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Application of mycorrhizae as biological agent to optimize potassium fertilization for enhancing biomass and essential oil yield of citronella (*Cymbopogon nardus* L.) under shaded conditions

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ABSTRACT

Citronella (*Cymbopogon nardus* L.) is an economically valuable commodity in Indonesia which is used in perfumes, insect repellents, and for its aromatic properties. The plant could be cultivated with other crops in intercropping to optimize of agricultural land. Intercrops might challenge with citronella for resources, such as water, nutrients and light, potentially affecting citronella growth and yield. The application of mycorrhizae and potassium fertilizer is a strategy to optimize intercropping with citronella. The effect of mycorrhizae application with different potassium fertilizer dosages under 25% shading conditions on the growth and yield of citronella were determined. Split-plot design was employed to arrange the treatments. Mycorrhizae inoculation was expected to not only enhance yields but also improve the efficiency of potassium fertilizer use, contributing to the stability of agroforestry-based agriculture under shaded conditions. The obtained results showed that the application of mycorrhizae together with 40 K_2O kg ha^{-1} fertilizer increased growth and yield parameters, including leaf number 25.15%, leaf area 3.04%, total fresh biomass 25.06%, and total dry biomass 31.79%. The treatment also elevated essential oil yield by 3.05%, essential oil content 57.16%, and citronellal content 13.12%.

Keywords: soil microorganism, nutrients, agroforestry.

INTRODUCTION

Citronella (*Cymbopogon nardus* L.) belongs to the genus *Cymbopogon* and the family Gramineae. It is an aromatic plant and known as source of an essential oil widely used in the pharmaceutical, aromatic, perfume, and food industries. In Indonesia, citronella is an economic valuable commodity and one of the top export commodities, besides patchouli oil and vetiver oil. The main constituents of citronella essential oil are citronellal (32–45%), geraniol (12–18%), and citronellol (12–15%) (Kaur et al., 2021). Essential oils are classified as terpenoid compounds produced through secondary metabolic processes by the mevalonic acid (MVA) pathway and methylerythritol phosphate (MEP) pathway (Verma and Shukla, 2015). Secondary metabolism is a continuation of primary metabolism, functioning as a plant defense mechanism. These two metabolic processes are interrelated and key indicator of optimal plant growth and development. Primary metabolism begins with the breakdown of CO_2 and H_2O, facilitated by sunlight through the process of photosynthesis (Martin et al., 2018).

Citronella is classified as C4 plant, which requires optimal light intensity to support its photosynthetic activity (Costa et al., 2020). High light intensity enhances the accumulation of essential oils in plants. Due to limited land availability, citronella is often cultivated as an intercrop in forest plantations under agroforestry systems. However, under shaded conditions, light intensity of intercropping is lesser than that of monoculture (Li et al., 2020). Different citronella varieties have different response to light intensity. Seraiwangi 1 variety demonstrated greater tolerance under 25% shading compared to 50% and 75% shading (Danata et al., 2023). Nevertheless, even under 25% shading, reductions in growth, physiological responses, oil yield, and essential oil quality including citronellal, citronellol, and geraniol contents were still occurred. These reductions are attributed to decreased stomata conductance under shaded conditions, which limits CO_2 uptake as a primary substrate in photosynthesis, subsequently disrupting nutrient distribution and the assimilation process (Pirasteh et al., 2016).

Improving citronella tolerance under shaded environments of intercropping requires proper nutrient management and enhanced nutrient uptake efficiency (Rahmah et al., 2023), such as the addition of potassium fertilizer. Potassium fertilization contributes to physiological and biochemical mechanisms, such as nutrient and stomata conductance (Mostofa et al., 2022). The application of K^+ also promotes root growth, thereby increasing root surface area for water absorption, which in turn supports photosynthetic activity (Hasanuzzaman et al., 2018). In addition to its role in plant growth, elevated potassium levels influence the biosynthesis of plant compounds. For example, increased essential oil content in basil has been associated to potassium application, indicating its involvement in the metabolic pathways of biologically active substances. Similar findings were reported by El Gendy et al. (2015) and Chrysargyris et al. (2017), who stated that potassium acts as cofactor for enzymes involved in terpenoid biosynthesis, which is essential for essential oil production.

Excessive use of chemical fertilizers can lead to soil degradation and environmental pollution. One of pro-ecological techniques to address this issue is the utilization of mycorrhizae as a biological agent to enhance nutrient uptake efficiency. Mycorrhizae have hyphae expected to assist the plant roots in expanding the nutrient absorption area. The hyphae structures penetrate root cortical cells to form arbuscules. These branched arbuscules provide a large surface area for nutrient exchange (Wang and Wu, 2017). Enhanced plant growth consequently increases leaf biomass, which supports higher photosynthate production. These photosynthates contribute to secondary metabolic processes, including the formation of glandular trichomes on the leaves, where terpenoid constituents of essential oils are synthesized and stored (Khan et al., 2023). Moreover, the application of mycorrhizae to the roots of aromatic plants has been shown to enhance both the quantity and quality of essential oils (Qoreishi et al., 2023) as mycorrhizae influence the synthesis of secondary metabolites, including essential oil production in citronella (Fokom et al., 2019). Another study reported that arbuscular mycorrhizae inoculation increased the essential oil content by up to 88% in lemongrass (*Cymbopogon citratus*). This enhancement may be attributed to the ability of mycorrhizae colonization to alter secondary metabolism by stimulating the production of hormones, such as auxins, cytokinins, and gibberellins (Hazzoumi et al., 2017).

This approach is consistent with the principles of sustainability in application of pro-ecological technologies and products, as well as the principles of sustainable environmental engineering through the optimal utilization of land resources. This study aimed to explore further sustainable approaches to improving tolerance of citronella (*Cymbopogon nardus* L.) under shaded conditions through the application of mycorrhizae and potassium fertilization. Mycorrhizae are expected to optimize nutrient uptake, while potassium fertilization may assist in stomata opening, particularly under shaded conditions. Therefore, this combined application of added potassium and mycorrhizae is expected to enhance the growth and yield of citronella plants as well as improve the quality of the essential oil produced as a secondary metabolite.

MATERIAL AND METHODS

This research was conducted from July to December 2024 at the Research Farm of the Faculty of Agriculture, University of Brawijaya, located in Jatimulyo Subdistrict, Lowokwaru District, Malang City, East Java, Indonesia. The research site is situated at an altitude of 526 meters above sea level (m asl). The average daily temperature at the site ranges from 24 to 26 °C, with an average monthly rainfall of 296 mm (Malang City Central Bureau of Statistics, 2024). The materials used in this study included *Cymbopogon nardus* (L.) Rendle var. Seraiwangi 1 seedlings were obtained from the Testing Center for Standards of Medicinal and Aromatic Plants Instruments (BPSI TROA), mycorrhizae spores were obtained from the Plant Pest and Disease Laboratory, University of Brawijaya together with manure, and chemical fertilizers (KCl, urea, and SP-36). The equipment used included a measuring tape (range 0–2.000 mm, accuracy ± 1 mm), digital balance (range 0–10.000 g, accuracy ± 0.001 g), oven (range 80–100 °C, accuracy ± 1 °C), leaf area meter (LAM) (range 0–3000 cm^2, accuracy ±1%), spectrophotometer (wavelength range 190–1100 nm, accuracy ± 0.3 nm), soil plant analysis development (SPAD) meter (range 0–99.99 SPAD units, accuracy ± 1.0 SPAD unit), and gas chromatography-mass spectrometry (GC-MS) (mass accuracy ± 0.001 amu).

This study employed a split-plot design to arrange the treatments on a research area measuring 15 × 30 m. The first factor, serving as the main plot was mycorrhizae application, consisting of two levels: without mycorrhizae and mycorrhizae application. The second factor, assigned to the sub-plots, was potassium fertilization, consisting of five levels: K_2O at 0 (control), 20 kg ha^{-1}, 40 kg ha^{-1}, 60 kg ha^{-1}, and 80 kg ha^{-1}. Observations were conducted at 12 and 24 weeks after planting (WAP) to assess plant growth and yield parameters of citronella (*Cymbopogon nardus* L.).

The measurement of growth parameters included leaf number, leaf area, total fresh biomass, and total dry biomass. The measured yield and essential oil quality parameters included oil yield percentage, total oil yield, as well as the concentrations of citronellal, citronellol, and geraniol. Additional observations were conducted to evaluate the effects of mycorrhizae, including percentage of colonization and root infection, as well as nutrient uptake parameters, particularly nitrogen and phosphorus uptake. Leaf number was recorded by counting healthy, pest and disease-free leaves. Leaf area was measured using a leaf area meter (LAM) following the average leaf area (ALA) method (Fang et al., 2019) calculated as:

$$Leaf\ area = \frac{X}{Number\ of\ leaf\ samples} \quad (1)$$

where: X – total leaf area of all leaf samples measured using the LAM.

Fresh biomass was determined by weighing freshly harvested sample plants using digital balance. Dry biomass was measured by weighing oven-dried sample plants after 48 hours at 80 °C (until constant dry biomass obtained) (Danata et al., 2023) using a digital balance. Essential oil yield percentage was determined from the oil obtained through steam distillation of citronella leaves for 4 hours, using the following formula (Mwithiga et al., 2022):

$$Essential\ oil\ yield\ (\%) = \frac{Volume\ of\ essential\ oil\ obtained}{Fresh\ biomass\ of\ distilled\ leaves} \times 100\% \quad (2)$$

The primary essential oil components analyzed included citronellal, citronellol, and geraniol, determined using GC-MS analysis. Mycorrhizae colonization was observed by cutting approximately 1 cm segments of infected roots, washing them with distilled water, soaking them in 20% KOH for 48 hours, followed by immersion in 0.1 M HCl. The roots were then soaked for 48 hours in trypan blue solution and subsequently in a destaining solution for 24 hours. Root colonization was observed under a microscope and calculated using the following formula (Lu et al., 2015) :

$$Mycorrhizae\ colonization\ (\%) = \frac{Number\ of\ colonized\ roots}{Number\ of\ observed\ roots} \times 100\% \quad (3)$$

Data analysis

The data collected were analyzed using analysis of variance (ANOVA) at the 5% significance level to determine significant treatment effects. The experiment was replicated 3 times in total of 30 experimental units, with each unit consisting of 40 citronella plants. If significant differences were detected, further analysis was conducted using the honestly significant difference (HSD) test at a 5% error level to compare differences between treatment means.

RESULTS AND DISCUSSION

Growth parameters

This research focused on citronella (*Cymbopogon nardus* L.) as an alternative intercrop in an agroforestry cultivation system under 25% shading. Citronella has the potential as an intercrop due to its shallow, clumped adventitious root system (Rahmah et al., 2023). The results of the conducted research demonstrated that the application of mycorrhizae with potassium fertilization at certain dosage significantly influenced the growth of citronella plants. Application of mycorrhizae combined with K_2O fertilization at dosage of 40 kg ha^{-1} increased leaf number 25.15%, leaf area 3.04%, total fresh biomass 25.06%, and total dry biomass 31.79% when it was compared to K_2O dosage of 0 kg ha^{-1}, 20 kg ha^{-1}, 60 kg ha^{-1}, and 80 kg ha^{-1} (Figure 1). The products of photosynthesis are released by the plant as exudates into the rhizosphere to feed the mycorrhizae, primarily through the arbuscules formed by the hyphal structures (Ma et al., 2022). Therefore, greater nutrient production by the plant can enhance mycorrhizae population density. The presence of mycorrhizae in rhizosphere was reflected in the percentage of root infection observed in citronella plants. The conducted study showed that K_2O fertilization at 80 kg ha^{-1} resulted in 70%

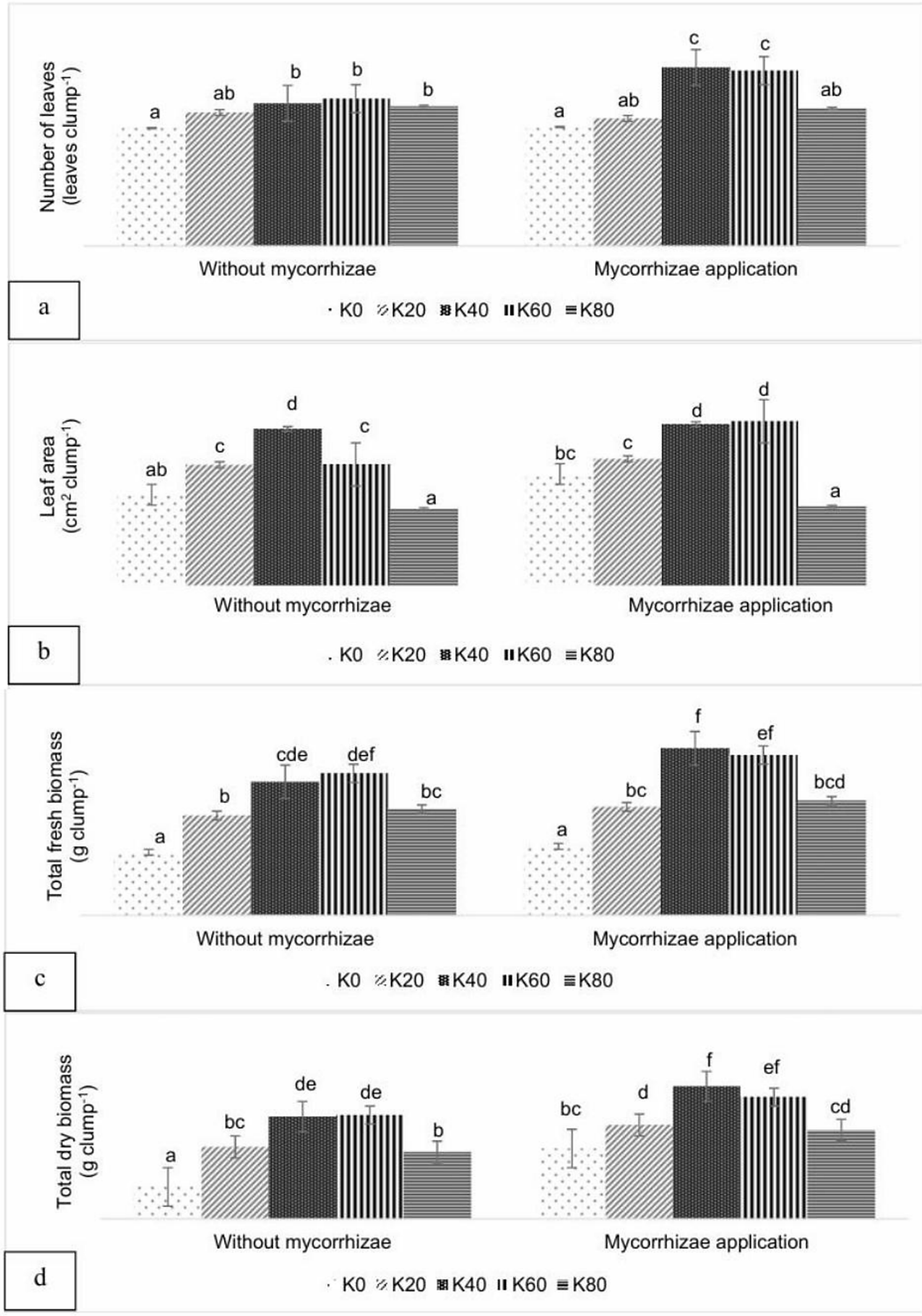

Figure 1. The effect of mycorrhizae treatment with different dosages of potassium fertilizer on the number of leaves (a), leaf area (b), total fresh biomass (c), and total dry biomass (d). Bars with different letters indicate significant differences according to the honestly significant difference (HSD) test at the 5% significance level

root infection rate, both in treatments without mycorrhizae and mycorrhizae application (Figure 2). Subsequent increases in root infection percentage were observed under treatments combining mycorrhizae application with K_2O dosages of 60 kg ha^{-1}, 40 kg ha^{-1}, 20 kg ha^{-1}, and 0 kg ha^{-1}, reaching 70%, 65%, 60%, and 60%, respectively compared to the non-mycorrhizae treatments at the same fertilization levels (Figure 2). Mycorrhizae enhance potassium uptake both actively and passively through the extension of hyphae surrounding the root. Potassium strengthens the root system by maintaining osmotic balance within root cells, thereby supporting nutrient absorption from the soil (Sarwar et al., 2023).

Growth parameters such as leaf number and leaf area significantly influenced the fresh biomass accumulation, as indicated by correlation values of 0.93 and 0.69. This is because increased leaf number and larger leaf area enhance light interception, which boosts photosynthetic rates. Higher photosynthetic activity leads to greater plant biomass and, consequently, higher dry biomass accumulation (Lulie, 2016). The conducted study showed that mycorrhizae application combined with K_2O fertilization at 40 kg ha^{-1} increased fresh biomass by 25.06% and dry biomass by 31.79% compared to other treatment combinations. This finding is supported by previous research by Abdelhameid (2019), which reported that mycorrhizae combined with potassium fertilization increased sorghum biomass by 14.40%.

However, applying mycorrhizae with a high potassium fertilization dosage of 80 kg ha^{-1} resulted in a decline in several growth parameters. While potassium fertilization at this dosage increased mycorrhizae spore numbers and root infection, it reduced citronella growth compared to the 40 kg ha^{-1} dosage. According to Wu et al., (2021) this may be due to nutrient competition between the plant and the mycorrhizae. Mycorrhizae rely on plant-derived exudates as a food source, meaning that as the mycorrhizae population in the rhizosphere increases, the plant's energy demands to sustain them also rise. Under shaded conditions, C4 plants such as citronella may not generate sufficient nutrients to simultaneously support both plant growth and mycorrhizae development. In this situation, the mycorrhizae hyphae prioritize the absorption of nutrients that are otherwise difficult for the roots to access, such as nitrogen and phosphorus (Wang et al., 2019).

Nitrogen and phosphorus uptake showed a strong relationship with dry biomass accumulation in citronella, with determination coefficients (R^2) of 0.64 and 0.79, respectively (Figure 3). Nutrient uptake increased notably in the treatment of mycorrhizae application with K_2O fertilization

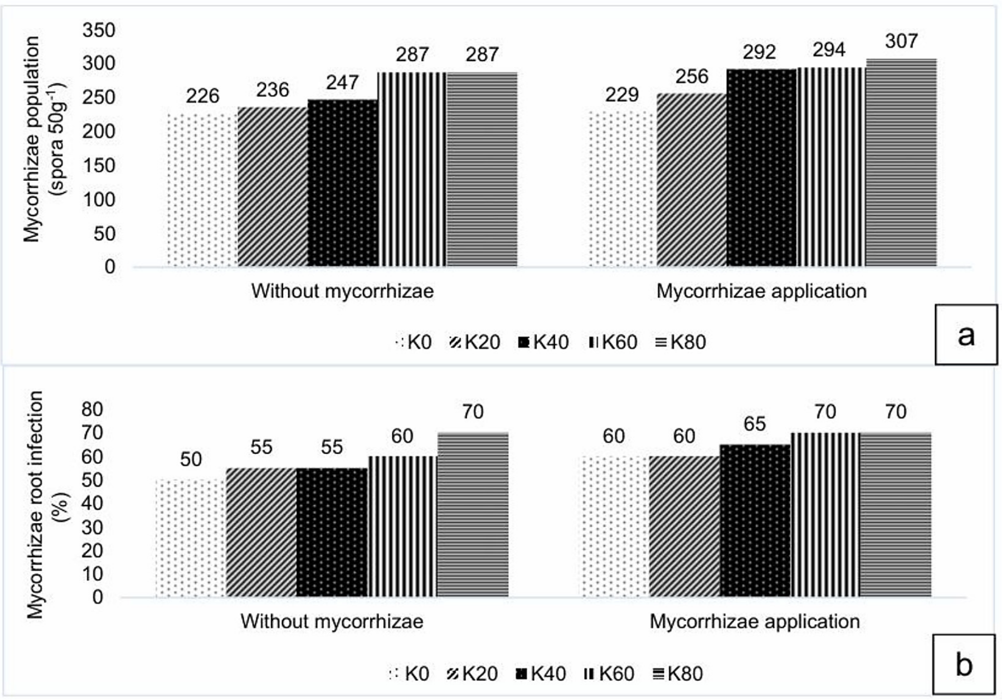

Figure 2. The effect of mycorrhizae treatment with different dosages of potassium fertilizer on the mycorrhizae population (a) and mycorrhizae root infection (b)

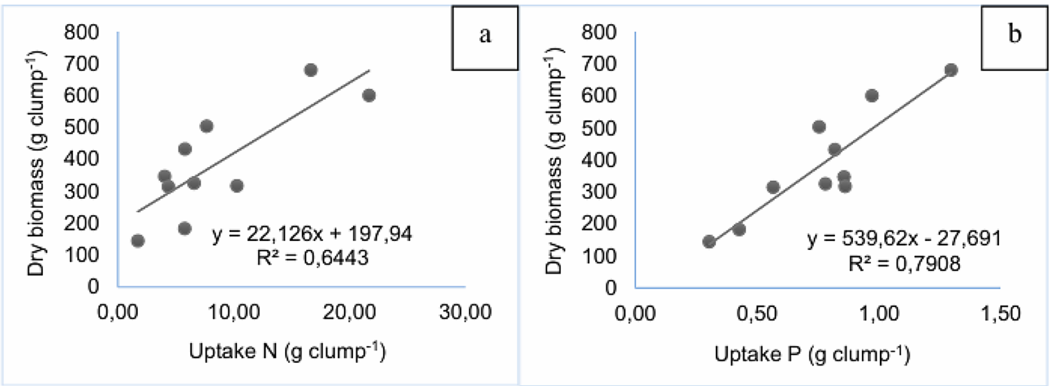

Figure 3. Relationship between dry biomass of citronella (*Cymbopogon nardus* L.) and nitrogen uptake (a), and phosphorus uptake (b)

at 40 kg ha^{-1}. Mycorrhizae hyphae produce the protease enzymes that convert organic nitrogen into ammonium and nitrate through deamination, making these forms more accessible to plants. Additionally, mycorrhizae facilitate the phosphorus uptake by producing phosphatase enzymes, which convert organic phosphorus into inorganic phosphate ions readily absorbed by the roots (Wu et al., 2021). The nitrogen and phosphorus uptake contributes to cytokinin biosynthesis, which is associated with meristematic cell division. Cytokinin, which are purine-based hormones with adenine as the core molecule, consist of carbon, hydrogen, and amino acid groups. These amino acids originate from the nitrogen assimilated by the plant as ammonium. Furthermore, phosphorus, absorbed as phosphate ions, plays a key role in ATP production, which provides the energy needed for cytokinin biosynthesis and its distribution throughout the plant (Khan et al., 2023). Therefore, efficient nutrient absorption can enhance plant growth, as reflected by increased dry biomass accumulation (Talaat et al., 2015).

The dry biomass accumulation of citronella plants under mycorrhizae treatment with K_2O fertilization followed a quadratic regression pattern (Figure 4). Both treatments without mycorrhizae and with mycorrhizae application showed relatively high determination coefficients (R^2) of 0.94 and 0.83, respectively. The quadratic regression equations describing the relationship between K_2O fertilization dosage and dry biomass were without mycorrhizae: $y = -0.2295x^2 + 21.076x + 129.14$ and with mycorrhizae application: $y = -0.1422x^2 + 13.86x + 135.41$. On the basis of these equations, the calculated optimum K_2O dosages were 45.92 kg ha^{-1} without mycorrhizae and 48.71 kg ha^{-1} with mycorrhizae application. Applying the optimum fertilizer dosage not only helps reduce production costs but also minimizes

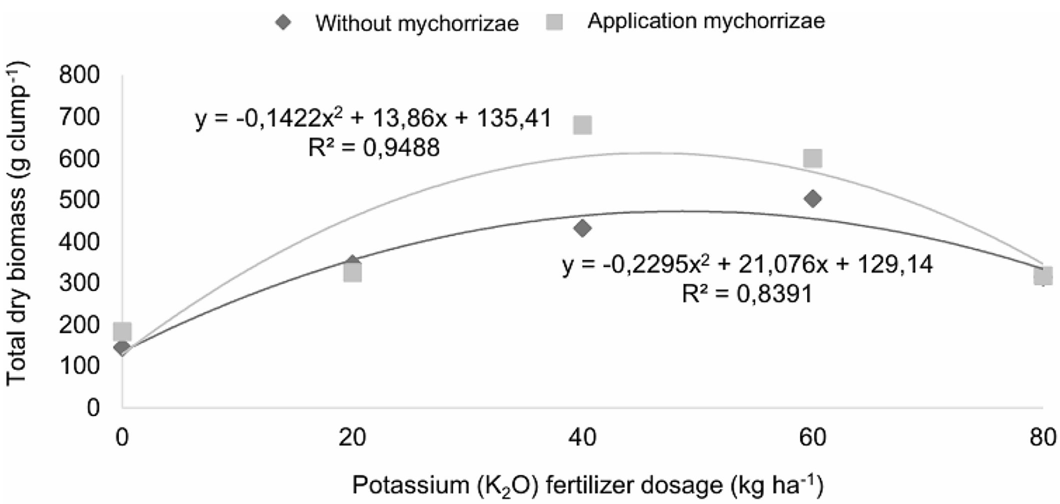

Figure 4. The relationship between potassium (K_2O) fertilizer dosage under different mycorrhizae treatments and dry biomass of citronella (*Cymbopogon nardus* L.)

nutrient imbalance in the plant. Excessive or insufficient potassium levels can disrupt the uptake of nitrogen and phosphorus, ultimately hindering plant growth (Gendy et al., 2015)

Potassium dosage management must also be carefully considered to ensure that citronella achieves optimal leaf growth and maximized harvest yields (Ozims, 2017). On the basis of on the results of this research, both growth and yield parameters of citronella showed improvement when K_2O was applied at dosage of 40 kg ha^{-1}, under both non-mycorrhizae and mycorrhizae treatments, compared to dosages of 0 kg ha^{-1}, 20 kg ha^{-1}, 60 kg ha^{-1}, and 80 kg ha^{-1}. These findings are consistent with the previous research by Singh et al. (2014), which reported that the application of K_2O at 40 kg ha^{-1} resulted in the best growth performance of citronella plants compared to K_2O dosages of 0 kg ha^{-1}, 20 kg ha^{-1}, 80 kg ha^{-1}, and 120 kg ha^{-1}.

This outcome is consistent with the concept of relative nutrient use efficiency, where the additional potassium supplied was utilized more effectively due to the enhanced nutrient absorption capacity and root colonization provided by mycorrhizae. Furthermore, higher potassium availability was associated with increased spore production and root infection intensity (Figure 2), which reinforced the mutualistic relationship and sustained nutrient acquisition (Choudhary et al., 2019). From the perspective of pro-ecological technologies and products, mycorrhizae represent an environmentally friendly innovation that reduces reliance on synthetic fertilizers while maximizing the efficiency of the applied nutrients. This aligns with the principles of sustainable agriculture, as the biological enhancement of nutrient uptake minimizes potential nutrient leaching and mitigates soil degradation (Kalamulla et al., 2022). In shaded environments, where physiological stress may limit plant growth, mycorrhizae inoculation serves as a natural bio-stimulant, improving resource utilization and supporting the biosynthesis of key essential oil components (Sun and Shahrajabian, 2023).

Yield and quality parameters

In addition to enhancing growth, the application of mycorrhizae with potassium fertilization also influenced the yield and quality of citronella essential oil. Essential oil yield was obtained through steam distillation of fresh citronella leaves, and in this study, it showed a strong correlation (r = 0.88) and a high coefficient of determination (R^2 = 0.97). The observed variables included oil yield, essential oil content, and the

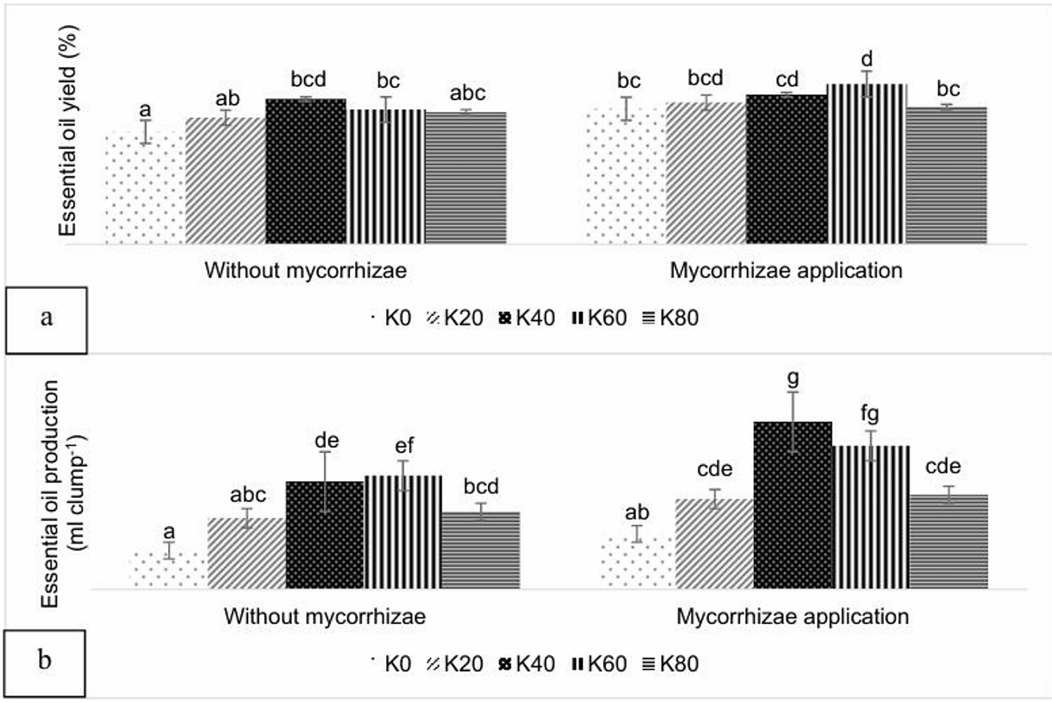

Figure 5. The effect of mycorrhizae treatment with potassium fertilizer dosages on essential oil yield (a) and essential oil production (b). Bars with different letters indicate significant differences according to the honestly significant difference (HSD) test at the 5% significance level

main components of the essential oil namely citronellal, citronellol, and geraniol. Distillation results demonstrated that the application of mycorrhizae together with K_2O at a dosage of 40 kg ha^{-1} significantly increased both essential oil yield and recovery (Figure 5).

Citronella leaves contain glandular trichomes located on the epidermis, which serve as the production and storage sites for essential oils. Glandular trichomes consist of secretory cells capable of synthesizing essential oils. To produce essential oils, the glandular trichomes are supported by parenchyma cells, which generate photosynthates such as isopentenyl diphosphate (IPP), serving as precursors for secondary metabolism. The secondary metabolites produced include terpenoids and phenolic compounds. Terpenoid compounds, derived from isoprene units (C_5), are synthesized through secondary metabolic pathways: the mevalonate (MVA) pathway in the cytoplasm and the methylerythritol phosphate (MEP) pathway in chloroplasts and plastids, ultimately producing aromatic essential oil compounds such as monoterpenes (C_{10}) and sesquiterpenes (C_{15}) (Verma and Shukla, 2015).

Application of mycorrhizae improves biomass and phosphorus uptake. Phosphorus plays an important role in the biosynthesis of the hormone cytokinin, which stimulates formation of terpenoid compounds. Additionally, cytokinin influences cell division and differentiation, including leaf expansion, where trichomes in citronella serve as the production sites for essential oil (Zhao et al., 2022). Therefore, the presence of mycorrhizae has a direct impact on increasing essential oil production. According to Qaderi et al.(2023), mycorrhizae assists in solubilizing potassium, which regulates stomatal opening, thereby enhancing

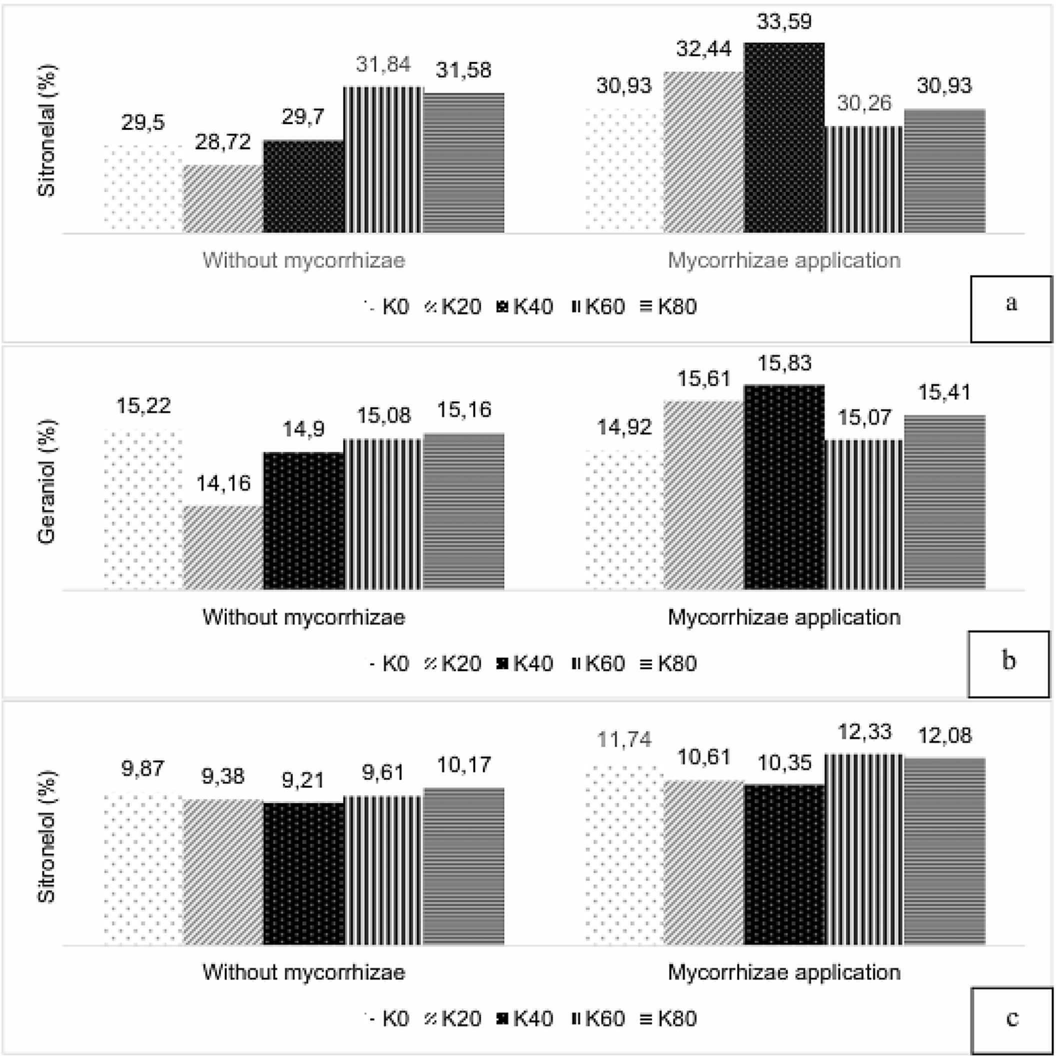

Figure 6. The effect of mycorrhizae treatment with potassium fertilizer dosages on the content of citronellal (a), geraniol (b), and citronellol (c)

photosynthesis. Increased photosynthesis leads to greater carbon assimilation, which serves as a substrate for secondary metabolism, particularly in terpenoid biosynthesis, resulting in higher essential oil yields. Previous studies by El Gendy et al. (2015) and Chrysargyris et al. (2017) showed that potassium acts as cofactor for enzymes involved in terpenoid biosynthesis, specifically in the production of IPP.

Citronella essential oil is composed of various chemical constituents with differing percentages, which can be analyzed using GC-MS. The working principle of gas chromatography (GC) involves separating the compounds in the essential oil based on their volatility and interaction with the chromatography column, while mass spectrometry (MS) identifies the compounds based on their mass and ion fragmentation patterns (Carrasco et al., 2015). Volatile compounds elute from the column more quickly. The percentage of each component is reflected in the chromatogram peaks, meaning that the higher the percentage of a compound, the taller the corresponding chromatogram peak (Solekha et al., 2024). According to Kaur et al. (2021), the major constituents of citronella essential oil include citronellal (32–45%), geraniol (12–18%), and citronellol (12–15%). This is consistent with the results obtained in the present study, where the GC-MS analysis revealed three main components: citronellal (27.86–35.32%), geraniol (13.09–17.22%), and citronellol (7.29–13.06%) (Figure 6).

Citronellal (3,7-dimethyl-6-octenal) is a monoterpene aldehyde ($C_{10}H_{18}O$) in essential oil with a boiling point of approximately 201–207 °C. It can be synthesized through the direct conversion of geraniol to citronellal. Geraniol (3,7-dimethyl-2,6-octadien-1-ol) is a monoterpene alcohol ($C_{10}H_{18}O$) with a boiling point reaching 229–502 °C. In essential oil biosynthesis, geraniol is produced via the mevalonate pathway, facilitated by the enzyme geraniol synthase (GES) (Rihayat et al., 2020). Geraniol exhibits antiviral, antibacterial, anti-inflammatory, and antitumor properties (Tahya et al., 2022). Citronellol (3,7-dimethyl-6-octen-1-ol) is a monoterpene alcohol ($C_{10}H_{20}O$) formed through the reduction of citronellal. It is soluble in alcohol but insoluble in water, with a boiling point of approximately 225 °C (Braga et al., 2018)

The citronellal component in citronella essential oil tends to be higher than that of geraniol and citronellol. Citronellal is classified as an aldehyde compound, which has more chemically stable properties compared to geraniol and citronellol, both of which are alcohol compounds. The compounds with high volatility pass through the GC column more easily, resulting in higher percentage readings. Additionally, the MS detector is more sensitive to volatile compounds, producing ions that are easily detected and thus increasing the peak intensity in the mass spectrum (Carrasco et al., 2015). Furthermore, potassium fertilization acts as a cofactor for the enzyme geraniol dehydrogenase (GeDH), which catalyzes the oxidation reaction converting geraniol to citronellal (Wang et al., 2019).

CONCLUSIONS

On the basis of the observations of several growth parameters, the application of mycorrhizae can increase some growth parameters and the yield of essential oils produced compared to the treatments without mycorrhizae application under shaded conditions. The application of mycorrhizae with K_2O fertilization at dosage 40 kg ha^{-1}, compared to K_2O fertilization dosages 0 kg ha^{-1}, 20 kg ha^{-1}, 60 kg ha^{-1}, and 80 kg ha^{-1}, significantly enhanced growth parameters, including leaf number (25.15%), leaf area (3.04%), total fresh biomass (25.06%), and total dry biomass (31.79%). Additionally, it improved essential oil quality parameters, namely essential oil yield (3.05%), essential oil content (57.16%), and citronellal content (13.12%). Although the optimum K_2O fertilization dosage was slightly higher with mycorrhizae (48.71 kg ha^{-1}), compared to without mycorrhizae (45.92 kg ha^{-1}), the improvement in yield was substantial due to enhanced nutrient uptake efficiency, higher spore production, and greater root colonization. This strategy represents a pro-ecological technology that aligns with sustainability in environmental engineering by improving nutrient use efficiency and reducing environmental risks associated with excessive fertilizer application. The results highlight the potential of integrating biological agents with targeted nutrient management as a sustainable solution for maximizing productivity in shaded agricultural systems.

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