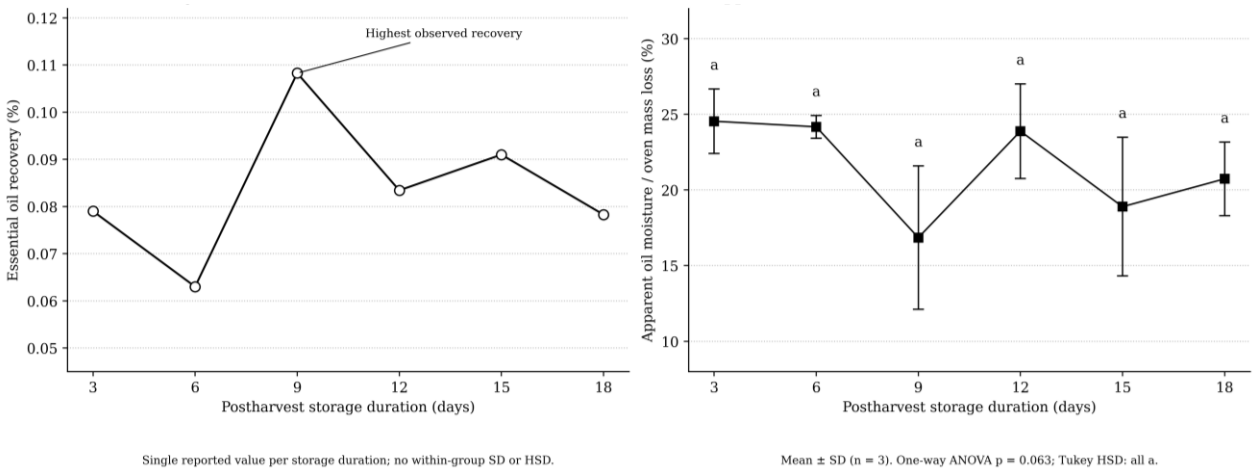


Figure 5. Changes in essential oil recovery (A) and apparent moisture content (B) across six postharvest storage durations with a constant two-hour distillation time. The panel B error bars represent standard deviation (n = 3); equal letters indicate no significant differences according to Tukey HSD.

The postharvest assessment was distilled for two hours, allowing storage duration (3, 6, 9, 12, 15 and 18 days) to be examined as factor. Oil recovery ranged from 0.0630% after six days of storage to 0.1083% after nine days, with an overall descriptive mean of 0.0838%. The nine-day storage period gave the highest observed recovery under the fixed two-hour distillation procedure. Apparent oil moisture, estimated using the oven-based mass-loss procedure, varied from 16.85 ± 4.75% (nine days) to 24.55 ± 2.14% (three days). Independent water determination, preferably using a validated moisture-specific method, is required to establish whether storage duration affects water contamination of the recovered oil. Relative density ranged from 0.694 ± 0.311 (nine days) to 0.884 ± 0.003 (12 days). The reported ethanol-solubility requirement varied from 1:2.5 to 1:5.3 across storage durations, indicating descriptive differences in oil–ethanol mixing behavior. Sensory assessment provided a different response pattern. Mean panel scores increased from 2.30 ± 0.95 at 12 days to 3.27 ± 0.87 at 18 days.

The low sensory scores observed in some storage treatments can be associated with the strong aroma of citronella essential oil, which could be perceived as less pleasant by certain panelists. The characteristic fragrance of citronella oil is primarily associated with volatile monoterpenoids, including citronellal, citronellol, and geraniol (Suarantika et al., 2023). Asben et al. (2025) demonstrated that increasing citronella oil concentration intensified aroma perception, although the highest sensory preference was obtained at an intermediate oil concentration of 7.5% rather than 10%. This finding suggests that a lower sensory acceptance score does not necessarily

indicate poorer chemical quality, as highly concentrated aromatic compounds may generate an intense fragrance that is less preferred by some individuals. Furthermore, Baccarani et al. (2021) demonstrated that the relationship between odorant concentration, perceived intensity, and hedonic response varies according to the chemical characteristics of the odorant. The higher sensory scores observed after prolonged storage in the present study may therefore reflect a more acceptable aroma profile rather than superior retention of bioactive constituents.

CONCLUSION

Growing-medium composition and nominal sack capacity significantly influenced the vegetative growth and root development of *Cymbopogon nardus* over the 12-week cultivation period. Significant main effects were observed for vegetative growth characteristics and root length, while significant interactions between growing-medium composition and sack capacity were identified for tiller number ($p = 0.0177$) and root length ($p = 0.0316$). The P1J3 treatment, comprising a 3:1:1 mixture of topsoil, rice husks, and manure in 50-kg-capacity sacks, produced the highest mean leaf number (96.50 ± 23.44 leaves per sack), tiller number (29.25 ± 1.89 tillers per sack), and root length (46.00 ± 2.45 cm). This treatment also yielded the highest estimated dry biomass, suggesting that favorable root-zone conditions may promote vegetative development and increase the quantity of plant material potentially available for essential oil extraction.

In the separately analyzed postharvest experiment, the highest reported essential oil recovery (0.1083%) was obtained after nine days of storage, whereas the highest mean sensory acceptability score (3.27 ± 0.87) was recorded after 18 days. Storage duration did not significantly affect the measured oil moisture content or relative density, although sensory evaluation scores differed significantly among storage periods. These findings indicated that the most favorable storage duration for essential oil recovery differed from that for sensory acceptability. Future research should incorporate direct measurements of organ-specific dry biomass, treatment-specific essential oil yield per sack, and the chemical composition of the extracted oil, particularly its citronellal, citronellol, and geraniol contents, to provide a more comprehensive assessment of biomass productivity and essential oil quality in C. nardus.

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