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EVALUATING FOLIAR SULPHUR AND POTASSIUM APPLICATIONS FOR ENHANCED GROWTH AND ESSENTIAL OIL YIELD IN *CALENDULA OFFICINALIS*

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Abstract

Nutrients are crucial for high-quality and profitable crop production, with sulfur and potassium being particularly essential for enhancing crop growth and overall quality. The study aimed to evaluate the impact of foliar-applied Sulphur and potassium on calendula's essential oil yield and overall growth. Conducted at MNS-University of Agriculture during the winter of 2022-23. Calendula seeds were planted and transplanted in specified spacing and conditions. The research involved eight treatments in a randomized complete block design with three replications and a control group, totaling 810 plants. Foliar spray of Potassium and Sulphur was applied both separately and in different combinations. It was observed that different treatments significantly affected calendula's vegetative, reproductive, and essential oil-related parameters. The findings revealed enhanced plant growth, flowering, and yield due to fertilizer application, notably increasing essential oil yield from flowers. However, the essential oil yield from leaves did not display significant changes. Physical properties of the essential oil, including density, refractive index, and specific gravity, varied across treatments. Gas chromatography-mass spectrometry (GC-MS) analysis identified various components contributing to the essential oil's chemical composition, comprising major, minor, and trace elements. These results offer insights for refining fertilizer application techniques to optimize the quality essential oil production from calendula flowers.

Key words: Chromatography, Fertilizer, Flower, Leaves, Reproductive, Vegetative

Introduction

Horticulture is the science and art of growing plants for food, medicine, and decoration. It includes a variety of activities, such as the management, planting, and propagation of ornamental, edible, and horticultural plants. Floriculture is the study of the development, promotion, and management of flowers and decorative plants (Gabellini & Scaramuzzi, 2022). One of the primary production divisions of floriculture is plant gardening in green spaces, together with the production, promotion, and sale of cut flowers and bedding plants (Chandel *et al.,* 2023). *Calendula officinalis* is well established as a medicinal plant, but the literature remains uneven because most studies emphasize pharmacological activity, phytochemical profiling, extraction efficiency, and product standardization rather than agronomic strategies for maximizing essential oil yield and composition (Zournatzis *et al*., 2024; Ak *et al*., 2020; Yurchenko, 2025). *Calendula officinalis* has long attracted scientific attention because of its broad medicinal use, rich phytochemical diversity, and commercial importance in cosmetics, pharmacy, and herbal products (Verma *et al*., 2018; Dhingra *et al*., 2022). Reviews consistently summarize its anti-inflammatory, wound-healing, antioxidant, antimicrobial, gastroprotective, and other therapeutic effects, while analytical studies focus on flavonoids, triterpenoids, carotenoids, volatile oils, and related markers used for quality control and standardization (Jan & John, 2017; Shahane *et al*., 2023; Yurchenko, 2025).

Statistics show that in Pakistan, 7080-hectare area produces between 10,000 and 12,000 tons of fresh flowers each year. Only 0.5% of Pakistan's agricultural land is used for floricultural crops, while 5% of that land is used for horticulture (Ahmad *et al.,* 2024). A total of 7080 ha is used for floriculture, of which 2 shares are in Punjab (4450 ha), KpK (1012 ha), Sindh (1214 ha), Baluchistan (a few hundred), and Gilgit Baltistan (which is only starting to make a name for itself in the floriculture world). There were 2500 farmers, 1000 middlemen, and salespeople working in the floriculture sector nationwide. Top flowers grown and supplied throughout the nation include roses, gladioli, marigolds, chrysanthemums, and tuberoses. Pakistan's largest flower market is in Pattoki (Ahmad *et al.,* 2024).

Calendula officinalis is a widely cultivated ornamental and medicinal plant that is extensively grown in China,

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Europe, India, and the United States because of its therapeutic and commercial importance (Givol *et al*., 2019). Belonging to the family Asteraceae, it is recognized by numerous common names across different regions of the world. It is commonly known as pot marigold, common marigold, garden marigold, or simply marigold in English-speaking countries. In India, it is referred to as Zergul, in Germany as Terbium, in Romania as Galbinele, in China as Chin Chan Ts'ao, and in Sweden as Ringblomma (Muley *et al*., 2009). The wide range of vernacular names reflects the global distribution, cultural significance, and long-standing medicinal and ornamental use of *C. officinalis*.

Plant essential oils are broad-spectrum, volatile molecules with antifungal action that are both eco-friendly and more popular with the general population (Karamat *et al.,* 2020). Essential oils (EOs) are substances that give plants their distinctive aroma, flavor, and ability to ward off diseases (Perczak *et al.,* 2019). The medical, fragrance, and food processing industries have shown a great deal of interest in these properties as well as their varied biological activities (Ayaz *et al.,* 2017). EOs has anxiolytic and depressive properties. Certain chemical substances, alkaloids, flavonoids, glycosides, and primarily phenolics, have these properties (Yasin *et al.,* 2021). Flower essential oils (EOs) are liquids that contain aromatic and volatile components that are extracted from edible flowers using a variety of extraction techniques, including supercritical fluid extraction, steam distillation, solvent extraction, and microwave-assisted extraction (Zhao *et al.,* 2019).

The results shown by Mishra *et al*., (2012) explain the uses of essential oil extracted by calendula, to prevent changes induced by UV-B in skin tissue's antioxidant content. Calendula essential oil is often used in cosmetic formulations for skin care since it helps with cell renewal, softening of the skin, skin inflammation and smoothing, and wound healing and has a high antioxidant capacity (Okoye, 2011; Lohani *et al.,* 2019).

Sulphur is an essential ingredient for the robust development of crops. It ranks second in terms of importance behind NPK (Boroomand & Grouh, 2012). It is a part of the pigment's cystine, amino acids, methionine, and chlorophyll (Saleem *et al.,* 2019). Oilseed crops require higher amounts of S for growth and oil yield since S is necessary for the development of big grains and the synthesis of oil (Saleem *et al.,* 2019).

Potassium is the nutrient that most ornamental plants need in larger amounts. According to Benites *et al.,* (2010) and Marschner (2012), The preservation of the osmotic equilibrium in plant cells, the control of gas exchange and transpiration, the activation of enzymes, protein synthesis, photosynthesis, and stress tolerance are all directly impacted by potassium (K). K is a nutrient that plants require in huge amounts and whose uptake frequently outpaces that of nitrogen. In addition to having a greater K content than the other cations in plant tissues, K also efficiently regulates a variety of physiological and biochemical processes (Bajwa, 1994). Earlier sulfur–potassium work in oil-bearing crops mainly established that these nutrients improve yield, oil content, or quality in broad agronomic terms, especially in soybean, sunflower, sesame, and mustard (Ahmad *et al*., 2018; Ullah *et al*., 2018; Dhingra *et al.*, 2022). Reviews also frame potassium and sulfur largely as general regulators of photosynthesis, nutrient transport, oil biosynthesis, and seed maturation across oilseeds rather than as crop-specific drivers of essential-oil optimization (Karmakar *et al*., 2024).The objective of the study was to evaluate and screen the effective concentrations of Sulphur and potassium nutrients on the quality essential oil production in the leaves and flowers of *Calendula officinalis*.

Material and Methods

The experiment was conducted during the winter season of 2022-2023 at the floriculture research area of MNS-University of Agriculture, Multan. *Calendula officinalis* seeds were sown in silt soil, and healthy seedlings were transplanted in an open field on raised beds at a spacing of 15 cm between plants and 90 cm between rows. The experiment was laid out in a Randomized Complete Block Design (RCBD) to minimize the effects of field variability. The experimental area was divided into three homogeneous blocks (replications), and each block contained all eight treatments, including the control. Treatments were randomly assigned within each block, ensuring that every treatment appeared once per replication. Each experimental unit consisted of 30 plants, resulting in 90 plants per treatment (30 plants × 3 replications) and a total of 810 plants (9 treatments × 30 plants × 3 replications) in the experiment. The plants received foliar applications of potassium (K) and sulfur (S), both individually and in combination. The first foliar application occurred one month after seedling transplantation, followed by additional applications on a fortnightly basis, resulting in three total foliar applications. Uniform plant protection measures and cultural practices were maintained for all experimental plants. Data collection occurred on both vegetative and reproductive growth parameters of Calendula, focusing on the response to foliar applications of S and K, both alone and in combination. Five randomly selected plants were assessed in each treatment. Calendula flowers were collected in the early morning, cleaned of dust particles, weighed, and subjected to hydro distillation for essential oil extraction. The essential oils obtained from fresh flowers were analyzed using Gas Chromatography-Mass Spectrometry (GC-MS) to estimate composition and yield. Following compound identification by GC-MS, essential oil components were categorized as major, minor, and trace components, following the methodology.

The experiment was comprised of the following set of treatments:

- T0: Control
- T1: Sulphur (S) 0.12g/l
- T2: Sulphur (S) 0.25g/l
- T3: Potassium (K) 0.5g/l
- T4: Potassium (K) 0.75g/l
- T5: S (0.12g/l) + K (0.5g/l)
- T6: S (0.12g/l) + K (0.75g/l)
- T7: S (0.25g/l) + K (0.5g/l)
- T8: S (0.25g/l) + K (0.75g/l)

Vegetative parameters: Various vegetative parameters were calculated including plant height (cm), no. of leaves per plant, no. of branches, shoot length (cm), stem diameter (cm), and leaf area(cm^2).

Reproductive parameters: Various reproductive parameters were calculated including days to bud opening, days to flowering, flowering period, no. of flower per plant, flower diameter (cm), flower weight (g), total yield per plant, and dry matter percentage.

Essential oil parameters: Various essential oil parameters were calculated including Essential oil yield from fresh Flowers (%) and Essential oil yield from dry Flowers (%). Essential oil yield was calculated by the use of the following mention formula:

$$\%\ \text{Age (EO)} = \frac{\text{EO extracted (ml)}}{\text{Total weight of petels}} \times 100$$

Physical properties of essential oil: Parameters regarding physical properties of essential oil were color (a, b, l), density, and refractive index.

Statistical analysis

The recorded data were subjected to analysis of variance (ANOVA) appropriate for a Randomized Complete Block Design (RCBD) to determine the significance of treatment effects. The statistical analysis was performed using Statistix 9.1 software (Analytical Software, Tallahassee, FL, USA). Treatment means were compared using the Least Significant Difference (LSD) test at the 5% probability level ($p \leq 0.05$). Data are presented as mean values ± standard error (SE), and differences among treatments were considered statistically significant at $p \leq 0.05$.

Results

Vegetative parameters:

Plant Height (cm): The combined application of sulfur (S) at 0.25 g and potassium (K) at 0.75 g (T8) resulted in the greatest improvement in plant height, producing the maximum mean plant height of 59.33 cm (Table 1). This treatment proved to be the most effective in promoting vegetative growth, indicating that the higher potassium level, when combined with sulfur, significantly enhanced plant development. The second-highest plant height (52.00 cm) was recorded under the application of 0.25 g sulfur + 0.50 g potassium (T7), demonstrating that this treatment also positively influenced plant growth, although its effect was slightly lower than that of T8. In contrast, the control treatment (T0), where no sulfur or potassium was applied, produced the minimum mean plant height of 30.33 cm.

Number of leaves per plant: The results revealed that the combined application of sulfur (S) at 0.25 g L^{-1} and potassium (K) at 0.75 g L^{-1} (T8) produced the highest mean number of leaves per plant, recording 164.66 leaves (Table 1). This treatment was found to be the most effective in enhancing leaf production, suggesting that the optimum combination of sulfur and potassium significantly promoted vegetative growth and foliage development. The second-highest number of leaves per plant (130.33) was observed under treatment T7, where plants received 0.25 g L^{-1} sulfur + 0.50 g L^{-1} potassium. Although slightly lower than T8, this treatment also markedly improved leaf production compared with the other treatments. In contrast, the control treatment (T0), which received no sulfur or potassium supplementation, recorded the lowest mean number of leaves per plant (40.67).

Number of branches per plant: The results indicated that the combined application of sulfur (S) at 0.25 g L^{-1} and potassium (K) at 0.75 g L^{-1} (T8) produced the highest mean number of branches per plant, recording 24.00 branches (Table 1). This treatment was the most effective in promoting branch development, suggesting that the optimum combination of sulfur and potassium enhanced vegetative growth by stimulating the formation of lateral shoots. The second-highest number of branches (21.67) was observed under treatment T7, which received 0.25 g L^{-1} sulfur + 0.50 g L^{-1} potassium. Although slightly lower than T8, this treatment also significantly improved branching compared with the remaining treatments. In contrast, the control treatment (T0), which received no sulfur or potassium application, recorded the lowest mean number of branches per plant (9.78).

Shoot length (cm): The control treatment (T0) had an average shoot length of 15.17, Applying 0.12g/l of S (T1) resulted in an increased shoot length compared to the control, with an average of 17.67. Further increasing the S dosage to 0.25g/l (T2) led to a larger improvement in shoot length, averaging 19.67. Applying 0.5g/l of K (T3) resulted in a shoot length of 17.33. Increasing the K dosage to 0.75g/l (T4) resulted in a substantial improvement in shoot length, with an average of 22.83. The combination treatment of 0.12g/l S and 0.5g/l K (T5) resulted in a further increase in shoot length, with an average of 24.67. Increasing the K dosage to 0.75g/l in combination with 0.12g/l S (T6) led to a slightly higher shoot length of 25.33. When 0.25g/l S was combined with 0.5g/l K (T7), the shoot length further increased to an average of 26.00. The highest shoot length was observed with the combined treatment of 0.25g/l S and 0.75g/l K (T8), averaging at 29.67 (Table 1).

Stem diameter per plant (mm): The control treatment (T0) had an average stem diameter of 2.63 mm, serving as the baseline for comparison. Application of 0.12g of S (T1) resulted in a decrease in stem diameter compared to the control group, with an average of 2.18 mm. However, increasing the S dosage to 0.25g/l (T2) led to a significant improvement in stem diameter, with an average of 3.84 mm. In contrast, the application of 0.5g/l of K (T3) resulted in a stem diameter of 3.38 mm. Further increasing the K dosage to 0.75g/l (T4) resulted in a slight improvement, with an average diameter of 3.55 mm (Table 1). The combination treatment of 0.12g/l S and 0.5g/l K (T5) did not lead to a substantial increase in stem diameter. However, combining 0.12g/l S with 0.75g/l K (T6) and 0.25g/l S with 0.5g/l K (T7) resulted in significant improvements, with average stem diameters of 5.07 mm and 5.01 mm, respectively (Table 1). The highest stem diameter was observed with the combined treatment of 0.25g/l S and 0.75g/l K (T8), averaging 5.28 mm.

Leaf area (cm^2): The results demonstrated that the foliar application of sulfur (S) at 0.25 g L^{-1} combined with potassium (K) at 0.75 g L^{-1} (T8) produced the maximum leaf area, with a mean value of 18.33 cm^2 (Table 1). This treatment was found to be the most effective in promoting leaf expansion, indicating that the combined application of sulfur and potassium enhanced photosynthetic surface area and overall vegetative growth. The next highest leaf area was recorded under T7, where plants received 0.12 g L^{-1} sulfur + 0.75 g L^{-1} potassium, with a mean value of 18.66 cm^2. This treatment also performed considerably better than the remaining treatments, demonstrating the positive influence of foliar-applied sulfur and potassium on leaf development. In contrast, the control treatment (T0), in which plants were grown without any foliar application of sulfur or potassium, recorded the minimum leaf area of 10.33 cm^2.

Reproductive parameters

Days to bud opening: The results presented in Table 2 demonstrate the effect of different foliar applications of sulfur (S) and potassium (K) on the number of days required for flower bud opening. Among all the treatments, T8, which received 0.25 g L^{-1} sulfur and 0.75 g L^{-1} potassium, exhibited the earliest bud opening, requiring a minimum of 29.45 days. This finding indicates that the combined application of sulfur and potassium at these concentrations effectively accelerated floral development and promoted earlier bud emergence. In contrast, the control treatment (T0), where no foliar application of sulfur or potassium was provided, required the maximum number of days (43.22 days) for bud opening. The delayed flowering observed in the control plants suggests that the absence of these essential nutrients slowed the physiological processes associated with flower initiation and development.

Days to flowering: Based on the results the control treatment (T0) took an average of 58.78 days to flower. Applying 0.12g/l of S (T1) resulted in a significant reduction in the number of days to flowering, with an average of 47.33 days. This suggests that this particular dosage of S accelerated the flowering process (Table 2). Further increasing the S dosage to 0.25g/l (T2) led to a more pronounced effect, with an average of 37.22 days to flowering. On the other hand, applying 0.5g/l of K (T3) resulted in an average of 41.55 days to flowering, indicating a slight reduction compared to the control group. Increasing the K dosage to 0.75g/l (T4) led to a more notable decrease in the time to flowering, with an average of 36.89 days. The combination treatments of 0.12g S with 0.5g/l K (T5) and 0.75g/l K (T6) showed varying effects on the flowering time, with average values of 46.89 days and 43.11 days, respectively. Combining 0.25g/l S with 0.5g/l K (T7) resulted in an average of 40.00 days to flowering, while the combination of 0.25g/l S with 0.75g/l K (T8) exhibited the shortest time to flowering at 39.45 days.

Flowering period: The results presented in Table 2 demonstrated that the foliar application of sulfur (S) and potassium (K) influenced the duration of the flowering period. Compared with the control treatment (T0), plants receiving sulfur and potassium generally exhibited a longer flowering period, indicating that these nutrients contributed to prolonged floral development and enhanced reproductive performance. Among the treatments, T4, which received 0.75 g L^{-1} potassium, and T5, consisting of 0.12 g L^{-1} sulfur + 0.50 g L^{-1} potassium, showed a modest increase in flowering duration, recording mean values of 1.11 and 1.67, respectively. These treatments extended the flowering period slightly compared with the untreated control, suggesting that both potassium alone and its combination with a lower concentration of sulfur had a positive effect on flower longevity. A more pronounced increase in flowering duration was observed under the combined applications of sulfur and potassium. T6 (0.12 g L^{-1} sulfur + 0.75 g L^{-1} potassium) recorded a flowering period of 1.89, while T7 (0.25 g L^{-1} sulfur + 0.50 g L^{-1} potassium) further increased the flowering duration to 2.33. The maximum flowering period (2.56) was recorded in T8, where plants received 0.25 g L^{-1} sulfur + 0.75 g L^{-1} potassium.

No. of flowers per plant: The results presented in Table 2 revealed that the foliar application of sulfur (S) and potassium (K), either individually or in combination, significantly increased the number of flowers per plant compared with the untreated control. The control treatment (T0), which received no foliar application of sulfur or potassium, produced the lowest mean number of flowers per plant (41.89), indicating that nutrient deficiency adversely affected floral initiation and development. Among the individual nutrient treatments, T2, in which plants received 0.25 g L^{-1} sulfur, and T4, receiving 0.75 g L^{-1} potassium, each produced 68.67 flowers per plant, representing a substantial improvement over the control. These findings demonstrate that the individual application of sulfur or potassium enhanced flower production by promoting better vegetative growth and supporting the physiological processes involved in flowering. An even greater increase in flower production was observed when sulfur and potassium were applied together. Treatment T6 (0.12 g L^{-1} sulfur + 0.75 g L^{-1} potassium) recorded 75.45 flowers per plant, while T7 (0.25 g L^{-1} sulfur + 0.50 g L^{-1} potassium) produced 75.22 flowers per plant. The highest mean number of flowers per plant (84.11) was obtained under T8, where plants received the combined foliar application of 0.25 g L^{-1} sulfur + 0.75 g L^{-1} potassium.

Flower diameter (cm): The results presented in Table 2 indicated that foliar application of sulfur (S) and potassium (K) significantly improved flower diameter compared with the untreated control. The control treatment (T0), in which no sulfur or potassium was applied, produced the smallest mean flower diameter of 1.96 cm, suggesting that the absence of these essential nutrients adversely affected flower growth and development. Among the individual nutrient treatments, T2, receiving 0.25 g L^{-1} sulfur, produced a mean flower diameter of 3.67 cm, while T4, supplied with 0.75 g L^{-1} potassium, recorded a slightly lower but comparable flower diameter of 3.60 cm. These values were substantially greater than those observed in the control treatment, indicating that the individual application of sulfur or potassium effectively enhanced flower size by promoting improved nutrient uptake, cell expansion, and overall floral development. The combined application of sulfur and potassium produced an even greater improvement in flower diameter. T7, consisting of 0.25 g L^{-1} sulfur + 0.50 g L^{-1} potassium, recorded a mean flower diameter of 3.88 cm, demonstrating the beneficial synergistic effect of these nutrients on flower growth. The maximum flower diameter (4.38 cm) was observed under T8, where plants received 0.25 g L^{-1} sulfur + 0.75 g L^{-1} potassium.

Flower weight (g): The results presented in Table 2 demonstrated that the foliar application of sulfur (S) and potassium (K), either individually or in combination, significantly increased flower weight compared with the untreated control. The control treatment (T0), in which no sulfur or potassium was applied, produced the lowest mean flower weight of 1.06 g, indicating that the absence of these essential nutrients limited flower development and biomass accumulation. Among the individual nutrient treatments, T2, receiving 0.25 g L^{-1} sulfur, produced a mean flower weight of 2.00 g, while T4, supplied with 0.75 g L^{-1} potassium, recorded a higher flower weight of 2.36 g. These values were considerably greater than that of the control, demonstrating that the individual application of sulfur or potassium effectively enhanced flower biomass by improving plant growth, nutrient utilization, and assimilate translocation. The combined application of sulfur and potassium further improved flower weight. T5, consisting of 0.12 g L^{-1} sulfur + 0.50 g L^{-1} potassium, produced a mean flower weight of 2.15 g, whereas T6 (0.12 g L^{-1} sulfur + 0.75 g L^{-1} potassium) recorded 2.28 g. The highest mean flower weight (2.51 g) was obtained under T8, where plants received 0.25 g L^{-1} sulfur + 0.75 g L^{-1} potassium. This treatment proved to be the most effective in enhancing flower biomass, indicating that the higher combined concentrations of sulfur and potassium provided the most favorable nutritional conditions for flower development.

Total yield per plant (g): The results presented in Table 2 revealed that the foliar application of sulfur (S) and potassium (K), either individually or in combination, significantly enhanced the total yield per plant compared with the untreated control (T0). The control treatment (T0), in which no sulfur or potassium was applied, produced the lowest total yield per plant, with a mean value of 83.78, indicating that the absence of these essential nutrients limited plant productivity. Among the individual nutrient treatments, T2 (0.25 g L^{-1} sulfur) produced a total yield of 137.33 per plant, while T4 (0.75 g L^{-1} potassium) further increased the yield to 142.00 per plant, demonstrating the positive influence of both sulfur and potassium on plant growth and yield formation. The combined application of sulfur and potassium resulted in even greater improvements in productivity. Treatment T6, consisting of 0.12 g L^{-1} sulfur + 0.75 g L^{-1} potassium, produced a total yield of 150.89 per plant, whereas T7, receiving 0.25 g L^{-1} sulfur + 0.50 g L^{-1} potassium, recorded a comparable yield of 150.44 per plant. The highest total yield per plant (168.22) was obtained under T8, where plants were treated with 0.25 g L^{-1} sulfur + 0.75 g L^{-1} potassium.

Dry matter percentage (%): The results as shown in (Table 2) revealed that the treatments, including S and K, had varying effects on the dry matter percentage compared to the control treatment (T0) (58.84). Treatment T1 (S 0.12g/l) showed a slight increase (60.60), while T2 (S 0.25g/l) and T4 (K 0.75g/l) exhibited a decrease in the dry matter percentage 57.23 and 59.28 respectively. T5 (S 0.12g/l+ K 0.5g/l) and T6 (S 0.12g/l+ K 0.75g/l) had similar dry matter percentages as the control treatment (59.34 and 61.34). However, T7 (S 0.25g/l+ K 0.5g/l) showed a lower dry matter percentage (52.38), while T8 (S 0.25g/l+ K 0.75g/l) demonstrated a higher dry matter percentage (63.93).

Essential oil parameters

Essential oil yield from fresh flowers (%): The results of the MS-GC were noted that the application of S at 0.12g/l (T1) and 0.25g/l (T2) resulted in similar essential oil yield percentages (0.020% and 0.020%). Additionally, the treatments with K at 0.5g/l (T3) and 0.75g/l (T4) exhibited slightly higher essential oil yields (0.21% and 0.022%). The combined treatments of S at 0.12g/l with K at 0.5g/l (T5) (0.023%), S at 0.12g/l with K at 0.75g/l (T6) (0.028%), S at 0.25g/l with K at 0.5g/l (T7) (0.029%), and S at 0.25g/l with K at 0.75g/l (T8) (0.036%) showed further increases in the essential oil yield from fresh flowers. While the lowest essential oil yield percentage was noticed in control (T0) which was 0.018% as shown in (Table 3).

Essential oil yield from dry flowers (%): The control treatment (T0) yielded an essential oil yield from fresh flowers of 0.010. Applying S at 0.12g/l (T1) and 0.25g/l (T2) affects the essential oil yield from dry flowers but remained at 0.011%. However, the application of K at 0.5g/l (T3) increased the essential oil yield to 0.013%, and at 0.75g/l (T4), it further rose to 0.014%. Combining S (0.12g/l) with K (0.5g/l) (T5) resulted in an essential oil yield of 0.015, while combining S (0.12g/l) with higher K (0.75g/l) (T6) led to an essential oil yield of 0.018%. Similarly, combining higher S (0.25g/l) with moderate K (0.5g/l) (T7) resulted in an essential oil yield of 0.019%, and combining both higher S (0.25g/l) and K (0.75g/l) (T8) produced the highest essential oil yield from dry flowers of 0.020% (Table 3).

Physical properties of essential oil

Density (g/cm^3): The results in (Table 4) indicated that the density of the samples varied among the different treatments. The control treatment (T0) had a density of 0.77, while treatments involving S and K showed slightly higher or lower densities. Specifically, T1 (S 0.12g/l) and T2 (S 0.25g/l) had densities of 0.80, T3 (K 0.5g/l) had a density of 0.73, and T4 (K 0.75g/l) had the lowest density of 0.70. The combination treatments, T5 (S 0.12g/l + K 0.5g/l) and T7 (S 0.25g/l + K 0.5g/l), exhibited a density of 0.73, while T6 (S 0.12g/l + K 0.75g/l) and T8 (S 0.25g/l + K 0.75g/l) had the highest density of 0.87.

Refractive index: The results from the (Table 4) revealed that the refractive index varied among the different treatments. The control treatment (T0) had a refractive index of 1.50. Treatments involving S and K showed slight variations in refractive index values. Specifically, T1 (S 0.12g/l) exhibited a refractive index of 1.48, T2 (S 0.25g/l) and T3 (K 0.5g/l) had a refractive index of 1.49, and T4 (K 0.75g/l) had the same refractive index of 1.49. The combination treatments, T5 (S 0.12g/l + K 0.5g/l), T6 (S 0.12g/l + K 0.75g/l), and T7 (S 0.25g/l + K 0.5g/l), exhibited a refractive index of 1.47. (Table 4) presents the results of a study investigating the effects of various treatments (T0 to T8) (T0: control to T8: S (0.25g/l) + K (0.75g/l)) on color attributes, measured as a, b, and l. The treatments included different concentrations of Sulphur (S) and Potassium (K). Surprisingly, all treatment groups demonstrated identical color values, showing no significant variations in a (1.51), b (3.64), and l (56.53). The findings suggest that the treatments employed in the study had no discernible impact on the color attributes measured.

Table 1. vegetative parameters of *C. officinalis* after applications of different treatments.

Treatments	Vegetative parameters					
	Plant height	No. of leaves per plant	No. of branches per plant	Shoot length	Stem diameter per plant	Leaf area
T0: control	30.33^{e}	40.67^{e}	9.78^{e}	15.17^{d}	2.63^{b}	10.33^{d}
T1: Sulphur (S) 0.12g/l	35.33de	42.11de	14.44e	17.67cd	2.18ab	11.67cd
T2: Sulphur (S) 0.25g/l	39.33d	49.78d	16.33de	19.67bc	3.84ab	13.33bc
T3: Potassium (K) 0.5g/l	34.67de	37.89de	15.44e	17.33cd	3.38ab	13.67bc
T4: Potassium (K) 0.75g/l	45.67c	51.56c	16.89de	22.83bc	3.55ab	14.33bc
T5: S (0.12g/l) + K (0.5g/l)	49.33bc	65.89bc	20.22cd	24.67abc	3.15ab	14.67b
T6: S (0.12g/l) + K (0.75g/l)	50.67bc	87.67bc	21.78c	25.33ab	5.07a	15.33b
T7: S (0.25g/l) + K (0.5g/l)	52.00b	130.33b	21.67b	26.00ab	5.01a	16.00ab
T8: S (0.25g/l) + K (0.75g/l)	59.33a	164.66a	24.00a	29.67a	5.28a	18.33a
CV	4.84	10.8	11.74	4.84	20.24	7.13

Table 2. Reproductive parameters of *C. officinalis* after application of different treatments.

Treatments	Reproductive parameters						
	Days to bud opening	Flowering period(days)	No. of flowers per plant	Flower diameter	Flower weight	Total yield per plant	Dry matter percentage
T0: control	43.22^{a}	1.00^{c}	41.89^{d}	1.96^{d}	1.06^{e}	83.78^{d}	58.84^{ab}
T1: Sulphur (S) 0.12g/l	37.33^{ab}	1.00^{c}	53.00^{cd}	3.09^{c}	1.83^{d}	106.00^{c}	60.60^{ab}
T2: Sulphur (S) 0.25g/l	27.22^{b}	1.00^{c}	68.67^{b}	3.67^{bc}	2.00^{d}	137.33^{b}	57.23^{b}
T3: Potassium (K) 0.5g/l	31.55^{ab}	1.00^{c}	53.00^{c}	3.11^{c}	1.88^{d}	106.00^{c}	57.39^{ab}
T4: Potassium (K) 0.75g/l	26.89^{b}	1.11^{c}	71.00^{b}	3.60^{bc}	2.36^{abc}	142.00^{b}	59.28^{ab}
T5: S(0.12g/l) + K (0.5g/l)	36.89^{ab}	1.67^{b}	68.67^{b}	3.50^{bc}	2.15^{cd}	137.33^{b}	59.34^{ab}
T6: S(0.12g/l) + K(0.75g/l)	33.11^{ab}	1.89^{b}	75.45^{ab}	3.24^{c}	2.28^{bcd}	150.89^{ab}	61.34^{ab}
T7: S(0.25g/l) + K (0.5g/l)	30.00^{b}	2.33^{a}	75.22^{ab}	3.88^{ab}	2.38^{ab}	150.44^{ab}	52.38^{ab}
T8: S(0.25g/l) + K(0.75g/l)	29.45^{b}	2.56^{a}	84.11^{a}	4.38^{a}	2.51^{a}	168.22^{a}	63.93^{a}
CV	12.7	9.99	4.92	6.01	8.19	5.42	8.75

Table 3. Essential oil obtained from the flowers of *C. officinalis* after application of different treatments.

Treatments	Essential oil parameters	
	Essential oil yield from fresh flower	Essential oil yield from dry flowers
T0: control	0.018^{e}	0.010^{f}
T1: Sulphur (S) 0.12g/l	0.020^{de}	0.011^{f}
T2: Sulphur (S) 0.25g/l	0.020^{cde}	0.011^{ef}
T3: Potassium (K) 0.5g/l	0.021^{cde}	0.013^{de}
T4: Potassium (K) 0.75g/l	0.022^{cd}	0.014^{cd}
T5: S (0.12g/l) + K (0.5g/l)	0.023^{c}	0.015^{cd}
T6: S (0.12g/l) + K (0.75g/l)	0.028^{b}	0.018^{b}
T7: S (0.25g/l) + K (0.5g/l)	0.029^{b}	0.019^{ab}
T8: S (0.25g/l) + K (0.75g/l)	0.036^{a}	0.020^{a}
CV	4.73	14.81

Table 4. Physical properties of essential oils obtained from *C. officinalis* after different treatments.

Treatments	Physical properties of essential oil				
	Density	Refractive index	Color		
			A	b	L
T0: control	0.77^{a}	1.50^{a}	1.51^{a}	3.64^{a}	56.53^{a}
T1: Sulphur (S) 0.12g/l	0.80^{a}	1.48^{a}	1.51^{a}	3.64^{a}	56.53^{a}
T2: Sulphur (S) 0.25g/l	0.80^{a}	1.49^{a}	1.51^{a}	3.64^{a}	56.53^{a}
T3: Potassium (K) 0.5g/l	0.73^{a}	1.49^{a}	1.51^{a}	3.64^{a}	56.53^{a}
T4: Potassium (K) 0.75g/l	0.70^{a}	1.49^{a}	1.51^{a}	3.64^{a}	56.53^{a}
T5: S (0.12g/l) + K (0.5g/l)	0.73^{a}	1.47^{a}	1.51^{a}	3.64^{a}	56.53^{a}
T6: S (0.12g/l) + K (0.75g/l)	0.87^{a}	1.47^{a}	1.51^{a}	3.64^{a}	56.53^{a}
T7: S (0.25g/l) + K (0.5g/l)	0.73^{a}	1.48^{a}	1.51^{a}	3.64^{a}	56.53^{a}
T8: S (0.25g/l) + K (0.75g/l)	0.87^{a}	1.50^{a}	1.51^{a}	3.64^{a}	56.53^{a}

Table 5. Major, minor and trace component of essential oil of *C. officinalis* obtained from the analysis using MS-GC.

Sr. #	Retention time	Major component of essential oil of *C. officinalis* Name of component	Percentage %
1.	9.82	m-Mentha-4,8-diene, (1S,3S)-(+)-	3.369
2.	17.069	6-Heptenoic acid, 4-methylene-5-methyl-, methyl ester	3.337
3.	17.34	1-Methylene-2b-hydroxymethyl-3,3-dimethyl-4b-(3-methylbut-2-enyl)-cyclohexane	3.072
4.	19.023	9-Nonadecene	7.593
5.	19.181	Cyclopentanecarboxaldehyde, 2-methyl-3-methylene	3.272
6.	19.355	1-Pentadecene	3.92
7.	21.477	1-Pentadecene	4.148
8.	21.618	Oxirane, decyl	3.501
9.	22.398	Octadecanoic acid	2.486
10.	23.46	1-Pentadecene	2.218
11.	25.414	Hexadecanoic acid, 2-hydroxy-1-(hydroxymethyl)ethyl ester	3.547
12.	27.132	Octadecanoic acid, 2,3-dihydroxypropyl ester	4.077
13.	14.643	Silane, diazidomethylphenyl	2.941
Sr. #	**Retention time**	**Minor component of essential oil of *C. officinalis*** **Name of component**	**Percentage %**
1.	10.241	Citronellol	1.788
2.	14.335	Gamma. -Muurolene	1.015
3.	15.486	Naphthalene, decahydro-4a-methyl-1-methylene-7-(1-methylethenyl)-, [4aR-(4a.alpha.,7.alpha.,8a.beta.)]-	1.962
4.	18.35	2-Ethyl-3-methyl-6,7-dihydro-5H-cyclopenta[b]pyridine-4-amine	1.217
5.	18.658	Shyobunone	1.343
6.	19.877	Decane, 3,8-dimethyl	1.092
7.	21.129	7-Isopropyl-1,1,4a-trimethyl-1,2,3,4,4a,9,10,10a octahydrophenanthrene	1.384
8.	23.634	5,8,11,14,17-Eicosapentaenoic acid, methyl ester, (all-Z)-	1.565
9.	23.791	Ferruginol	1.122
10.	25.24	Eicosane	1.073
11.	25.532	Bis(2-ethylhexyl) phthalate	1.208
12.	26.919	Octadecane, 1-iodo	1.406
13.	28.059	Hexane, 1-bromo-6-chloro	1.346
14.	29.249	2-Thiopheneacetic acid, 4-cyanophenyl ester	1.024
15.	29.333	Cyclohexanehexanoic acid, epsilon. -oxo	1.607
Sr. #	**Retention time**	**Trace component of essential oil of *C. officinalis*** **Name of component**	**Percentage %**
1.	8.188	1,6-Octadien-3-ol, 3,7-dimethyl	0.18
2.	8.191	1-Methylcycloheptanol	0.14
3.	8.365	Phenylethyl Alcohol	0.28
4.	8.826	Bicyclo[2.2.1]heptan-2-one, 1,7,7-trimethyl-, (1S)-	0.18
5.	8.888	Bicyclo[2.2.1]heptan-2-one, 1,7,7-trimethyl-, (1S)-	0.14
6.	8.916	Bicyclo[2.2.1]heptan-2-one, 1,7,7-trimethyl-, (1S)-	0.19
7.	9	(+)-2-Bornanone	0.75
8.	9.337	3-Cyclohexen-1-ol, 4-methyl-1-(1-methylethyl)-, (R)-	0.17
9.	9.41	Isoborneol	0.34
10.	9.533	Terpinen-4-ol	0.51
11.	9.573	L- alpha. -Terpineol	0.18
12.	9.679	alpha. -Terpineol	0.31
13.	9.994	6-Octen-1-ol, 3,7-dimethyl-, (R)-	0.31
14.	10.134	2-Cyclohexen-1-ol, 2-methyl-5-(1-methylethenyl)-, cis	0.24
15.	10.376	2,6-Octadien-1-ol, 3,7-dimethyl-, (Z)-	0.14
16.	10.544	(-)-Carvone	0.24
17.	10.617	2,6-Octadien-1-ol, 3,7-dimethyl-, (Z)-	0.92
18.	11.218	Phenol, 2,3,4,6-tetramethyl	0.20

Table 5. (Cont'd.)

19.	11.28	p-Cymen-7-ol	0.24
20.	11.353	4-Hydroxy-3-methylacetophenone	0.26
21.	11.656	Dodecane, 2,6,11-trimethyl	0.20
22.	12.021	Bicyclo[3.1.1]hept-2-en-6-one, 2,7,7-trimethyl	0.14
23.	12.178	Eugenol	0.40
24.	12.178	Methyleugenol	0.51
25.	12.847	gamma. -Muurolene	0.15
26.	13.599	cis-muurola-3,5-diene	0.14
27.	13.655	Bicyclo[4.4.0]dec-1-ene, 2-isopropyl-5-methyl-9-methylene	0.26
28.	13.846	Naphthalene, 1,2,4a,5,6,8a-hexahydro-4,7-dimethyl-1-(1-methylethyl)-	0.54
29.	14.003	Hexacosane	0.50
30.	14.104	Aromandendrene	0.43
31.	14.245	Isoledene	0.19
32.	14.284	gamma. -Muurolene	0.81
33.	14.862	gamma. -Muurolene	0.28
34.	17.597	beta. -Humulene	0.38
35.	17.676	Isopulegol	0.77
36.	17.855	Bicyclo[7.2.0]undec-4-ene, 4,11,11-trimethyl-8-methylene	0.40
37.	18.765	Formic acid, (2-methylphenyl)methyl ester	0.29
38.	19.433	Docosane	0.86
39.	19.512	Bicyclo[4.1.0]heptane, 3,7,7-trimethyl-, [1S-(1.alpha.,3.alpha.,6.alpha.)]-	0.33
40.	19.574	Hexadecanoic acid, methyl ester	0.59
41.	20.803	Caryophyllene oxide	0.20
42.	20.972	Heptadecanoic acid	0.70
43.	21.017	(2-Methylphenyl) methanol, ethyl ether	0.73
44.	21.202	Heptadecanoic acid	0.39
45.	21.337	cis-5,8,11,14,17-Eicosapentaenoic acid	0.59
46.	21.668	Octadecane, 2-methyl	0.37
47.	23.1	Oxalic acid, octyl 2-phenylethyl ester	0.59
48.	23.51	6-Octen-1-ol, 3,7-dimethyl-, acetate	0.18
49.	23.701	Triacontane	0.64
50.	24.077	Heptacosane	0.46
51.	24.257	5,8,11,14,17-Eicosapentaenoic acid, methyl ester, (all-Z)-	0.58
52.	24.336	Heptadecane	0.15
53.	24.903	Cyclononasiloxane, octadecamethyl	0.35
54.	24.987	Oxalic acid, heptyl 2-phenylethyl ester	0.28
55.	25.167	Triacontyl acetate	0.24
56.	25.913	Heptacosane	0.24
57.	26.043	Hexasiloxane, tetradecamethyl	0.38
58.	26.705	Heptanoic acid, 6-oxo-, trimethylsilyl ester	0.20
59.	26.756	Propanoic acid, 3-[(2-phenylethyl)sulfonyl]-, undecyl ester	0.27
60.	26.986	2,6-Octadiene, 2,6-dimethyl	0.13
61.	27.256	1,4-Benzenedicarboxylic acid, bis(2-ethylhexyl) ester	0.21
62.	27.761	3-Methyl-2-butenoic acid, allyl ester	0.50
63.	27.823	Squalene	0.82
64.	28.266	3,4-Seco-5.alpha.-cholestan-3-oic acid, 4-hydroxy-4-methyl-, .epsilon.-lactone, (4R)-	0.26
65.	28.429	(E)-2-Isopropyl-5-methylphenyl 2-methylbut-2-enoate	0.70
66.	28.48	3-Penten-2-one, 4-bromo	0.61
67.	28.833	Carbonic acid, dithio-, S-methyl O-(2-methylcyclohexyl) ester, cis	0.68
68.	29.024	Cyclohexanehexanoic acid, epsilon. -oxo	0.91
69.	29.165	2-Thiopheneacetic acid, 4-cyanophenyl ester	0.63
70.	29.62	Propanedinitrile, cyclohexyl(2-methylcyclohexyl)-	0.46

Gas chromatography-mass spectrometry (GC-MS): The chemical composition of the essential oil extracted from the flowers of *C. officinalis* was analyzed, and the results are presented in Table 5. The analysis revealed a complex mixture of volatile compounds, highlighting the diverse phytochemical profile of the floral essential oil. A total of 98 compounds were identified in the extracted oil, indicating the rich chemical diversity of *C. officinalis* flowers. Among the identified constituents, 13 were classified as major components, contributing substantially to the overall composition of the essential oil, while 15 compounds were identified as minor components, occurring in relatively lower concentrations. In addition to these, the essential oil contained 70 trace components, representing the largest group of detected compounds. Although these trace constituents were present in very small quantities individually, their collective presence reflects the complexity of the essential oil and may contribute to its characteristic aroma, biological activity, and therapeutic potential through synergistic interactions with the major and minor constituents.

Discussion

The present study evaluated the effects of foliar application of sulfur (S) and potassium (K) on the growth, flowering, yield, and essential oil characteristics of *Calendula officinalis* (pot marigold). The findings demonstrated that the application of these essential nutrients, particularly in combination, significantly improved vegetative growth, reproductive performance, and essential oil quality compared with the untreated control. These results highlight the important role of balanced sulfur and potassium nutrition in promoting plant productivity and enhancing the commercial value of *C. officinalis*. Furthermore, the study provides valuable information for developing efficient nutrient management strategies aimed at maximizing flower yield and improving the quality of essential oil for medicinal, pharmaceutical, and industrial applications.

Vegetative parameters

Enhancing growth and development: Vegetative growth in this study was assessed using plant height, leaf number, branch number, shoot length, stem diameter, and leaf area, which are standard indicators of plant vigor and canopy development. In *Calendula officinalis*, fertilizer-driven changes in height, leaf area, and related growth traits have been used to quantify treatment effects on productivity and physiology (Kholoptseva & Kurbatov, 2024). The results indicate that sulfur and potassium fertilization positively affected plant height in *C. officinalis*, consistent with prior calendula studies showing that potassium sulfate increased plant height and that higher NPK rates increased height, leaf number, and branch number (Hashemabadi *et al.*, 2012; Parveen *et al*., 2022). Additional evidence from marigold grown in calcareous soil showed that sulfur application, combined with phosphorus and biofertilization, increased plant height, leaf number, and branch number relative to the control (Mostafa, 2023).

Leaf production also responded significantly to fertilization, suggesting improved vegetative performance and photosynthetic capacity. In kiwifruit leaves, adequate potassium increased chlorophyll content, net photosynthetic rate, stomatal conductance, and PSII efficiency, whereas low potassium weakened photochemical energy dissipation (Qian *et al.,* 2007). In calendula, potassium application increased photosynthetic intensity, plant biomass, and leaf area, supporting the view that K nutrition promotes leaf development and canopy function (Kholoptseva & Kurbatov, 2024). Sulfur likely reinforced this response through its central role in plant metabolism. Sulfur is assimilated into S-containing amino acids such as cysteine and supports the synthesis of enzymes and coenzymes required for growth. Sulfur deficiency reduces growth, leaf size, and branching, while adequate sulfur improves chlorophyll concentration, protein status, and biomass accumulation (Garai & Tripathy, 2018).

Branch number likewise increased with fertilizer treatment, indicating enhanced lateral growth and a more productive plant architecture. Sulfur applications have repeatedly increased branch numbers, leaf area index, and dry matter production in other crops (Dawar *et al.,* 2023). In calendula specifically, higher fertilizer rates increased branches per plant, and these improvements were accompanied by greater flower production and yield-related traits (Parveen *et al*., 2022).

The beneficial effects of foliar-applied sulfur (S) and potassium (K) on vegetative growth were further confirmed by the significant improvements observed in shoot length, stem diameter, and leaf area. Plants treated with the combined application of sulfur and potassium exhibited superior vegetative performance compared with the untreated control, indicating that these nutrients play a vital role in promoting plant growth and development. The enhanced shoot elongation may be attributed to improved cell division and cell expansion, while the increase in stem diameter reflects greater structural development and mechanical strength (Kholoptseva & Kurbatov, 2024). Similarly, the enlargement of leaf area suggests enhanced leaf expansion and a greater photosynthetic surface, enabling plants to intercept lighter and produce higher amounts of photosynthates necessary for growth and reproductive development. The positive response of these vegetative parameters can be explained by the complementary physiological roles of sulfur and potassium. Sulfur is an essential constituent of amino acids, proteins, vitamins, and several enzymes, thereby supporting protein synthesis, chlorophyll formation, and metabolic activities. Potassium, on the other hand, regulates enzyme activation, osmotic balance, stomatal movement, water relations, and carbohydrate translocation. When applied together, these nutrients act synergistically to improve nutrient uptake, photosynthetic efficiency, and assimilate distribution, ultimately resulting in vigorous vegetative growth and enhanced plant performance. The present findings are in close agreement with those reported by Zhao *et al*., (2025) in sunflower, who observed that the combined application of sulfur and potassium significantly improved vegetative growth characteristics, including plant height, stem development, and leaf expansion, while also enhancing flowering performance. The consistency between the present study and the findings of Mostafa (2023) suggests that the synergistic interaction between sulfur and potassium is not limited to a single crop species but is broadly effective in promoting plant growth and reproductive development. Therefore, the improved shoot length, stem diameter, and leaf area recorded in the present study can be attributed to the balanced nutritional effects of sulfur and potassium, which collectively enhance physiological processes responsible for vigorous plant growth and increased productivity.

Reproductive parameters

Accelerating flowering and enhancing yield: The investigation into reproductive parameters shed light on the effects of varying S and K dosages on the different stages of *C. officinalis* development. These findings indicate that the combined application of S and K accelerated the flowering process in *C. officinalis*. Furthermore, application of S and K demonstrated reduced flowering times, indicating the potential of these nutrients to independently influence the reproductive phase. This aligns with existing literature suggesting that both S and K play roles in flowering and reproductive development in various plant species (Hasanuzzaman, *et al.,* 2018; Ramya & Dawson, 2023).

The positive impact of S and K on flowering was complemented by increased flower numbers, diameters, and weights in specific treatments. However, it is important to note that the impact on dry matter percentage varied among treatments, suggesting a complex interaction between S and K dosages on the physiological processes of *C. officinalis*. Dry matter percentage is a critical parameter as it affects the concentration of bioactive compounds in plants, including essential oils. Further research is needed to elucidate the specific mechanisms by which S and K influence dry matter accumulation in *C. officinalis*. The present findings demonstrate that the balanced application of sulfur (S) and potassium (K) significantly enhanced the reproductive performance of *C. officinalis*, as evidenced by improvements in flowering characteristics and overall yield. The superior performance of the combined nutrient treatments suggests a synergistic interaction between sulfur and potassium, resulting in improved flower initiation, development, and productivity. These improvements may be attributed to the essential physiological functions of both nutrients in regulating plant metabolism and reproductive growth. The results of this study are in agreement with the findings of Sardans & Peñuelas (2021), who reported that potassium plays a critical role in reproductive development by promoting flower initiation, pollen viability, assimilating translocation, and fruit development. Likewise, Narayan *et al*., (2023) highlighted the importance of sulfur in the synthesis of amino acids, proteins, and secondary metabolites that are directly associated with flower formation and reproductive success. Therefore, the enhanced flowering and yield observed in the present study can be attributed to the complementary roles of sulfur and potassium in improving plant physiological processes and reproductive efficiency.

Essential oil parameters

Enhancing aromatic properties: Sulfur and potassium application influenced essential-oil-related traits, and the strongest direct calendula evidence shows that potassium sulfate increased flower essential oil content and essential oil yield relative to lower K supply (Hashemabadi *et al.*, 2012). In that study, the maximum calendula essential oil content per square meter was obtained under 300 kg/ha K_2SO_4 with square planting (Hashemabadi *et al*., 2012). Evidence from other aromatic species points in the same direction: lavender showed higher essential oil yield under K_2SO_4 than under KCl, with a calculated maximum at 206 mg dm^{-3} K (Peçanha *et al*., 2023), and hydroponic lavender reached its highest oil yield at 300 mg L^{-1} K (Chrysargyris *et al*., 2017).

The essential oil of *C. officinalis* is chemically complex, with studies identifying 27 to 66 compounds depending on plant material and extraction method (Gazim *et al*., 2008; Gudzenko *et al*., 2023). Across studies, the oil is dominated mainly by monoterpenes, sesquiterpenes, and sesquiterpene alcohols rather than a single invariant profile (Kaškonienė *et al*., 2011). Major flower volatiles reported in calendula include α-cadinol, δ-cadinene, γ-cadinene, α-muurolol, and epi-α-cadinol, while composition varies with extraction procedure, developmental stage, and geographic source (Gudzenko *et al*., 2023). It is reasonable to say that major, minor, and trace constituents likely contribute collectively to calendula oil's aroma and bioactivity, but the supplied evidence does not specifically validate the exact compounds named in the draft as the principal calendula markers. Instead, the literature supports broader statements that calendula oils show antioxidant and enzyme-inhibitory activities and that the flower pharmacology is linked in part to its volatile oil fraction (Ak *et al*., 2021). Reviews also describe *C. officinalis* as a medicinal plant with volatile oils among its major phytochemical groups and multiple reported therapeutics uses (Al-Snafi, 2015; Dhingra *et al*., 2022).

Trace constituents present at low abundance add to the chemical diversity of essential oils, which are inherently complex mixtures of volatile compounds rather than single-ingredient products (Sadgrove *et al*., 2022). Across aromatic plants, GC-based analyses routinely identify dozens of constituents per oil, including many low-abundance compounds, underscoring that minor peaks are a normal feature of essential-oil chemistry (Moetamedipoor *et al.*, 2021). In Iranian mints, each oil contained 46–64 constituents, while only ten compounds were shared among species and those common compounds together accounted for just 0.5%–3.5% of total oils, showing how small-fraction constituents can still shape overall chemical identity (Moetamedipoor *et al*., 2021). For *C. officinalis*, potassium-containing fertilization increased growth, leaf area, and photosynthetic intensity, and adding potassium sulfate further increased plant weight and leaf area (Kholoptseva & Kurbatov, 2024). Sulfur-containing fertilization in calendula also improved growth and nutrient uptake under calcareous conditions (Mostafa *et al*., 2023). Potassium is best described here as a regulator of metabolic activity, photosynthetic function, and product quality rather than as directly proven to control essential-oil biosynthesis in calendula (Kholoptseva & Kurbatov, 2024; Tellam & Joy, 2023). Trace constituents, although each present at low abundance, increase the chemical diversity of *C. officinalis* essential oil and contribute to its overall compositional profile, which is typical of essential oils that contain dozens of volatile terpenoid and related compounds (Moetamedipoor *et al*., 2021; Sadgrove *et al*., 2022). Previous work in oilseed crops shows that sulfur fertilization improves yield and quality-related traits, particularly in sulfur-deficient canola systems, while combined potassium and sulfur nutrition can improve oil content in sunflower (Malhi, 2005; Tellam & Joy, 2023). In calendula, nutrient management that includes potassium and sulfur improves growth, nutrient uptake, and productivity-related traits, supporting the use of tailored fertilization strategies to enhance the value of raw material destined for essential-oil and allied industries (Mostafa *et al*., 2023; Kholoptseva & Kurbatov, 2024).

Conclusion

In conclusion, the findings of the present study clearly demonstrate that the balanced foliar application of sulfur (S) and potassium (K) plays a crucial role in enhancing the growth, flowering, yield, and essential oil composition of *C. officinalis*. Among the tested treatments, the combined application of sulfur and potassium consistently produced superior results across most vegetative, reproductive, and quality parameters, highlighting the synergistic interaction between these essential nutrients. Improved plant vigor, increased flower production, higher flower yield, and enhanced essential oil characteristics collectively indicate that proper nutrient management is an effective strategy for maximizing the agronomic and commercial value of *C. officinalis*. The outcomes of this research emphasize the importance of developing crop-specific nutrient management practices that are tailored to the physiological requirements of medicinal and aromatic plants. Optimizing sulfur and potassium fertilization not only improves crop productivity but also enhances the quality and quantity of essential oils, thereby increasing the economic value of the crop for growers and industries involved in the production of pharmaceuticals, cosmetics, nutraceuticals, and natural health products. Although the present study provides strong evidence supporting the beneficial effects of sulfur and potassium nutrition, further investigations are recommended to elucidate the physiological, biochemical, and molecular mechanisms responsible for these improvements. Future research should also focus on evaluating different nutrient concentrations, application schedules, environmental conditions, and cultivation systems to establish the most efficient fertilizer recommendations for maximizing both biomass production and essential oil quality.

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