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Research article

Lemongrass (*Cymbopogon flexuosus*) growth rate, essential oil yield and composition as influenced by different soil conditioners under two watering regimes

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ABSTRACT

The vast cultivation of lemongrass (*Cymbopogon flexuosus*) as an essential oil-bearing plant worldwide relies heavily on its compound citral that holds immense industrial potential. Soil fertility practices greatly affect the growth and quality of these plants, with a majority of the agricultural land globally grappling with water scarcity. In this respect, field experiments were conducted at the University of Embu research farm during the November 2021–September 2022 growing period and aimed to investigate the influence of two different factors, namely; (i) two watering regimes (rainfed and irrigated) and (ii) four soil conditioner levels (control (T1), cow manure (T2), cow manure plus NPK fertilizer (T3), and NPK fertilizer alone (T4)) on the growth and essential oil parameters of *C. flexuosus*. The field trials were arranged in a split-plot design with three replicates for each treatment. The essential oil from *C. flexuosus* was obtained using steam distillation method and analyzed for quality using gas chromatography with mass spectrometry (GC-MS) technique. Results revealed that treatments T4 and T3 improved the growth of *C. flexuosus* under rain-fed conditions, implying the plant's sensitivity to soil fertility practices and watering regimes. Herbage from rain-fed plants harvested after 120 days had high oil content, ranging from 0.17 to 0.23 %, while herbage from irrigated plants harvested after 180 days had the lowest oil content, ranging from 0.11 to 0.17 %. Using GC-MS, the main components of *C. flexuosus* oil were citral (75.97–87.70 %), geranyl acetate (0.80–4.91 %), geraniol (0.80–4.26 %), isogeranial (1.83–3.45 %), and isoneral (1.29–2.78 %). Notably, citral, a racemic mixture of geranial and neral, was found in a high concentration (87.70 %), meeting the acceptable international market standards for its use. Altogether, the major oil compounds, oil yield and growth properties of *C. flexuosus* in this experiment differed as a function of different soil conditioners under the two watering regimes, and so with the time scale. The outcomes of this research highlight implications for enhancing and bolstering the production of high-value lemongrass oil in Kenya, where it holds potential significance as a vital economic and export-oriented crop.

1. Introduction

Lemongrass (*Cymbopogon flexuosus*) is an aromatic perennial grass belonging to the Gramineae family and possessing enormous

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industrial potential [1]. The genus *Cymbopogon* is well-documented to yield essential oils of high quality that are widely applied in perfumery, food industries, cosmetics, soaps, deodorants and pharmaceutical products. Specifically, *C. flexuosus* is considered one of the primary species extensively cultivated in different regions of the globe owing to its essential oil's high citral concentration, which ranges between 65 and 85 % [2], but may vary because of myriad of factors like plant species, altitude and climatic conditions. Endemic to India, *C. flexuosus* is largely grown in several countries, including China, Indonesia, Mexico, Madagascar, Brazil, Haiti and Dominica [3]. Further, it has a broad distribution in subtropical and tropical zones across Africa, America and Asia. The *C. flexuosus* leaves and stems are mainly used in making soups, herbal teas, curries and beef products [4].

Lemongrass is also a valuable agricultural export crop that contributes substantially to both income generation and the inflow of foreign currency [5]. The lemongrass industry presents opportunities for research in cultivation, bioactive compounds, genetic diversity and post handling [6]. The market size and distribution of medicinal and aromatic plants (MAPs), including *C. flexuosus* differs vastly from region to region as well as from country to country, while the market gap includes value-added products, sustainable sourcing, quality control, and market penetration. These variations are driven by multiple attributes, such as culinary, industrial applications, different agricultural practices, ambiguous policies, plant distribution, overexploitation, topography and weather [7]. Addressing these gaps can contribute to the further growth and development of the lemongrass industry. The global market of MAPs is growing at a projected annual rate of 10–20 %, expected to reach around $5–7 trillion by 2050 [8]. However, 80 % of MAPs imports and exports are controlled by 12 countries, predominately in Europe and Asia. China leads in MAPs exports, accounting for 15 % globally, while India occupies second position with only a 0.5 % contribution [7]. In Africa, the MAPs trade is dominated by Egypt and Morocco.

The *C. flexuosus* exhibits variation in essential oil composition and morphological traits at inter- and intra-specific levels [9]. Previous work has demonstrated that although *C. flexuosus* can persist in a wide array of climatic conditions and soil types, optimum growth is achieved on well-drained sandy loam soil characterized by adequate sunshine and high soil fertility [3,10]. The plant is often grown as a ratoon crop, where the initial cuts occurs four to six months after planting, with subsequent cuts following at intervals of two to three months, contingent on ecological conditions and management practices at the cultivation site [11]. The harvesting of leaves and stalk is implemented by cutting at very near the ground level [12].

The chemical compositions and potential applications of essential oils from various *Cymbopogon* species, including *C. flexuosus*, have undergone extensive investigation [11,13]. The accumulation and biosynthesis of essential oils in *Cymbopogon* species primarily occur in young and rapidly growing leaves [14]. Specifically, the oil of *C. flexuosus* tends to accumulate in oil cells situated within parenchymal tissues [13,15]. The *Cymbopogon* oils are typically obtained from either fresh or dried herbage by the use of hydro- and steam-distillation techniques among other extraction methods [16]. The most frequently utilized analytical method for the essential oil analysis of *Cymbopogon* is gas chromatography-mass spectrometry (GC-MS) [17], followed by the supercritical fluid extraction gas chromatography [18]. More recently, the analysis of essential oil compositions has been further enhanced through the development of high-performance liquid chromatography coupled with gas chromatography (HPLC-GC) [19]. The *C. flexuosus* oil is largely composed of citral (65–85 %) [20]. Other major compounds of the oil include geraniol, citronellal, citronellol, geranyl acetate, nerol, alpha-pinene, limonene, linalool, caryophyllene and methyl heptanone [14,21]. In industry, essential oils of *Cymbopogon* are employed in fragrance, perfumery, food, pharmaceutical products and biofuel [2,11,22]. The oil is also applied for the β-ionones, beta-carotene and vitamin A syntheses, particularly from the citral compound [23]. Besides these benefits, *Cymbopogon* oils display multiple bio-activities, namely but not limited to anti-fungal, anti-oxidant, anti-cancer, anti-bacterial, anti-inflammatory, anti-viral, anti-parasitic and larvicidal [2,23,24].

Aromatic plants, including *Cymbopogon* species can be categorized by analyzing the ecological conditions in which they are cultivated and harvested [16,21]. The growth and oil production of *Cymbopogon* species is affected by several environmental factors, such as water, soil fertility practices, temperature and harvesting time [25]. Lemongrass is traditionally cultivated as a rainfed crop in high-rainfall areas. The plant, however, grows well under irrigation in semi-arid conditions for optimal growth [26]. Importantly, lemongrass irrigation requirements vary from one ecological region to another relying on the status of soil fertility, climatic conditions and soil type [27]. A study conducted on *C. flexuosus* revealed that increasing the irrigation level to a ratio of 0.75 of Irrigation water to Cumulative pan evaporation (IW: CPE) resulted in a notable increase in plant height, number of stalks, stalk width, number of branches, and stalk yield. Additionally, applying a nitrogen rate of 150 kg ha^{-1} considerably increased plant height and stalk yield [26]. Singh [28] apprised that maintaining soil moisture levels at a ratio of 0.75 IW: CPE resulted in a marked increase in plant height, leaf area index (LAI), herbage yield, and oil yield compared to those plants maintained at ratios of 0.25 and 0.50 IW: CPE. Moreover, applying a nitrogen rate of 100 kg ha^{-1} produced the maximum yield, but oil quality and quantity were not influenced by nitrogen levels and irrigation in the same study. In another study, *C. citratus* amended with compost (8 ton/fed) and 75 % NPK combined with effective micro-organisms and yeast recorded the greatest growth and essential oil values [29]. Supplying appropriate nutrients is vital for the healthy growth of all crops, including medicinal plants that produce essential oils. Utilizing proper fertilization techniques can greatly boost the quantity and quality of the essential oils these plants generate as well as their growth and development [30,31]. Currently, the integrated provision of nutrients to plants by combining both inorganic and organic sources is gaining prominence as an essential component of environmentally sustainable farming practices. Despite numerous research efforts in this area, it is crucial to emphasize the existing research gap regarding the effects of organic fertilizers on the components and production yields of lemongrass oil.

Lemongrass (*C. flexuosus*) production under different soil fertility practices and watering regimes has not been extensively investigated in Kenya since its introduction around the 1940s [32]. This has resulted in an absence of clarity among producers regarding the production and economic efficiency of lemongrass. With this background, this study aimed to investigate the influence of two different factors: (i) two water application regimes (rainfed and irrigated plots) and (ii) four soil conditioner levels (control plots (without any amendment), cow manure, cow manure plus NPK fertilizer, and NPK fertilizer alone) on improving the growth and essential oil parameters of *C. flexuosus* in the upper midland 2 agro-ecological zone. The outcomes of this research would carry implications for enhancing and boosting the production of high-value lemongrass oil in Kenya, where it holds potential significance as a crucial economic and export-oriented crop.

2. Materials and methods

2.1. Description of the study site

The present study was carried out at the University of Embu research farm ((longitude, 0° 35′ 25″ S) and (latitude, 37° 25′ 31″ E)) during the November 2021–September 2022 growing period. The farm is positioned at an altitude of 1494 m above sea level and falls within the upper midland 2 agro-ecological zone. The average annual rainfall received in this area is 1230 mm, and the rainfall pattern occurs in two phases with long rains occurring from March to June and short rains occurring from October to December. The monthly average temperature in the area is 19.5 °C, with maximum and minimum temperatures of 25 °C and 14 °C, respectively, as reported by Jaetzold [33]. The main soil type in the area is classified as *humic Nitisols*, characterized by deep, moderately to high inherent fertility, and highly weathered with friable clay [34]. The soil chemical properties of the study site is composed of soil pH (5.94), total nitrogen (0.19 %), phosphorus (0.98 mg kg^{-1}) and potassium (30 mg kg^{-1}) [35], and available nitrogen (2013 mg kg^{-1}) [36].

2.2. Field experimental trials and design

Well-developed (two months old) lemongrass cuttings (*Cymbopogon flexuosus* variety Krishna), propagated on site under phytosanitary conditions, were used for field trial establishment. The experiment consisted of two different factors namely; (i) two watering regimes (rainfed and irrigated) or hard-to-change factors [37] and (ii) four soil amendments or easy-to-change factors [37], including control (without any amendment) (T1), amendment with cow manure (T2), amendment with cow manure plus fertilizer (T3), and amendment with fertilizer alone (T4). Plots were amended with recommended doses of cow manure at a rate of 4640 kg ha^{-1} [38] and/or with NPK fertilizer at a rate of 300 kg ha^{-1} [39] at planting. After four months, an additional dose of the same treatments was applied to the respective treatments. Two-month lemongrass cuttings of around ±29.9 cm in length were transplanted in field plots arranged in a split-plot design, whereby each treatment was replicated three times making a total of 24 plots. Each plot, measuring 5 m by 5 m, comprised 5 rows with 10 plants within each row. Plants were spaced at 50 cm within a row and 100 cm between rows. By spot watering (flooding of the basin around the plant), the first irrigation was done immediately after transplanting, followed by irrigation twice per week depending upon weather conditions to the corresponding plots. Weed management was implemented uniformly across the plots by use of a hand-hoe once a month or whenever necessary [40]. A schematic framework illustrating the relationships between the study variables is given (see Fig. 1), while pictures of the field where lemongrass was grown are shown in Fig. 2.

2.3. Agronomic data collection

At two periods, data was collected at planting ((0 days), 30, 60, 90, 120 and 180 days). Plant data was collected from 10 randomly selected plants per plot. In particular, plant height (PHT), number of tillers per plant (NOT), and number of leaves per plant (NOL) were assessed. Plant height (cm) was determined using a tape measure from the surface of the soil to the point of the arch of the topmost leaf

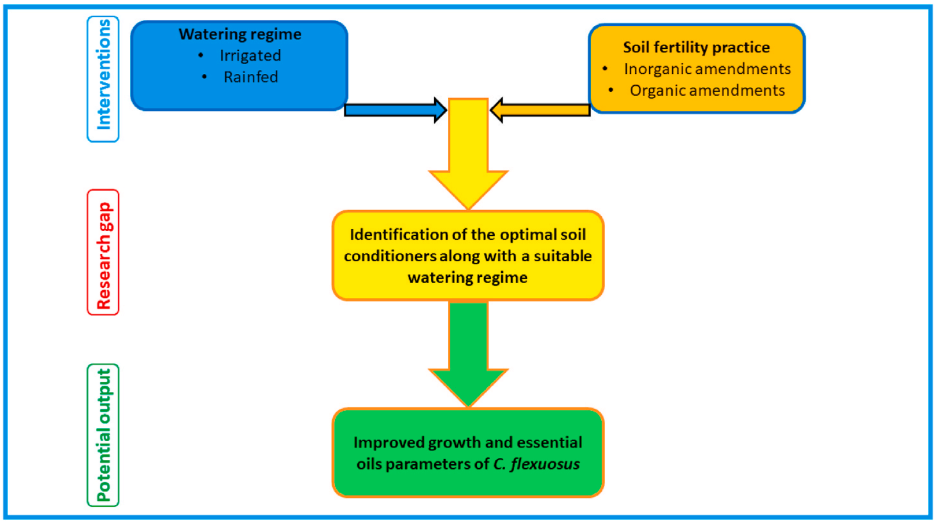

Fig. 1. Schematic representation visualizing how the study variables are interconnected.

Fig. 2. Lemongrass field view.

whose tip was pointing down [41]. The number of tillers and leaves per plant was examined by a visual count of the functional tillers and leaves as described by Yeshitila [41].

2.4. *Essential oil content and composition analysis*

2.4.1. *Determination of essential oil content*

Fresh lemongrass herbage consisting of the leaves and part of the stalk from the central rows of a field plot was cut very near the ground level at 120 and 180 days after transplanting (DAT), and immediately weighted using a balance according to Linares et al. [12]. The essential oil to be used for composition analysis and oil content determination was recovered from freshly harvested herbage using the steam distillation method. A 5 kg of fresh leaves plus stalks of lemongrass were steamed with 7 L of tap water for 2 h or until no oil was collected from the condenser of the steam distiller (model 10-15-20 gallon capacity, HeartMagic Essential Oil Distillers, US). The mode of heating was done using liquefied petroleum gas (LPG). At the end of each distillation, the oil was separated and subsequently weighted on an analytical balance (Model BP3003B Biobase). The yield (%, w/w) of oil extracted for every run was computed using Eq. (1) as outlined by Ranitha et al. [42]. After extraction, the essential oils were stored in amber flasks at −20 °C awaiting further analysis. The extraction was repeated three times.

$$\text{Essential oil content} \ (\%, \text{w}/\text{w}) = \frac{\text{Weight of extracted oil (g)}}{\text{Weight of fresh sample (g)}} \times 100 \tag{1}$$

2.4.2. *Herbage yield*

The herbage yield was determined by harvesting from the inner rows of the plots as explained in section 2.4.1, followed by weighing the material and then dividing the mass by the harvested area. The herbage yield is then reported in kg ha^{-1}.

2.4.3. *Oil yield*

To determine the oil yield in kg ha^{-1}, the obtained oil content in section 2.4.1 was multiplied by herbage yield (kg ha^{-1}) from section 2.4.2 following the protocol by Singh et al. [40].

2.4.4. *Determination of essential oil composition*

The identification of lemongrass oil constituents was evaluated using Gas chromatography with mass spectrometry (GC-MS - QP2010SE) by the Shimadzu corporation, and SLB - 5MS fused silica capillary column (30 m × 0.25 mm, film thickness 0.25 μm). A 25 μL of lemongrass was mixed in 1 mL n-hexane. The GC-MS system was operated under the following conditions: carrier gas (helium), flow rate (1.0 mL/min), split ratio (1:50), injection temperature (200 °C), and injection volume (1.0 μL). Then, the oven temperature was maintained at 60 °C for 1 min, followed by 60–250 °C at a rate of 10 °C/min for 25 min. The GC-MS solution software version 4.45 (Shimadzu, Kyoto, Japan) was used to acquire data, while bi-dimensional visualization was generated using Chromsquare software version 2.3. The NIST Chemistry WebBook (https://webbook.nist.gov/chemistry/#) and PubChem (https://pubchem.ncbi.nlm.nih.gov/) databases were employed for the characterization of lemongrass essential oil components.

2.5. Statistical analysis

To explore the influence of treatments on plant height, number of tillers per plant, number of leaves per plant and essential oil yield and composition, the data was subjected to analysis of variance (ANOVA) using the R vegan package [43]. Data transformation via arcsine was performed where necessary to meet the assumptions of normality before statistical analysis. To account for variation between these factors, the Turkey HSD test was performed using R package agricolae [44]. The results are presented in graphs and differences at $P < 0.05$ were regarded as significantly different.

3. Results and discussion

3.1. Response of *C. flexuosus* to soil conditioners under two watering regimes

The results of the influence of different treatments on NOT, NOL and PHT are presented in Figs. 3–5, respectively. All the three parameters generally increased with the advancement of crop age. At 120 DAT, the NOT, NOL and PHT of plants under irrigation ranged from 34.1 to 67.7, 164.4–344.4 and 60.8–66.2 cm, respectively, while the values under rain-fed conditions varied from 40.6 to 95.4, 192.9–335.7 and 61.13–71.5 cm, respectively. These findings are comparable with those of previous related studies such as that of Mahmoud et al. [45] who recorded values of NOT of *C. citratus* ranging from 17.0 to 147.0 with irrigation intervals at 5, 10, 15 and 20 DAT in Egypt, while Singh et al. [26] observed 39–45.6 NOT and 81.2–122.4 cm PHT in *C. flexuosus* grown under irrigation levels (0.3, 0.5 and 0.8 IW: CPE ratio) with four different application rates of nitrogen in India. Shahi et al. [46] revealed a PHT range of 35.7–166.7 cm and 16.0–90.0 NOT of *C. flexuosus* under different organic and inorganic soil amendments in India. Mahmoud et al. [47] reported between 11.5 and 173.8 NOL of *C. citratus* due to various water intervals and NPK fertilizer application in Egypt. However, the inconsistency among these studies might depend on different harvesting times, soil conditioners and plant species.

The biggest change in both the NOT and NOL occurred in the last 30 days (90–120 DAT), with the highest difference being due to soil amendments and only minor differences due to the watering regimes (Figs. 3 and 4). It was also apparent that between 0 and 60 DAT across different soil conditioners and under the two watering regimes, there was suppressed growth of plants with respect to NOT and NOL, while there was an accelerated development in all three growth indices thereafter (Figs. 3–5).

In particular, the NOT of plants grown under both irrigation and rain-fed conditions was significantly lower in T1 than in the other three amendments for the growing period of 60–120 DAT. However, under the rain-fed production, NOT was higher in T3 on 30, 90 and 120 DAT than both T2 and T4 (Fig. 3). These results indicates that the synergistic effects of cow manure combined with the NPK fertilizer (T3) supported by rainfall were able to attain the maximum NOT of *C. flexuosus*. Organic amendment such as cow manure provides a valuable source of nutrients to the soil, which can enhance the plant's overall health and vigor [48]. While the NPK fertilizer contain mineral macronutrients N, P and K that perform counter roles in enhancing plant's vegetative growth characteristics and are pivotal for plant development and quality enhancement [49]. In addition, coupling manure and NPK fertilizer can provide a balanced nutrient supply to lemongrass, promoting better tiller development. Shahi et al. [46] found poultry manure and vermicompost to be superior in boosting high NOT of *C. flexuosus* as compared with other treatments in India. However, a combination of NPK fertilizer with farmyard manure showed no substantial difference on NOT when compared to the other treatments in the same study. The

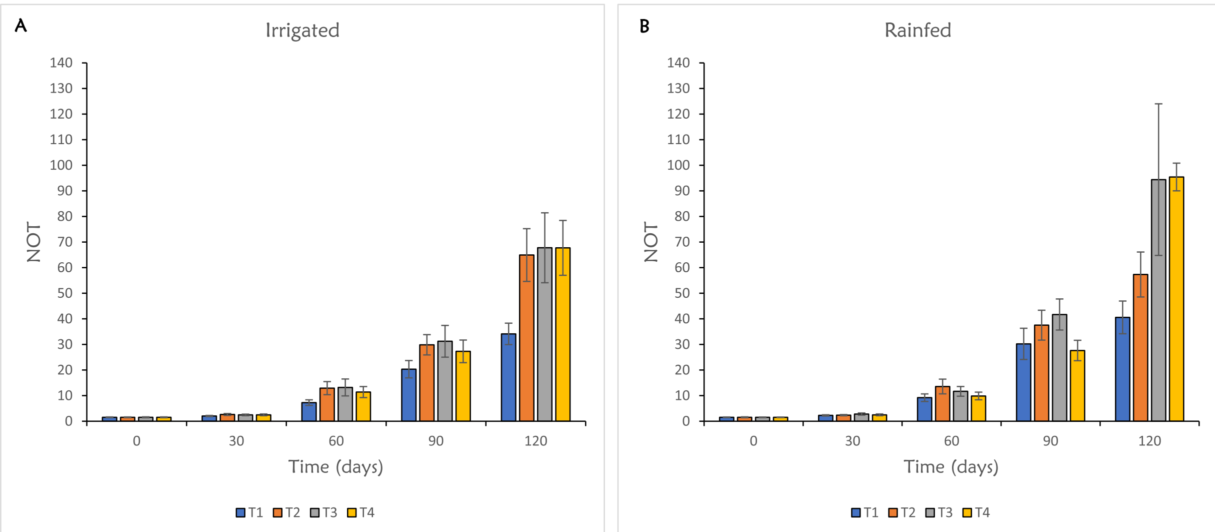

Fig. 3. The mean number of tillers (NOT) per plant of *C. flexuosus* at various stages of growth and grown under two watering regimes (irrigated twice a week (A) and rainfed (B)) and four soil amendments (T1, control; T2, amendment with cow manure; T3, amendment with cow manure plus NPK fertilizer; and T4, amendment with NPK fertilizer alone).

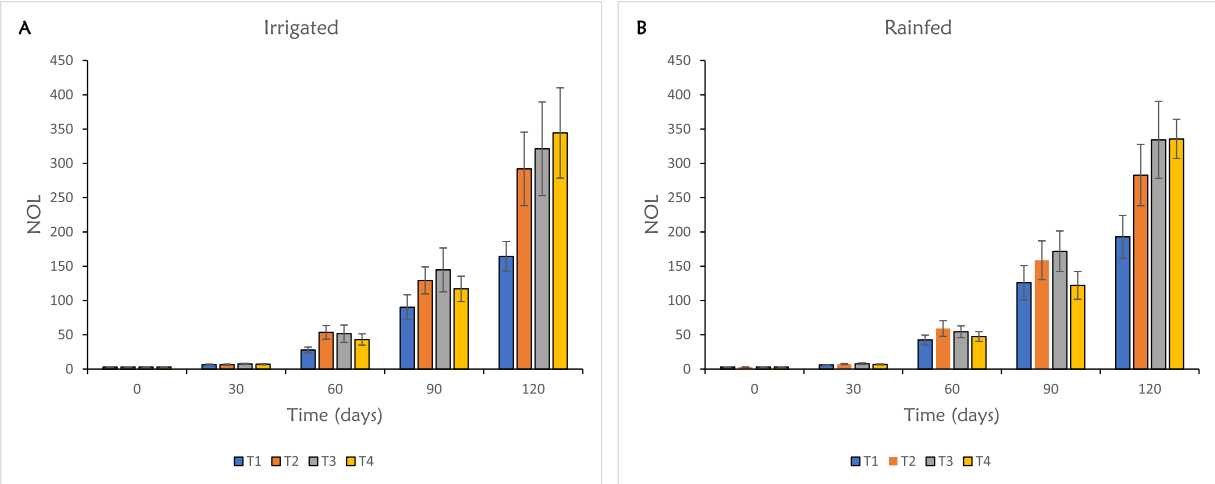

Fig. 4. The mean number of leaves (NOL) per plant of *C. flexuosus* at various stages of growth and grown under two watering regimes (irrigated twice a week (A) and rainfed (B)) and four soil amendments (T1, control; T2, amendment with cow manure; T3, amendment with cow manure plus NPK fertilizer; and T4, amendment with NPK fertilizer alone).

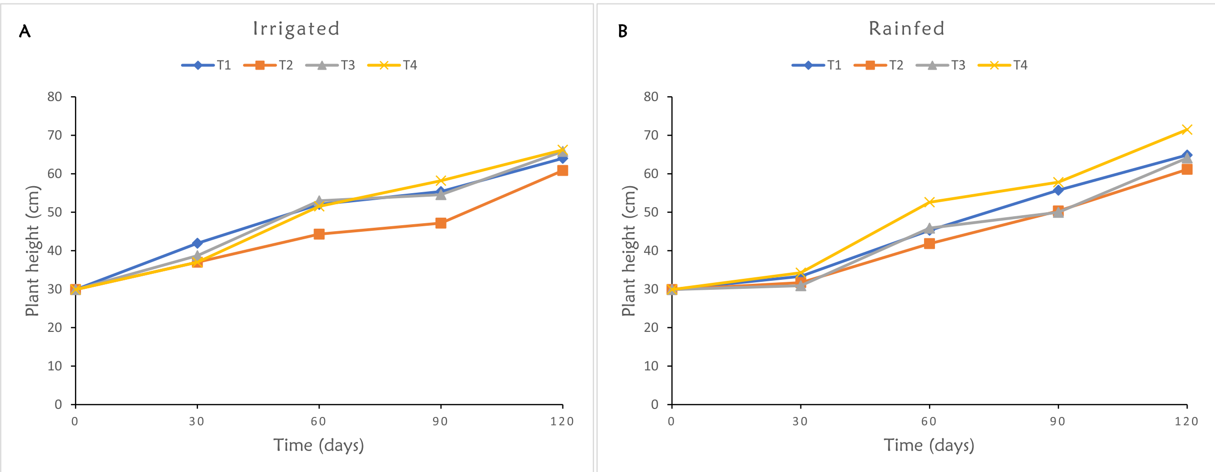

Fig. 5. The mean plant height of *C. flexuosus* at various stages of growth and grown under two watering regimes (irrigated twice a week (A) and rainfed (B)) and four soil amendments (T1, control; T2, amendment with cow manure; T3, amendment with cow manure plus NPK fertilizer; and T4, amendment with NPK fertilizer alone).

discrepancy between these two studies perhaps could be attributable to various factors, such as ecological conditions, rainfall and soil conditioners [25,50].

The highest mean NOL was observed on 120 DAT with the NPK fertilizer (T4) being marginally higher than T3 when growing the crop under both irrigation and rain-fed production (Fig. 4). This outcome aligns with the existing information by Gajbhiye et al. [51], which demonstrates a notable increase in the leaf count per lemongrass clump due to the NPK fertilizer application. The NPK fertilizer compose of three essential macronutrients, including N, P and K, where N plays a significant role as a primary constituent of enzymes, amino acids and vital energy carriers like ATP and chlorophyll [52]. Phosphorus is crucial for key cellular processes, including glucose metabolism, bio-oxidation, photosynthesis and cell division [53]. Additionally, potassium exhibits a synergistic relationship with carbohydrates, acting as an osmotic regulator [52]. In essence, these three macronutrients work in harmony, with nitrogen nurturing green growth, phosphorus tending to reproduction and roots, and potassium coordinating the plant's equilibrium and fortitude. Together, they form the foundation upon which a flourishing and resilient plant thrives. Also, the NOL was higher in plants grown under irrigated condition compared to those grown under the rain-fed growing condition (Fig. 4). A study by Mahmoud et al. [47] associated a high number of leaves per hill of *C. citratus* with irrigation after every five days and 100 % NPK input.

The PHT of plants growing under all soil conditioners increased steadily with age to reach maximum values at 120 days for both rain-fed and irrigated conditions (Fig. 5), and there was no significant difference ($P > 0.05$) that could be attributed to soil amendment or watering method. On the contrary, Ultra [54] found that lemongrass height was markedly augmented by the input of NPK fertilizer (rate 120 kg N ha^{-1}, 90 kg P_2O_5, and 90 kg K_2O kg ha^{-1}) under regular irrigation during the whole growing period. In addition, the plant height of *C. citratus* and *C. flexuosus* was greatly improved due to NPK fertilization at various application rates [29,55]. In the current study, however, there was no significant difference in PHT between different treatments at 30, 60, 90 and 120 days under the two watering regimes.

3.2. Essential oil content (%, w/w) of *C. flexuosus*

The oil yield content from herbs can be affected by diverse features, including weather, soil management practices, irrigation, the quality of herbage distilled and season [25,56]. Altering the frequency of irrigation as well as the NPK fertilization levels can influence the plant's metabolic processes, potentially leading to an elevation in metabolite levels, especially carbohydrates. These carbohydrates serve as the building blocks for oil production, a phenomenon that has also been observed in the case of lemongrass [47]. The average essential oil content from herbage harvested at 120 and at 180 days after transplanting (DAT) and recovered from the herbage using the steam distillation method is depicted in Fig. 6. Oil content of plants grown under rain-fed conditions and harvested at 120 DAT varied markedly ($P = 0.006$) from a low of 0.17 % in T3 treatments to a high of 0.23 % in T4 treatments. This is comparable to oil values of *C. flexuosus* ranging from 0.05 to 1.70 % and from 0.17 to 0.24 % reported in India [4] and in Kenya [57], respectively. Conversely, relatively higher values of *C. flexuosus* essential oil content under various soil nutrient management have been documented when compared to values of this study (0.17–0.23 %). For instance, values of 0.39–0.55 % oil yield content was obtained in Mississippi [31], 0.65 % in Colombia [58], and 0.67–0.86 % in India [59]. The variation in these findings might be attributable to multiple factors, including rainfall, soil fertility practices, temperature and climatic conditions [25] or efficiency of the distiller. The oil content for materials harvested at 180 DAT under rainfed conditions ranged from a low of 0.15 % in plots treated with T3 to a high of 0.19 % in plots treated with T4 ($P = 0.035$). These findings are analogous with values observed at 120 DAT as previously described in this study.

Comparing the oil content of materials harvested at 120 DAT (0.17–0.23 %) and the oil content of materials harvested on 180 DAT (0.15–0.19 %), it is noted that the oil content was lower in all conditions of either soil amendment (except for T3) or watering regimes for the 180 DAT harvest (Fig. 6). For irrigated plants and amended with manure and fertilizer (T3), the oil content remained constant for the two harvests. The findings of Zheljazkov et al. [31] in Mississippi, however, indicated higher oil yield in nitrogen input at rates of 40 or 80 kg ha^{-1}. On the other hand, Singh et al. [60] demonstrated that the oil yield content of *C. flexuosus* cultivated under various levels of N, P and K fluctuated at different harvesting intervals, with the highest yield being recorded during the first cut. A similar trend was observed in the current study with oil yield obtained from various treatments under irrigation, although not significantly different ($P > 0.05$) in both harvesting intervals (Fig. 6).

3.3. Herbage yield (kg ha^{-1}) of *C. flexuosus*

The mean values of fresh herbage yield of *C. flexuosus* across different treatments under irrigation and rainfed conditions and harvested at 120 and 180 DAT are presented in Fig. 7. It is evident that the yield for all plots under rain-fed conditions is significantly higher than the yield of plants receiving the same soil amendment but growing under irrigation, which is also the case for both the first and the second herbage cut. During the first harvest (120 DAT), the yield of 14,200 kg ha^{-1} in T4 was significantly ($P = 0.001$) higher than that of 11,800 kg ha^{-1} in T3 for materials grown under irrigated conditions. The plants grown under rainfed conditions had the highest herbage yield of 15,480 kg ha^{-1} in T4 and the lowest yield was 13,440 kg ha^{-1} in T2, although the difference was not

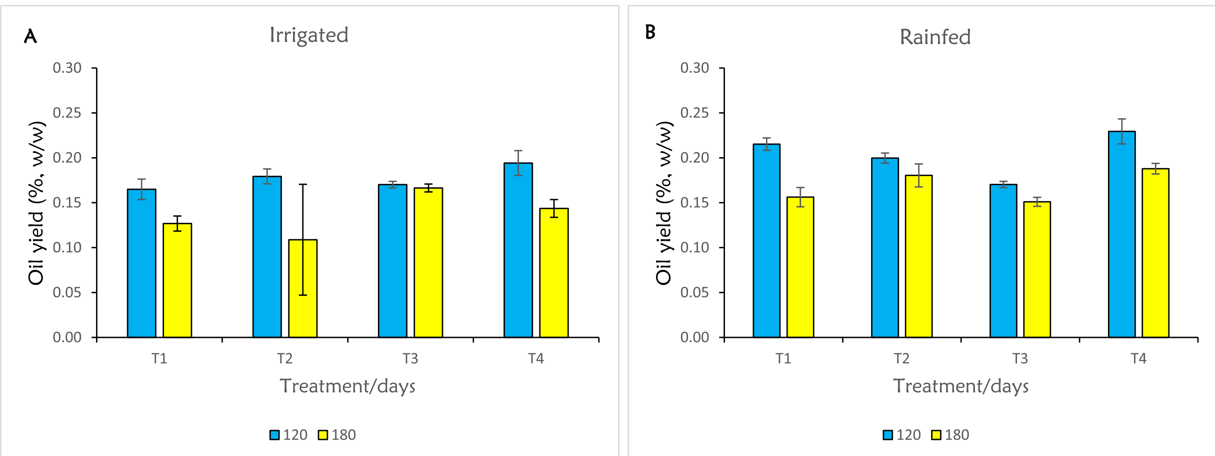

Fig. 6. Essential oil content (%, w/w) of *C. flexuosus* plants grown under two watering regimes (irrigated twice a week (A) and rainfed (B)) and four soil amendments (T1, control; T2, cow manure; T3, cow manure plus NPK fertilizer; and T4, NPK fertilizer alone) at first harvest (120) and second harvest (180) days after transplanting.

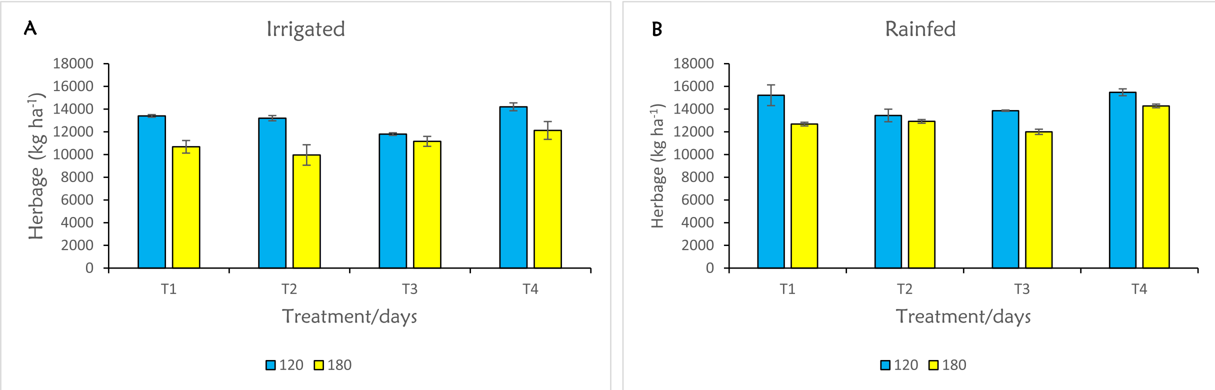

Fig. 7. Herbage yield of *C. flexuosus* grown under two watering regimes (irrigated twice a week (A) and rainfed (B)) and four soil amendments (T1, control; T2, cow manure; T3, cow manure plus NPK fertilizer; and T4, NPK fertilizer alone) at first harvest (120) and second harvest (180) days after transplanting.

statistically significant. These findings corroborate with the results reported previously by Singh et al. [60] and Thakur et al. [61].

In the second harvest (180 DAT) (Fig. 7), there was a slight decrease in the herbage yield under both watering regimes, with maximum yield observed with the NPK fertilizer (T4) application. This phenomenon perhaps could be linked to the short growth duration (120–180 DAT), as well as the mineral macronutrients N, P and K from the NPK fertilization that perform crucial roles in enhancing plant's vegetative growth characteristics and are crucial for plant development and quality enhancement. Similarly, Singh et al. [60] found no response in lemongrass herbage yield to various amendments until the second year. For plants grown under rain-fed conditions, herbage yield was a high of 14,280 kg ha^{-1} in T4 and a low of 12,000 kg ha^{-1} in T3, while the plants grown under irrigated conditions had the highest yields of 12,120 kg ha^{-1} in T4 and the lowest yield of 9960 kg ha^{-1} in T2. These values are comparable to previously reported figures by Mwithiga et al. [57] and Singh et al. [40].

3.4. Essential oil yield (kg ha^{-1}) of C. flexuosus

The computed essential oil yield in kg ha^{-1} is presented in Fig. 8. The yield was higher in plots treated with NPK fertilizer (T4) application under both watering systems at 120 DAT (Fig. 8). The oil yield values ranged from a high of 131.28 kg ha^{-1} in T4 to a low of 100.42 kg ha^{-1} in T3 under irrigation, while with rainfed crop production, the oil yield values ranged between 189.70 kg ha^{-1} in T4 to 118.02 kg ha^{-1} in T3. These results agree with the reports by Singh et al. [60] who recorded 165.80–399.20 kg ha^{-1} of *C. flexuosus* oil yield under different N and P concentrations.

At 180 DAT, the oil yield values in this study slightly declined with higher mean values obtained in the T4 amendment (Fig. 8). Reduced essential oil yield is correlated with diminished herbage yield [31]. Another possible reason for this decline could be attributed to depressed rains during this season.

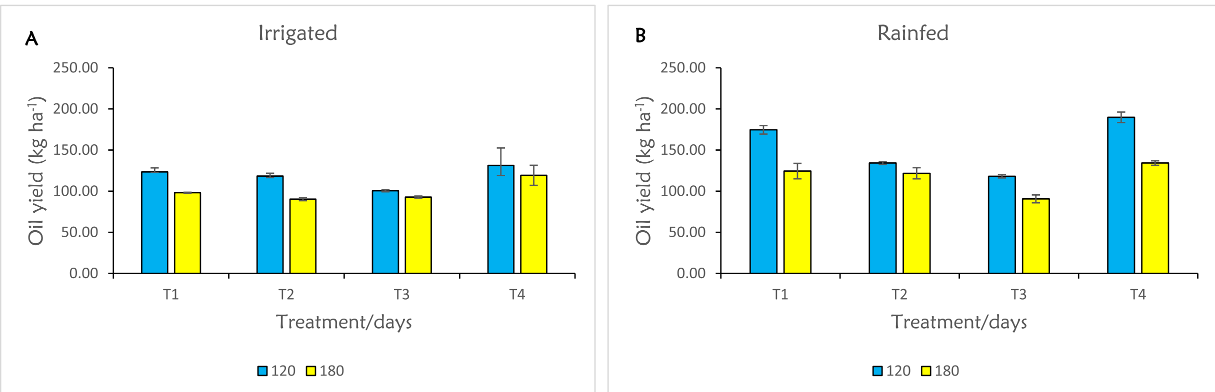

Fig. 8. Essential oil yield (kg ha^{-1}) of *C. flexuosus* grown under two watering regimes (irrigated twice a week (A) and rainfed (B)) with different sources of soil amendments (T1, control; T2, cow manure; T3, cow manure plus NPK fertilizer; and T4, NPK fertilizer alone) at first harvest (120) and second harvest (180) days after transplanting.

3.5. Chemical composition of essential oil of *C. flexuosus*

The composition of essential oils extracted from herbage harvest after 120 days of transplanting (DAT), and analyzed using the GC-MS method is tabulated in Table 1 (Irrigated block) and Table 2 (Rainfed block). The constituents are listed in the order of increasing retention time of each compound. At 120 DAT, a total of 62 compounds were identified in the oil obtained from crops grown under different soil amendments and under rain-fed conditions (Table 2), which is a relatively higher number than the 48 compounds identified in the oil from plants grown under similar soil amendment conditions but under irrigation (Table 1). The oils of plants grown under irrigated conditions and from treatments T3 and T1 had 42 and 40 compounds, respectively, while oils from treatments T2 and T4 plots had 36 and 34 compounds, respectively. Under the rain-fed production, T4 had the highest mean number of oil constituents (40), followed by T2 (38), while the lowest was noted in both treatments T1 (35) and T3 (35). This indicates variation in the number of oil compounds with respect to changes in watering regime across different soil conditioners. Mahmoud et al. [45] showed that the

Table 1
The percentage composition of the different compounds and the total number of compounds found in the essential oils of *C. flexuosus* extracted using steam distillation and analyzed using the GC-MS method. The herbage was from plants grown under four levels of soil amendments (T1, control; T2, cow manure; T3, cow manure plus NPK fertilizer; and T4, NPK fertilizer alone) and irrigated for 120 days from transplanting to harvesting.

	Irrigated					
Peak no.	Component	T1	T2	T3	T4	*P*-value
1	3-Carene	0.05 ab ± 0.003	0.06a ± 0.017	0.05 ab ± 0.026	0.00b ± 0.000	0.031*
2	Camphene	0.33a ± 0.029	0.49a ± 0.199	0.44a ± 0.225	0.06a ± 0.032	0.139
3	1-Octyn-3-ol	0.01a ± 0.006	0.00a ± 0.00	0.00a ± 0.000	0.00a ± 0.000	0.063
4	Sulcatone	0.61a ± 0.098	0.40 ab ± 0.003	0.47 ab ± 0.038	0.38b ± 0.006	0.042*
5	Octanal	0.17a ± 0.000	0.11bc ± 0.012	0.14 ab ± 0.003	0.08c ± 0.017	0.005**
6	D-limonene	0.11a ± 0.017	0.13a ± 0.038	0.10a ± 0.055	0.02a ± 0.012	0.214
7	*trans*-β-Ocimene	0.22a ± 0.003	0.27a ± 0.017	0.15a ± 0.087	0.17a ± 0.026	0.391
8	alpha-Pinene	0.06 ab ± 0.009	0.07 ab ± 0.038	0.14a ± 0.003	0.00b ± 0.000	0.009**
9	2-Hexyl hydroperoxide	0.17a ± 0.098	0.29a ± 0.020	0.13a ± 0.072	0.13a ± 0.072	0.549
10	3-Hexyl hydroperoxide	0.14a ± 0.081	0.23a ± 0.017	0.10a ± 0.058	0.11a ± 0.061	0.564
11	Eucalyptol/1,8-Cineole	0.03a ± 0.014	0.00a ± 0.000	0.00a ± 0.000	0.00a ± 0.000	0.062
12	beta-Ocimene	0.09a ± 0.005	0.10a ± 0.006	0.09a ± 0.014	0.11a ± 0.009	0.453
13	4-Nonanone	0.25a ± 0.020	0.22a ± 0.003	0.23a ± 0.009	0.22a ± 0.049	0.824
14	Linalool	1.06a ± 0.133	0.39b ± 0.006	0.43b ± 0.017	0.37b ± 0.023	<0.001***
15	4,5-Epoxycarene	0.15a ± 0.009	0.08 ab ± 0.003	0.08 ab ± 0.003	0.04b ± 0.023	0.041*
16	exo-Isocitral	0.43a ± 0.020	0.33b ± 0.003	0.37 ab ± 0.026	0.38 ab ± 0.014	0.027*
17	Citronellal	0.50a ± 0.137	0.11b ± 0.000	0.15b ± 0.023	0.15b ± 0.020	0.006**
18	2,2-Dimethylocta-3,4-dienal	0.19a ± 0.110	0.21a ± 0.012	0.21a ± 0.009	0.10a ± 0.058	0.565
19	Isoneral	1.46a ± 0.081	1.29a ± 0.003	1.43a ± 0.078	1.48a ± 0.052	0.18
20	Octanoic acid	0.00a ± 0.000	0.00a ± 0.000	0.03a ± 0.014	0.02a ± 0.012	0.138
21	Rosefuran epoxide	0.04a ± 0.023	0.00a ± 0.000	0.00a ± 0.000	0.00a ± 0.000	0.063
22	Isogeranial	2.02a ± 0.081	1.83a ± 0.012	2.00a ± 0.107	1.98a ± 0.089	0.392
23	trans-Carveol	0.05a ± 0.026	0.00a ± 0.000	0.02a ± 0.009	0.00a ± 0.000	0.123
24	*trans*-3(10)-Caren-2-ol	0.03a ± 0.017	0.00a ± 0.000	0.00a ± 0.000	0.04a ± 0.020	0.138
25	Decanal	0.39a ± 0.043	0.24b ± 0.029	0.19b ± 0.000	0.16b ± 0.009	<0.001***
26	Borneol	0.27a ± 0.055	0.11 ab ± 0.064	0.11 ab ± 0.064	0.00b ± 0.000	0.048*
27	L-alpha-terpineol	0.00a ± 0.000	0.08a ± 0.046	0.08a ± 0.046	0.00a ± 0.000	0.138
28	1-Myrcenol	0.00a ± 0.000	0.08a ± 0.043	0.08a ± 0.043	0.05a ± 0.026	0.347
29	cis-Cyclodecene	0.06a ± 0.035	0.00a ± 0.000	0.04a ± 0.023	0.00a ± 0.000	0.136
30	Citronellol	1.48a ± 0.297	0.10b ± 0.058	0.06b ± 0.035	0.05b ± 0.029	<0.001***
31	Citral (neral + geranial)	79.90b ± 0.828	82.38a ± 0.040	84.44a ± 1.227	87.32a ± 0.534	<0.001***
32	Neric acid/Geranic acid	0.13b ± 0.009	0.11c ± 0.012	0.07c ± 0.038	0.15a ± 0.017	<0.001***
33	Myrcenyl acetate	0.06a ± 0.032	0.00a ± 0.000	0.00a ± 0.000	0.00a ± 0.000	0.133
34	Geraniol	3.74a ± 0.199	2.82 ab ± 0.162	1.90bc ± 0.372	1.41c ± 0.257	0.003**
35	Bornyl acetate	0.00a ± 0.000	0.07a ± 0.038	0.07a ± 0.038	0.00a ± 0.000	0.1197
36	Phenol, 2-methoxy-3-(2-propenyl)-	0.12a ± 0.023	0.16a ± 0.003	0.11b ± 0.032	0.09b ± 0.049	0.001***
37	Geranyl acetate	3.94a ± 1.270	4.91a ± 0.393	3.76a ± 0.274	2.47a ± 0.153	0.297
38	cis-Caryophyllene	0.34a ± 0.193	0.00a ± 0.000	0.39a ± 0.222	0.00a ± 0.000	0.063
39	Germacrene D	0.05a ± 0.003	0.05a ± 0.000	0.05a ± 0.000	0.05a ± 0.000	0.299
40	Dodecanal	0.00a ± 0.000	0.03a ± 0.017	0.03a ± 0.014	0.05a ± 0.003	0.063
41	Caryophyllene	0.38b ± 0.217	0.80a ± 0.017	0.42b ± 0.240	0.79a ± 0.055	0.003**
42	trans-Isoeugenol	0.18a ± 0.029	0.35a ± 0.069	0.35a ± 0.072	0.28a ± 0.043	0.061
43	Humulene	0.09c ± 0.003	0.11a ± 0.003	0.10b ± 0.006	0.10b ± 0.012	<0.001***
44	beta-copaene	0.14b ± 0.078	0.45 ab ± 0.049	0.27 ab ± 0.153	0.52a ± 0.046	0.030*
45	gamma-Muurolene	0.00b ± 0.000	0.00b ± 0.000	0.23a ± 0.133	0.00b ± 0.000	<0.001***
46	Caryophyllene oxide	0.17c ± 0.095	0.40bc ± 0.046	0.42 ab ± 0.038	0.46a ± 0.009	0.003**
47	Shyobunol/6-epi-shyobunol	0.00a ± 0.000	0.00a ± 0.000	0.00a ± 0.000	0.04a ± 0.000	0.063
48	Humulene epoxide I	0.00a ± 0.000	0.00a ± 0.000	0.02a ± 0.009	0.00a ± 0.000	0.063
Total number of compounds identified		40	36	42	34	

Means followed by the same letters within the same row are not significantly different. *$P < 0.05$, **$P < 0.01$ and ***$P < 0.001$.

Table 2
The percentage composition of the different compounds and the number of compounds found in the essential oils of *C. flexuosus* extracted using steam distillation and analyzed using the GC-MS method. The herbage was from plants grown under four levels of soil amendments (T1, control; T2, cow manure; T3, cow manure plus NPK fertilizer; and T4, NPK fertilizer alone) and rain-fed for 120 days from transplanting to harvesting.

	Rainfed					
Peak no.	Component	T1	T2	T3	T4	*P*-value
1	3-Carene	0.00a ± 0.000	0.00a ± 0.000	0.00a ± 0.000	0.02a ± 0.012	0.063
2	2-Nitrohexane	0.11 ab ± 0.064	0.24a ± 0.003	0.00b ± 0.000	0.00b ± 0.000	0.003**
3	Camphene	0.03a ± 0.014	0.03a ± 0.017	0.16a ± 0.043	0.21a ± 0.095	0.065
4	Sulcatone	0.68a ± 0.009	0.98a ± 0.231	0.96a ± 0.035	0.79a ± 0.023	0.275
5	Octanal	0.05a ± 0.029	0.20a ± 0.052	0.11a ± 0.003	0.08a ± 0.012	0.066
6	D-Limonene	0.12b ± 0.014	0.75a ± 0.05	0.10b ± 0.00	0.35 ab ± 0.182	0.013*
7	*trans*-β-Ocimene	0.00a ± 0.000	0.00a ± 0.000	0.14a ± 0.081	0.09a ± 0.049	0.135
8	alpha-Pinene	0.11a ± 0.014	0.05a ± 0.029	0.08a ± 0.043	0.13a ± 0.072	0.78
9	Eucalyptol/1,8-Cineole	0.18 ab ± 0.075	0.88a ± 0.416	0.08 ab ± 0.003	0.03b ± 0.014	0.026*
10	beta-Ocimene	0.05b ± 0.006	0.08 ± ab0.003	0.10 ab ± 0.020	0.10a ± 0.006	0.031*
11	gamma-Terpinene	0.00a ± 0.000	0.07a ± 0.038	0.00a ± 0.000	0.00a ± 0.000	0.063
12	4-Nonanone	0.21a ± 0.0100	0.49a ± 0.087	0.45a ± 0.104	0.40a ± 0.081	0.175
13	Isoterpinolene	0.00a ± 0.000	0.08a ± 0.046	0.00a ± 0.000	0.02a ± 0.009	0.11
14	rosefuran	0.04a ± 0.003	0.05a ± 0.026	0.00a ± 0.000	0.02a ± 0.012	0.135
15	Linalool	0.65b ± 0.040	1.38a ± 0.121	0.66b ± 0.006	0.50b ± 0.017	<0.001***
16	4,5-Epoxycarene	0.00b ± 0.000	0.00b ± 0.000	0.06 ab ± 0.031	0.08a ± 0.000	0.008**
17	Phellandral	0.00a ± 0.000	0.00a ± 0.000	0.05a ± 0.026	0.00a ± 0.000	0.063
18	Nonanal	0.00a ± 0.000	0.04a ± 0.023	0.00a ± 0.000	0.00a ± 0.000	0.063
19	Chrysanthenone	0.00a ± 0.000	0.07a ± 0.040	0.00a ± 0.000	0.00a ± 0.000	0.063
20	Pinane	0.05a ± 0.029	0.00a ± 0.000	0.00a ± 0.000	0.00a ± 0.000	0.063
21	exo-Isocitral	0.53a ± 0.032	0.48a ± 0.274	0.44a ± 0.003	0.43a ± 0.009	0.873
22	Citronellal	0.00b ± 0.000	0.00b ± 0.000	0.46a ± 0.104	0.35a ± 0.095	<0.001***
23	2,2-Dimethylocta-3,4-dienal	0.00b ± 0.000	0.00b ± 0.000	0.27a ± 0.014	0.10 ab ± 0.058	0.002**
24	Isoneral	1.93 ab ± 0.115	2.78a ± 0.427	1.72b ± 0.026	1.61b ± 0.058	0.016*
25	Pinocarvone	0.00a ± 0.000	0.05a ± 0.029	0.00a ± 0.000	0.00a ± 0.000	0.063
26	Rosefuran epoxide	0.09a ± 0.049	0.00a ± 0.000	0.00a ± 0.000	0.00a ± 0.000	0.063
27	Isogeranial	2.53a ± 0.165	3.45a ± 0.716	2.28a ± 0.017	2.23a ± 0.003	0.139
28	*trans*-3(10)-Caren-2-ol	0.00a ± 0.000	0.00a ± 0.000	0.00a ± 0.000	0.01a ± 0.003	0.063
29	Vinylcyclooctane	0.00a ± 0.000	0.00a ± 0.000	0.06a ± 0.032	0.06a ± 0.032	0.138
30	*cis*-4-Decenal	0.00a ± 0.000	0.04a ± 0.023	0.00a ± 0.000	0.00a ± 0.000	0.063
31	Decanal	0.12 ab ± 0.066	0.00b ± 0.000	0.22a ± 0.014	0.18a ± 0.029	0.008**
32	Borneol	0.10a ± 0.058	0.00a ± 0.000	0.00a ± 0.000	0.08a ± 0.046	0.138
33	*trans*-4-Thujanol	0.00a ± 0.000	0.00a ± 0.000	0.00a ± 0.000	0.04a ± 0.000	0.063
34	endo-Borneol	0.00a ± 0.000	0.63a ± 0.361	0.00a ± 0.000	0.00a ± 0.000	0.062
35	Terpineol	0.00a ± 0.000	0.50a ± 0.286	0.00a ± 0.000	0.00a ± 0.000	0.063
36	Cyclodecanol	0.17a ± 0.098	0.00a ± 0.000	0.00a ± 0.000	0.00a ± 0.000	0.062
37	D-Verbenone	0.08a ± 0.049	0.00a ± 0.000	0.00a ± 0.000	0.03a ± 0.014	0.12
38	Citronellol	0.30a ± 0.173	0.27a ± 0.156	0.38a ± 0.095	0.36a ± 0.147	0.851
39	2,3-epoxy-gerianial	0.00b ± 0.000	0.00b ± 0.000	0.03 ab ± 0.017	0.05a ± 0.001	0.010**
40	Citral (neral + geranial)	84.37a ± 1.775	75.97b ± 1.432	85.59a ± 0.152	87.70a ± 0.736	<0.001***
41	α-Terpinyl acetate	0.00b ± 0.000	0.00b ± 0.000	0.00b ± 0.000	0.09a ± 0.012	<0.001***
42	Cyclooctyl acetate	0.00b ± 0.000	0.00b ± 0.000	0.09a ± 0.012	0.00b ± 0.000	<0.001***
43	Neric acid/Geranic acid	0.00b ± 0.000	0.00b ± 0.000	0.10a ± 0.000	0.08a ± 0.006	<0.001***
44	Myrcenyl acetate	0.07a ± 0.038	0.12a ± 0.069	0.00a ± 0.000	0.00a ± 0.000	0.133
45	2-Isopropenyl-5-methylhex-4-enal	19.85a ± 11.458	36.75a ± 21.215	0.00a ± 0.000	0.00a ± 0.000	0.141
46	Geraniol	3.23 ab ± 0.730	4.26a ± 0.141	2.12bc ± 0.089	1.56c ± 0.092	0.003**
47	Bornyl acetate	0.12a ± 0.069	0.42a ± 0.242	0.00a ± 0.000	0.00a ± 0.000	0.12
48	Phenol, 2-methoxy-3-(2-propenyl)-	0.24a ± 0.014	0.20a ± 0.038	0.00b ± 0.000	0.05b ± 0.029	<0.001***
49	Geranyl acetate	1.42a ± 0.280	1.99a ± 0.800	1.80a ± 0.268	0.80a ± 0.066	0.297
50	cis-Caryophyllene	0.00a ± 0.000	0.00a ± 0.000	0.38a ± 0.217	0.00a ± 0.000	0.063
51	6-Hepten-3-ol	0.00b ± 0.000	0.00b ± 0.000	0.10a ± 0.003	0.04 ab ± 0.020	0.002**
52	Germacrene D	0.03a ± 0.017	0.08a ± 0.043	0.03a ± 0.014	0.00a ± 0.000	0.299
53	Dodecanal	0.00a ± 0.000	0.05a ± 0.026	0.00a ± 0.000	0.00a ± 0.000	0.062
54	Caryophyllene	1.17 ab ± 0.21	1.83a ± 0.012	0.27c ± 0.153	0.53bc ± 0.023	0.003**
55	trans-Isoeugenol	0.00a ± 0.000	0.13a ± 0.072	0.08a ± 0.009	0.10a ± 0.017	0.061
56	Humulene	0.15b ± 0.026	0.24a ± 0.009	0.08c ± 0.009	0.07c ± 0.003	<0.001***
57	beta-copaene	0.03 ab ± 0.017	0.00b ± 0.000	0.10 ab ± 0.055	0.16a ± 0.003	0.030*
58	gamma-Muurolene	0.18a ± 0.035	0.22a ± 0.075	0.00b ± 0.000	0.00b ± 0.000	<0.001***
59	Caryophyllene oxide	0.52 ab ± 0.043	0.69a ± 0.095	0.30c ± 0.023	0.40bc ± 0.023	0.003**
60	Shyobunol/6-epi-shyobunol	0.00a ± 0.000	0.00a ± 0.000	0.00a ± 0.000	0.02a ± 0.009	0.063
61	(Z)-Isoelimicin	0.11a ± 0.061	0.00a ± 0.000	0.06a ± 0.032	0.00a ± 0.000	0.132
62	Humulene epoxide I	0.00a ± 0.000	0.04a ± 0.020	0.00a ± 0.000	0.00a ± 0.000	0.063
Total number of compounds identified		35	38	35	40	

Means followed by the same letters within the same row are not significantly different. *$P < 0.05$, **$P < 0.01$ and ***$P < 0.001$.

water deficit positively affected the proportion of lemongrass essential oil constituents.

The composition of essential oils for the second harvest (180 DAT) is tabulated in Table 3 (Irrigated block) and Table 4 (Rainfed block). A similar trend in terms of compounds present was observed at 180 DAT as with 120 DAT, whereby a total of 55 components were recovered in oil from different treatments under rain-fed conditions (Table 4), which is more compared with the 49 constituents identified under irrigation (Table 3). The number of compounds observed from Treatments T2 was 43, T1 was 42, which was higher than that of T3 and T4 observed to be 40 and 33, respectively. Under rain-fed conditions, the oil from treatment T3 had 44 different compounds, while that from T2, T4 and T1 had 39, 38, and 34 compounds, respectively. As mentioned previously, there is variation in the number of oil compounds with respect to changes in watering regime across different soil amendments.

The major components of the *C. flexuosus* oil in the two harvests in this study included citral (75.97–87.70 %), geranyl acetate (0.8–4.91 %), geraniol (0.8–4.26 %), isogeranial (1.83–3.45 %) and isoneral (1.29–2.78 %), which is in line with previously published

Table 3

The percentage composition of the different compounds and the number of compounds found in the essential oils of *C. flexuosus* extracted using steam distillation and analyzed using the GC-MS method. The herbage was from plants grown under four levels of soil amendments (T1, control; T2, cow manure; T3, cow manure plus NPK fertilizer; and T4, NPK fertilizer alone) and irrigated for 180 days from transplanting to harvesting.

	Irrigated					
Peak no.	Component	T1	T2	T3	T4	*P*-value
1	3-Carene	0.01a ± 0.006	0.00a ± 0.000	0.00a ± 0.000	0.00a ± 0.000	0.123
2	Camphene	0.17a ± 0.038	0.16a ± 0.017	0.14a ± 0.003	0.15a ± 0.069	0.164
3	Sulcatone	0.60a ± 0.107	0.42b ± 0.014	0.44 ab ± 0.003	0.53 ab ± 0.023	0.027*
4	Octanal	0.08 ab ± 0.003	0.10a ± 0.009	0.10a ± 0.012	0.07 ab ± 0.017	0.042*
5	D-Limonene	0.18a ± 0.040	0.30a ± 0.009	0.21a ± 0.058	0.20a ± 0.113	0.217
6	*trans*-β-Ocimene	0.14a ± 0.023	0.15a ± 0.038	0.12a ± 0.023	0.20a ± 0.020	0.335
7	alpha-Pinene	0.02 ab ± 0.009	0.02 ab ± 0.009	0.02 ab ± 0.009	0.03a ± 0.014	0.002**
8	2-Hexyl hydroperoxide	0.20a ± 0.020	0.26a ± 0.003	0.28a ± 0.017	0.26a ± 0.003	0.358
9	3-Hexyl hydroperoxide	0.17a ± 0.017	0.22a ± 0.003	0.25a ± 0.017	0.22a ± 0.006	0.138
10	beta-Ocimene	0.04 ab ± 0.020	0.04 ab ± 0.023	0.03b ± 0.017	0.09a ± 0.003	0.033*
11	4-Nonanone	0.17a ± 0.049	0.16a ± 0.012	0.17a ± 0.017	0.31a ± 0.006	0.161
12	Linalool	0.40a ± 0.040	0.46a ± 0.003	0.40a ± 0.035	0.37a ± 0.017	0.274
13	4,5-Epoxycarene	0.03a ± 0.017	0.06a ± 0.032	0.00a ± 0.000	0.04a ± 0.023	0.345
14	Phellandral	0.04a ± 0.020	0.04a ± 0.020	0.08a ± 0.002	0.03a ± 0.014	0.421
15	exo-Isocitral	0.40a ± 0.012	0.37 ab ± 0.006	0.36b ± 0.000	0.37 ab ± 0.006	0.019*
16	Citronellal	0.44a ± 0.072	0.19a ± 0.023	0.25a ± 0.012	0.19a ± 0.110	0.230
17	2,2-Dimethylocta-3,4-dienal	0.20a ± 0.012	0.11a ± 0.064	0.22a ± 0.003	0.19a ± 0.014	0.250
18	Isoneral	1.64a ± 0.107	1.39b ± 0.003	1.40b ± 0.003	1.49 ab ± 0.012	0.032*
19	*trans*-2-Caren-4-ol	0.00a ± 0.000	0.02a ± 0.012	0.02a ± 0.012	0.00a ± 0.000	0.138
20	Rosefuran epoxide	0.00a ± 0.000	0.00a ± 0.000	0.00a ± 0.000	0.04a ± 0.020	0.063
21	Isogeranial	2.22a ± 0.075	1.96b ± 0.026	1.99b ± 0.006	2.08 ab ± 0.014	0.007**
22	trans-Cyclodecene	0.00a ± 0.000	0.06a ± 0.032	0.06a ± 0.032	0.00a ± 0.000	0.138
23	*cis*-p-mentha-1(7),8-dien-2-ol	0.03a ± 0.014	0.00a ± 0.000	0.00a ± 0.000	0.00a ± 0.000	0.063
24	1,4-Undecadiene	0.04a ± 0.020	0.00a ± 0.000	0.00a ± 0.000	0.00a ± 0.000	0.063
25	trans-Carveol	0.02a ± 0.012	0.00a ± 0.000	0.02a ± 0.012	0.00a ± 0.000	0.138
26	Vinylcyclooctane	0.06a ± 0.032	0.00a ± 0.000	0.05a ± 0.026	0.07a ± 0.040	0.353
27	Decanal	0.17a ± 0.023	0.17a ± 0.003	0.16a ± 0.009	0.14a ± 0.038	0.653
28	endo-Borneol	0.00a ± 0.000	0.03a ± 0.014	0.00a ± 0.000	0.00a ± 0.000	0.063
29	cis-Cyclodecene	0.00a ± 0.000	0.08a ± 0.043	0.00a ± 0.000	0.00a ± 0.000	0.063
30	Citronellol	0.39a ± 0.107	0.09a ± 0.052	0.22a ± 0.023	0.18a ± 0.043	0.063
31	Citronellyl acetate	0.03a ± 0.014	0.02a ± 0.009	0.02a ± 0.009	0.00a ± 0.000	0.075
32	2,3-epoxy-gerianial	0.00a ± 0.000	0.02a ± 0.009	0.00a ± 0.000	0.00a ± 0.000	0.063
32	1-Myrcenol	0.00a ± 0.000	0.08a ± 0.046	0.00a ± 0.000	0.00a ± 0.000	0.063
33	Citral (neral + geranial)	84.66a ± 0.961	85.86a ± 0.393	84.99a ± 0.110	86.47a ± 0.217	0.141
34	Hexahydropseudoionone	0.05a ± 0.026	0.08a ± 0.046	0.06a ± 0.035	0.00a ± 0.000	0.347
35	Neric acid/Geranic acid	0.12a ± 0.009	0.12a ± 0.012	0.13a ± 0.014	0.06a ± 0.032	0.150
36	Geraniol	1.87a ± 0.156	1.63a ± 0.095	1.74a ± 0.159	0.80a ± 0.378	0.060
37	Phenol, 2-methoxy-3-(2-propenyl)-	0.15a ± 0.058	0.14a ± 0.078	0.04a ± 0.020	0.19a ± 0.110	0.653
38	Geranyl acetate	2.33a ± 0.046	2.63a ± 0.508	3.19a ± 0.188	2.59a ± 0.014	0.252
39	Germacrene D	0.06a ± 0.009	0.04a ± 0.000	0.05a ± 0.003	0.25a ± 0.121	0.092
40	Dodecanal	0.01 ab ± 0.006	0.03 ab ± 0.014	0.04a ± 0.006	0.00b ± 0.000	0.042*
41	Caryophyllene	0.92a ± 0.104	0.80a ± 0.020	0.88a ± 0.066	0.67a ± 0.035	0.091
42	trans-Isoeugenol	0.29a ± 0.032	0.31a ± 0.009	0.29a ± 0.003	0.26a ± 0.020	0.387
43	Humulene	0.12a ± 0.014	0.10a ± 0.006	0.11a ± 0.009	0.09a ± 0.002	0.191
44	beta-copaene	0.59a ± 0.127	0.39a ± 0.064	0.49a ± 0.009	0.43a ± 0.055	0.350
45	α-Acorenol	0.01a ± 0.006	0.02a ± 0.009	0.02a ± 0.009	0.00a ± 0.000	0.353
46	Caryophyllene oxide	0.55a ± 0.072	0.51a ± 0.011	0.53a ± 0.020	0.23b ± 0.058	0.005**
47	Shyobunol/6-epi-shyobunol	0.05a ± 0.006	0.04a ± 0.000	0.04a ± 0.000	0.00b ± 0.000	<0.001***
48	(Z)-Isoelimicin	0.29a ± 0.165	0.15a ± 0.084	0.36a ± 0.040	0.79a ± 0.338	0.238
49	Neophytadiene	0.18a ± 0.084	0.05 ab ± 0.029	0.06 ab ± 0.023	0.00b ± 0.000	0.048*
Total number of compounds identified		42	43	40	33	

Means followed by the same letters within the same row are not significantly different. *$P < 0.05$, **$P < 0.01$ and ***$P < 0.001$.

Table 4
The percentage composition of the different compounds and the number of compounds found in the essential oils of *C. flexuosus* extracted using steam distillation and analyzed using the GC-MS method. The herbage was from plants grown under four levels of soil amendments (T1, control; T2, cow manure; T3, cow manure plus NPK fertilizer; and T4, NPK fertilizer alone) and rain-fed for 180 days from transplanting to harvesting.

	Rainfed					
Peak no.	Component	T1	T2	T3	T4	*P*-value
1	Tricyclene	0.00a ± 0.000	0.03a ± 0.014	0.00a ± 0.000	0.00a ± 0.000	0.063
2	3-Carene	0.00a ± 0.000	0.02a ± 0.009	0.05a ± 0.026	0.00a ± 0.000	0.123
3	Camphene	0.21a ± 0.029	0.32a ± 0.104	0.44a ± 0.225	0.06a ± 0.032	0.164
4	Sulcatone	0.33b ± 0.029	0.42 ab ± 0.017	0.46a ± 0.035	0.39 ab ± 0.003	0.027*
5	Octanal	0.11 ab ± 0.014	0.07b ± 0.014	0.14a ± 0.003	0.08 ab ± 0.017	0.042*
6	D-Limonene	0.12a ± 0.014	0.10a ± 0.014	0.10a ± 0.055	0.02a ± 0.012	0.217
7	*trans*-β-Ocimene	0.27a ± 0.029	0.25a ± 0.009	0.15a ± 0.087	0.17a ± 0.026	0.335
8	alpha-Pinene	0.04 ab ± 0.006	0.04bc ± 0.023	0.14a ± 0.003	0.00c ± 0.000	0.002**
9	2-Hexyl hydroperoxide	0.12a ± 0.069	0.00a ± 0.000	0.09a ± 0.052	0.12a ± 0.066	0.358
10	3-Hexyl hydroperoxide	0.00a ± 0.000	0.00a ± 0.000	0.08a ± 0.046	0.10a ± 0.058	0.138
11	beta-Ocimene	0.14a ± 0.012	0.10 ab ± 0.003	0.09b ± 0.014	0.11 ab ± 0.009	0.033*
12	Isoterpinolene	0.00a ± 0.000	0.01a ± 0.006	0.00a ± 0.000	0.00a ± 0.000	0.063
13	4-Nonanone	0.28a ± 0.029	0.11a ± 0.064	0.23a ± 0.009	0.22a ± 0.049	0.161
14	Linalool	0.28b ± 0.038	0.42a ± 0.023	0.43a ± 0.017	0.37 ab ± 0.023	0.013*
15	4,5-Epoxycarene	0.13a ± 0.011	0.12a ± 0.020	0.08a ± 0.003	0.04a ± 0.023	0.057
16	Octanoic acid	0.00a ± 0.000	0.00a ± 0.000	0.03a ± 0.014	0.02a ± 0.012	0.138
17	exo-Isocitral	0.48a ± 0.049	0.38a ± 0.029	0.37a ± 0.026	0.38a ± 0.014	0.135
18	Citronellal	0.14a ± 0.003	0.13a ± 0.009	0.15a ± 0.023	0.15a ± 0.020	0.731
19	2,2-Dimethylocta-3,4-dienal	0.32a ± 0.029	0.33a ± 0.055	0.21a ± 0.006	0.10b ± 0.058	0.048*
20	Isoneral	1.31a ± 0.006	1.41a ± 0.069	1.43a ± 0.075	1.48a ± 0.049	0.280
21	Isogeranial	2.00a ± 0.058	1.90a ± 0.020	2.00a ± 0.101	1.98a ± 0.084	0.725
22	trans-Carveol	0.00a ± 0.000	0.00a ± 0.000	0.02a ± 0.009	0.00a ± 0.000	0.063
23	*trans*-3(10)-Caren-2-ol	0.37a ± 0.003	0.00b ± 0.000	0.00b ± 0.000	0.04b ± 0.020	<0.001***
24	Decanal	0.36a ± 0.006	0.15a ± 0.084	0.19a ± 0.000	0.00a ± 0.009	0.147
25	Borneol	0.00a ± 0.000	0.00a ± 0.000	0.11a ± 0.064	0.00a ± 0.000	0.063
26	3-Decen-1-ol	0.00a ± 0.000	0.00a ± 0.000	0.06a ± 0.032	0.00a ± 0.000	0.063
27	L-alpha-Terpineol	0.00a ± 0.000	0.00a ± 0.000	0.08a ± 0.046	0.00a ± 0.000	0.063
28	cis-Cyclodecene	0.00a ± 0.000	0.00a ± 0.000	0.04a ± 0.023	0.00a ± 0.000	0.063
29	d-Campholylmethane	0.00a ± 0.000	0.00a ± 0.000	0.02a ± 0.012	0.00a ± 0.000	0.063
30	Citronellol	0.09a ± 0.049	0.10a ± 0.058	0.06a ± 0.035	0.05a ± 0.029	0.964
31	Citronellyl acetate	0.00a ± 0.000	0.02a ± 0.009	0.00a ± 0.000	0.00a ± 0.000	0.063
32	1-Myrcenol	0.00a ± 0.000	0.00a ± 0.000	0.08a ± 0.046	0.05a ± 0.026	0.134
33	Citral (neral + geranial)	85.79a ± 0.058	84.82a ± 1.088	84.46a ± 1.022	87.33a ± 0.309	0.114
34	2-Undecanone	0.00a ± 0.000	0.00a ± 0.000	0.00a ± 0.000	0.12a ± 0.066	0.063
35	Hexahydropseudoionone	0.00a ± 0.000	0.11a ± 0.064	0.00a ± 0.000	0.00a ± 0.000	0.063
36	Neric acid/Geranic acid	0.25a ± 0.029	0.11 ab ± 0.009	0.07b ± 0.038	0.15 ab ± 0.017	0.037*
37	Decanoic acid	0.09a ± 0.029	0.00b ± 0.000	0.00b ± 0.000	0.03b ± 0.014	0.003**
38	Geraniol	2.42a ± 0.289	2.39a ± 0.416	1.90a ± 0.378	1.41a ± 0.263	0.182
39	Bornyl acetate	0.12a ± 0.029	0.00b ± 0.000	0.07 ab ± 0.038	0.00b ± 0.000	0.007**
40	Phenol, 2-methoxy-3-(2-propenyl)-	0.00b ± 0.000	0.08 ab ± 0.043	0.11a ± 0.032	0.19a ± 0.009	0.007**
41	Geranyl acetate	2.69a ± 0.043	4.09a ± 0.886	3.76a ± 0.283	2.47a ± 0.162	0.090
42	Germacrene D	0.05a ± 0.006	0.04a ± 0.006	0.05a ± 0.000	0.05a ± 0.000	0.271
43	Isolongifolan-8-ol	0.00a ± 0.000	0.02a ± 0.009	0.00a ± 0.000	0.02a ± 0.009	0.138
44	Methyleugenol	0.00a ± 0.000	0.04a ± 0.023	0.00a ± 0.000	0.00a ± 0.000	0.062
45	Dodecanal	0.04a ± 0.003	0.03a ± 0.017	0.03a ± 0.014	0.05a ± 0.002	0.607
46	Caryophyllene	0.64a ± 0.058	0.73a ± 0.032	0.81a ± 0.020	0.79a ± 0.055	0.106
47	trans-Isoeugenol	0.29a ± 0.029	0.33a ± 0.055	0.35a ± 0.072	0.18a ± 0.101	0.321
48	Humulene	0.08a ± 0.009	0.10a ± 0.003	0.10a ± 0.006	0.10a ± 0.012	0.144
49	beta-copaene	0.56a ± 0.029	0.18b ± 0.104	0.49 ab ± 0.023	0.52a ± 0.043	0.042*
50	α-Acorenol	0.00a ± 0.000	0.00a ± 0.000	0.03a ± 0.014	0.03a ± 0.014	0.138
51	gamma-Muurolene	0.00a ± 0.000	0.18a ± 0.101	0.00a ± 0.000	0.00a ± 0.000	0.063
52	Caryophyllene oxide	0.47a ± 0.012	0.36b ± 0.017	0.42 ab ± 0.038	0.45 ab ± 0.012	0.035*
53	Shyobunol/6-epi-shyobunol	0.05a ± 0.006	0.00c ± 0.000	0.02bc ± 0.009	0.04 ab ± 0.000	0.001**
54	Humulene epoxide I	0.00a ± 0.000	0.02a ± 0.009	0.00a ± 0.000	0.00a ± 0.000	0.063
55	Neophytadiene	0.06a ± 0.014	0.02a ± 0.009	0.05a ± 0.003	0.07a ± 0.023	0.077
Total number of compounds identified		34	39	44	38	

Means followed by the same letters within the same row are not significantly different. $*P < 0.05$, $**P < 0.01$ and $***P < 0.001$.

papers [11,14,57,59,62]. Other compounds were recorded in minimal quantity accounting for less than 0.8 %. Nonetheless, although several constituents were found in trace amounts in this study, such as camphene, citronellal and D-limonene, in addition to prevalent compounds, including citral and geraniol, have been shown to be responsible for a strong and distinctive lemony fragrance of lemongrass [63]. Citral, a blend of two isoforms geranial and neral, occurred in high concentrations in this work, ranging between 75.97 and 87.70 % as per the acceptable standard threshold levels of 65–85 % for its applications in the international market [20,64].

This component is majorly responsible for the quality and biological potency of *C.* species essential oil, where higher citral content indicates higher purity [64,65], and also for generating ionones and vitamin B [11]. However, citral content, encompassing both neral and geranial, may exhibit variability due to the involvement of several factors, including plant species, altitude and climate [66,67].

Overall, the composition of *C. flexuosus* essential oil in this study differed as a function of different soil conditioners under rainfall and irrigation as well as the time scale, with NPK treatment T4 containing the highest amount of citral compound compared with other treatments regardless of watering regime. This indicates the effectiveness of inorganic farming to yield high-quality essential oil of *C. flexuosus*. Application of nitrogenous fertilizers in lemongrass has been elucidated to stimulate the plant's metabolic activity either directly or indirectly, leading to increased synthesis of organic compounds, including essential oils compound like citral [68]. Singh et al. [27], however, reported non-influence of the application of nitrogenous fertilizer and soil moisture regimes on citral and geraniol of *C. flexuosus* in India. Another study by Singh et al. [60] reported that input of nitrogen, potassium and phosphorus did not affect the citral content of *C. flexuosus*, but it was impacted by seasonal fluctuations.

There were significant differences ($P < 0.05$) in 20 and 23 compounds of *C. flexuosus* oil from treatments under irrigation (Table 1) and rainfall (Table 2), respectively, at 120 DAT. Whereas for essential oil of herbage harvested at 180 DAT, 11 and 14 constituents of *C. flexuosus* oil from treatments under irrigation (Table 3) and rainfall (Table 4), respectively, varied significantly in terms of nutrient content in the different soil amendments at $P < 0.05$. For instance, plants grown under irrigation and harvested at 120 DAT (Table 1), geranyl acetate varied from 2.47 % in T4 to 4.91 % in T2 and geraniol from 1.41 % in T4 to 3.74 % in T1, while at 180 DAT (Table 3), isogeranial ranged from 1.96 % in T2 to 2.22 % in T1 and isoneral from 1.39 % in T2 to 1.64 % in T1. For rain-fed material that was harvested at 120 DAT (Table 2), the geraniol composition differed from 1.56 % in T4 to 4.26 % in T2, and isogeranial from 2.23 % in T4 to 3.45 % in T2, whereas at 180 DAT (Table 4), the % geranyl acetate composition varied from 2.47 % in T4 to 4.09 % in T2 and geraniol from 1.41 % in T4 to 2.39 % in T2. Literature reports differ markedly with respect to the chemical composition of *C. flexuosus.* Pandey et al. [69] found 43.80 % citral, 5.27 % geranyl acetate, and 3.66 % *trans*-geraniol. Pathania et al. [67] reported 13.61–16.14 and 3.29–6.34 % for citral and geranyl acetate, respectively. Benoudjit et al. [70] recorded 41.80, 1.90, 0.13 and 0.09 % of isogeranial, isoneral, citral, and geranyl acetate, respectively, while da Cruz et al. [71] found 30.36–45.44 % citral, 2.81–7.43 % geraniol, and 1.87–2.39 % isoneral in *C. citratus*. The differences observed in terms of lemongrass essential oil composition are probably as a result of multiple factors, such as season, soil fertility practices, altitudinal and regional variation, and environmental factors, as documented by existing research [56,67,72]. These factors have demonstrated their impact on the biosynthesis of essential oils in aromatic plants, subsequently affecting the quality and quantity of the oils [25,73].

4. Conclusion

In this study, the *C. flexuosus* oil yield, composition of essential oil and agronomic properties differed as a function of different soil conditioners under rainfall and irrigation as well as the time scale. The optimal results were recorded in plants amended with the NPK fertilizer (T4) and a combination of cow manure and NPK fertilizer (T3) supported by rain-fed conditions. The main compounds of the *C. flexuosus* oil in the present study were citral, geranyl acetate, geraniol, isogeranial and isoneral, of which citral occurred in high concentrations (87.70 %) as per the acceptable standard threshold levels (65–85 %) for its applications in the international market. In terms of oil composition, citral content varied significantly at 120 days after transplanting across the four soil conditioners under the two watering regimes. With its maximum values being consistently observed in plants amended with the NPK fertilizer during the two harvest periods, indicating the effectiveness of inorganic farming to yield high-quality essential oil of *C. flexuosus*. Based on the limitation that this study was conducted in one agroecological zone with optimal rainfall pattern, future research to improve the growth and oil quality of *C. flexuosus* particularly under semi-arid conditions is needed.

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Data availability statement

No additional information is available for this paper.

CRediT authorship contribution statement

Gikuru Mwithiga: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Funding acquisition, Formal analysis, Data curation. **Samuel Maina:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Phyllis Muturi:** Writing – review & editing, Writing – original draft, Resources, Methodology, Funding acquisition, Conceptualization. **Josiah Gitari:** Writing – review & editing, Writing – original draft, Resources, Investigation, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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