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Optimization of irrigation regimes and harvesting stage for enhanced root yield, essential oil yield, and quality of Vetiver (*Chrysopogon zizanioides* L. Roberty)

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Abstract

A field experiment was conducted to evaluate the effect of irrigation levels and harvesting time on root yield and essential oil productivity of *Chrysopogon zizanioides* at Sri Krishnadevaraya College of Horticultural Sciences under semi-arid conditions. The experiment was laid out in a factorial randomized block design with three irrigation regimes (rainfed, 50% field capacity and 100% field capacity) and three harvesting stages (6, 9 and 12 months after planting). The results revealed that both irrigation and harvesting time significantly influenced root yield and oil parameters. The treatment receiving 100% field capacity irrigation and harvested at 12 months (I₃H₃) recorded the highest root biomass yield (24.36 t ha⁻¹), essential oil content (0.93%) and essential oil yield (197.48 kg ha⁻¹). Lower values were observed under rainfed conditions and early harvesting stage. GC-MS analysis indicated that major constituents such as vetiverol (30.24%), α -vetivone (21.86%) and β -vetivone (20.68%) were predominant and showed higher concentration under optimum irrigation and delayed harvesting. The study highlights that adequate irrigation combined with harvesting at full maturity significantly enhances root yield and oil productivity, thereby improving the economic potential of vetiver cultivation under semi-arid conditions of southern Andhra Pradesh.

Keywords: Vetiver, *Chrysopogon zizanioides*, irrigation regimes, harvesting stages, root yield, essential oil yield, GC-MS, semi-arid conditions

Introduction

Vetiver (*Chrysopogon zizanioides*) is a perennial aromatic grass of significant economic importance, widely cultivated in tropical and subtropical regions for its essential oil obtained from roots. The oil is highly valued in perfumery, cosmetics and pharmaceutical industries due to its excellent fixative properties and complex chemical composition. According to Adams (2001) [2], vetiver oil comprises a large number of sesquiterpenoid compounds, which contribute to its distinctive aroma and stability. India is one of the major producers of vetiver oil; however, productivity and quality are largely influenced by environmental conditions and crop management practices.

Among the various agronomic factors, irrigation plays a crucial role in determining growth, root development and essential oil biosynthesis in aromatic crops. Adequate soil moisture enhances nutrient uptake, photosynthetic efficiency and biomass accumulation, thereby improving root yield and oil productivity. Singh *et al.* (2002) [15] reported that optimum irrigation significantly increased root yield and oil content in aromatic grasses, whereas moisture stress adversely affected both yield and quality. Similarly, Maheshwari *et al.* (2010) [13] emphasized that proper water management is essential for maximizing essential oil yield and maintaining desirable chemical composition in medicinal and aromatic plants.

Harvesting time is another critical factor influencing root biomass and essential oil accumulation, as secondary metabolite synthesis is closely associated with plant maturity. Delayed harvesting allows greater translocation and accumulation of metabolites in roots, resulting in higher oil yield and improved composition. Kotoky *et al.* (2011) [10] observed significant variation in root yield and oil recovery with different harvesting stages, with maximum values recorded at full maturity.

In addition, Lavania (2003) ^[11] reported that harvesting at advanced growth stages enhances the concentration of major constituents such as vetiverol and vetivones, which are key determinants of oil quality.

The interaction between irrigation and harvesting time has been shown to influence not only yield but also the chemical profile of essential oils. Truong (1999) ^[16] highlighted the importance of environmental and management factors in determining biomass production and oil composition in vetiver. Despite these findings, limited information is available on the combined effect of irrigation regimes and harvesting stages under semi-arid conditions, particularly in the Rayalaseema region of Andhra Pradesh. Hence, the present study was carried out at Sri Krishnadevaraya College of Horticultural Sciences to assess the influence of varying irrigation regimes and harvesting intervals on root yield and essential oil productivity of *Chrysopogon zizanioides* under semi-arid conditions, with a view to determining optimal irrigation and harvest practices for enhancing yield and oil quality.

Materials and Methods

The field experiment was conducted at Sri Krishnadevaraya College of Horticultural Sciences during the cropping season under semi-arid agro-climatic conditions. The experimental site is located at approximately 14.68° N latitude and 77.60° E longitude, with an altitude of about 335 m above mean sea level. The region is characterized by low and erratic rainfall, high

temperature and prolonged dry spells. The soil of the experimental field was red sandy loam in texture, well-drained and slightly alkaline in reaction (pH 7.6-7.8), with low organic carbon content (0.42%), available nitrogen (210 kg ha⁻¹), medium available phosphorus (32 kg ha⁻¹) and available potassium (280 kg ha⁻¹).

The study was carried out on *Chrysopogon zizanioides* to evaluate the effect of irrigation levels and harvesting time on root yield and essential oil productivity, following standard agronomic procedures adopted for aromatic crops as reported by Singh *et al.* (2002) ^[15] and Maheshwari *et al.* (2010) ^[13]. The experiment was laid out in a Factorial Randomized Block Design (FRBD) with three replications (Fig.1). The treatments comprised two factors: irrigation levels and harvesting stages. Irrigation treatments included I₁: Rainfed (control), I₂: Irrigation at 50% field capacity and I₃: Irrigation at 100% field capacity. Harvesting was carried out at three stages, namely H₁: 6 months after planting, H₂: 9 months after planting and H₃: 12 months after planting, resulting in nine treatment combinations.

Uniform and healthy slips of vetiver were planted in well-prepared plots following recommended spacing and standard cultural practices. All intercultural operations such as weeding, nutrient management and plant protection were carried out uniformly across treatments. Irrigation scheduling was based on soil moisture levels and field capacity was maintained using standard procedures as described by Truong (1999) ^[16].

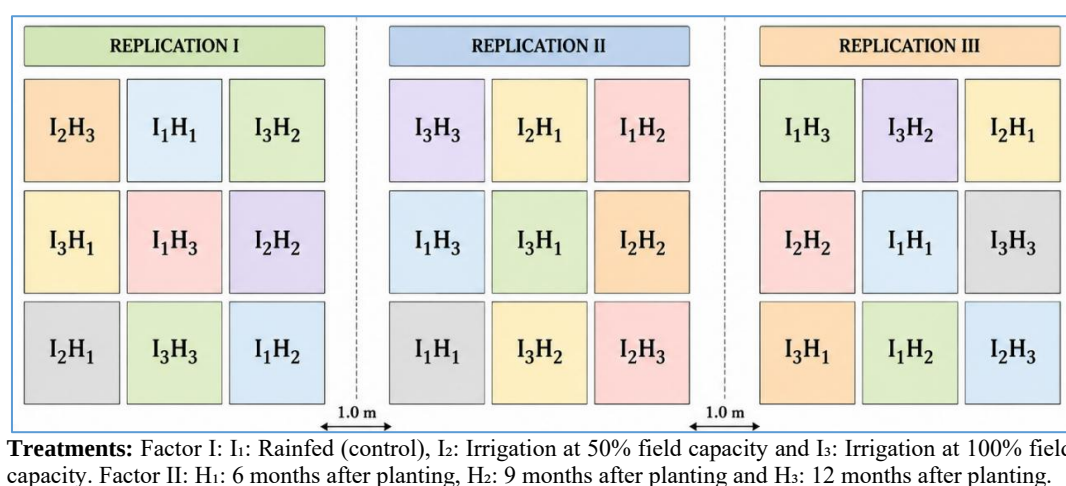


Fig 1: Lay out plan of experiment

At the respective harvesting stages, plants were carefully uprooted and roots were washed, cleaned and shade dried before recording observations. Root biomass yield was calculated on a hectare basis. Essential oil was extracted from dried root samples by hydro distillation using a Clevenger-type apparatus and oil content was expressed as percentage on dry weight basis. Essential oil yield (kg ha⁻¹) was computed by multiplying oil content with root yield, following the method described by Kotoky *et al.* (2011) ^[10].

The chemical composition of essential oil was determined using Gas Chromatography–Mass Spectrometry (GC–MS). Identification of compounds was carried out based on retention time and comparison with standard spectral libraries and the relative composition was expressed as percentage peak area, as outlined by Adams (2001) ^[2].

The experimental data were subjected to statistical analysis using analysis of variance (ANOVA) appropriate for FRBD as described by Gomez and Gomez (1984) ^[4]. The significance of

treatment effects was tested at 5% probability level and critical difference (CD) values were calculated for comparison of treatment means.

Results

Growth Parameters

The growth parameters of *Chrysopogon zizanioides* were significantly influenced by irrigation levels, harvesting time and their interaction (Table. 1). The treatment combination I₃H₃ (100% field capacity irrigation with harvesting at 12 months) recorded the highest values for all growth attributes, with plant height (155.48 cm), number of tillers per clump (26.83), clump spread (38.57 cm), leaves per tiller (9.17) and leaf area (56.27 cm²). The lowest values were observed under I₁H₁ (rainfed with harvesting at 6 months). Other treatment combinations showed intermediate values, with gradual increases observed from lower to higher irrigation levels and from early to late harvesting stages.

Root Parameters

Root parameters varied significantly across treatments (Table. 2). The interaction I₃H₃ recorded the highest number of roots per clump (68.75), root length (45.68 cm), fresh root weight (361.99 g plant⁻¹) and dry root weight (156.77 g plant⁻¹), resulting in the highest root biomass yield (24.36 t ha⁻¹). The lowest values were recorded under I₁H₁, where root biomass yield was 9.68 t ha⁻¹. Other treatment combinations showed progressive increases in root development with increasing irrigation levels and delayed harvesting.

Essential Oil Parameters

Essential oil content, oil yield and quality parameters were significantly influenced by irrigation and harvesting time (Table. 3). The highest essential oil content (0.93%), oil yield (197.48 kg ha⁻¹) and oil recovery (2.69%) were recorded under I₃H₃, while the lowest values were observed under I₁H₁. Quality parameters such as specific gravity (0.998) and refractive index (1.534) were also highest under I₃H₃. Intermediate values were recorded under other treatment combinations.

GC–MS Analysis

GC–MS analysis revealed the presence of multiple compounds in

vetiver oil, with vetiverol, α -vetivone and β -vetivone as major constituents (Table. 4). The highest concentrations of vetiverol (30.24%), α -vetivone (21.86%) and β -vetivone (20.68%) were recorded under I₃H₃. Lower concentrations were observed under I₁H₁. Other compounds such as khusimol, zizanol, spathulenol and β -caryophyllene also followed a similar trend, showing higher values under increased irrigation and delayed harvesting.

Economics

The economic analysis indicated that cost of cultivation, gross returns, net returns and benefit–cost ratio were influenced by irrigation levels and harvesting time (Table. 5). The highest cost of cultivation was recorded under I₃H₃ (₹1,00,200 ha⁻¹), while the lowest was observed under I₁H₁ (₹85,200 ha⁻¹). The treatment I₃H₃ recorded the highest gross returns (₹4,62,300 ha⁻¹) and net returns (₹3,62,100 ha⁻¹), along with the maximum benefit–cost ratio (4.61). The lowest economic returns and B:C ratio (1.71) were recorded under I₁H₁. Other treatment combinations showed intermediate economic performance, with increasing returns observed under higher irrigation levels and delayed harvesting stages.

Table 1: Effect of irrigation and harvesting time levels on growth parameters of *Chrysopogon zizanioides*

Treatments	Plant Height (cm)	Tillers Clump ⁻¹	Clump Spread (cm)	Leaves Tiller ⁻¹	Leaf Area (cm ²)
Irrigation (I)					
I ₁	118.43	18.47	27.97	6.82	38.41
I ₂	126.91	20.58	30.53	7.48	42.79
I ₃	135.76	22.49	33.21	8.06	46.83
SEd (±)	2.81	0.92	1.18	0.31	2.53
CD (0.05)	6.03	1.88	2.63	0.72	5.28
Harvesting Time (H)					
H ₁	112.57	17.32	26.76	6.51	35.04
H ₂	126.69	20.63	30.44	7.49	42.73
H ₃	141.87	23.58	34.52	8.31	50.33
SEd (±)	3.02	1.02	1.28	0.41	2.68
CD (0.05)	6.47	2.08	2.76	0.82	5.84
Interaction (I × H)					
I ₁ H ₁	108.24	16.48	25.37	6.21	32.54
I ₁ H ₂	118.58	18.73	28.08	6.79	38.63
I ₁ H ₃	128.53	20.19	30.36	7.43	44.18
I ₂ H ₁	112.38	17.28	26.83	6.47	35.08
I ₂ H ₂	126.83	20.64	30.23	7.62	42.84
I ₂ H ₃	141.47	23.82	34.47	8.36	50.58
I ₃ H ₁	117.06	18.14	27.96	6.88	37.42
I ₃ H ₂	134.76	22.47	33.08	8.03	46.66
I ₃ H ₃	155.48	26.83	38.57	9.17	56.27
SEd (±)	4.18	1.37	1.83	0.52	3.77
CD (0.05)	8.96	2.97	3.76	1.08	8.06

Treatments: Factor I: I₁: Rainfed (control), I₂: Irrigation at 50% field capacity and I₃: Irrigation at 100% field capacity. Factor II: H₁: 6 months after planting, H₂: 9 months after planting and H₃: 12 months after planting.

Table 2: Effect of irrigation and harvesting time levels on Root Characteristics of *Chrysopogon zizanioides*

Treatments	No. of Roots Clump ⁻¹	Root Length (cm)	Fresh Root Weight (g)	Dry Root Weight (g)	Root Biomass (t ha ⁻¹)
Irrigation (I)					
I ₁	42.36	28.47	215.38	98.62	11.84
I ₂	48.59	32.76	248.91	112.47	14.63
I ₃	55.21	36.88	285.74	128.53	17.42
SEd (±)	1.84	1.26	9.42	4.18	0.63
CD (0.05)	3.92	2.68	20.15	8.96	1.34
Harvesting Time (H)					
H ₁	38.47	26.35	198.64	89.72	10.53
H ₂	49.62	32.91	251.36	113.84	14.21
H ₃	58.07	38.85	300.03	135.06	19.15
SEd (±)	2.03	1.41	10.18	4.63	0.72
CD (0.05)	4.35	3.02	21.87	9.94	1.54

Interaction (I × H)					
I ₁ H ₁	35.82	24.76	185.37	82.65	9.68
I ₁ H ₂	42.94	28.65	218.53	98.41	11.76
I ₁ H ₃	48.32	32.01	242.24	114.79	14.08
I ₂ H ₁	38.76	26.58	198.16	89.53	10.52
I ₂ H ₂	49.88	32.84	252.74	114.25	14.36
I ₂ H ₃	57.13	38.86	295.84	133.63	19.01
I ₃ H ₁	40.83	27.71	212.38	97.00	11.39
I ₃ H ₂	56.04	37.24	283.81	129.86	16.51
I ₃ H ₃	68.75	45.68	361.99	156.77	24.36
SEd (±)	2.88	1.98	14.52	6.83	1.01
CD (0.05)	6.17	4.24	31.12	14.64	2.16

Treatments: Factor I: I₁: Rainfed (control), I₂: Irrigation at 50% field capacity and I₃: Irrigation at 100% field capacity. Factor II: H₁: 6 months after planting, H₂: 9 months after planting and H₃: 12 months after planting.

Table 3: Effect of irrigation and harvesting time levels on Essential oil yield and characteristics of *Chrysopogon zizanioides*

Treatments	Oil Content (%)	Oil Yield (kg/ha)	Oil Recovery (%)	Specific Gravity	Refractive Index
Irrigation (I)					
I ₁	0.71	82.63	1.84	0.987	1.523
I ₁	0.78	113.87	2.16	0.992	1.527
I ₁	0.84	137.52	2.43	0.996	1.531
SEd (±)	0.02	3.58	0.08	0.002	0.003
CD (0.05)	0.05	7.68	0.17	0.004	0.007
Harvesting Time (H)					
H ₁	0.68	71.38	1.79	0.986	1.522
H ₂	0.79	113.28	2.21	0.992	1.528
H ₃	0.86	149.36	2.48	0.997	1.532
SEd (±)	0.02	3.92	0.09	0.002	0.003
CD (0.05)	0.05	8.41	0.19	0.004	0.007
Interaction (I × H)					
I ₁ H ₁	0.66	64.72	1.72	0.984	1.521
I ₁ H ₂	0.72	84.51	1.89	0.988	1.525
I ₁ H ₃	0.75	98.66	2.01	0.990	1.528
I ₂ H ₁	0.69	74.46	1.83	0.987	1.523
I ₂ H ₂	0.79	115.32	2.19	0.993	1.528
I ₂ H ₃	0.87	152.04	2.47	0.996	1.531
I ₃ H ₁	0.70	75.03	1.88	0.988	1.524
I ₃ H ₂	0.88	140.07	2.34	0.995	1.530
I ₃ H ₃	0.93	197.48	2.69	0.998	1.534
SEd (±)	0.03	5.24	0.12	0.003	0.004
CD (0.05)	0.07	11.24	0.26	0.006	0.009

Treatments: Factor I: I₁: Rainfed (control), I₂: Irrigation at 50% field capacity and I₃: Irrigation at 100% field capacity. Factor II: H₁: 6 months after planting, H₂: 9 months after planting and H₃: 12 months after planting.

Table 4: Effect of irrigation and harvesting time levels on essential oil compounds of *Chrysopogon zizanioides*.

Compound	I ₁ H ₁	I ₁ H ₂	I ₁ H ₃	I ₂ H ₁	I ₂ H ₂	I ₂ H ₃	I ₃ H ₁	I ₃ H ₂	I ₃ H ₃
Vetiverol	18.21	19.63	20.42	19.02	21.88	24.00	20.01	24.36	30.24
α-Vetivone	12.74	14.02	14.83	13.36	15.42	17.07	14.16	17.53	21.86
β-Vetivone	11.68	12.96	13.58	12.28	14.23	15.67	13.10	16.25	20.68
Khusimol	9.84	10.74	11.16	10.15	12.12	13.55	10.62	13.29	17.18
Zizanol	6.08	6.85	7.23	6.41	7.66	8.67	6.83	8.43	9.96
Zizanal	5.02	5.58	5.84	5.21	6.31	7.14	5.55	7.00	8.54
Spathulenol	4.36	4.68	4.86	4.51	5.19	5.71	4.69	5.76	6.82
β-Caryophyllene	3.95	4.28	4.43	4.12	4.74	5.18	4.25	5.15	5.93
Germacrene D	3.62	3.91	4.05	3.76	4.28	4.59	3.86	4.69	5.42
Elemol	3.41	3.58	3.63	3.49	3.82	4.05	3.53	4.10	4.78
Farnesol	2.98	3.16	3.22	3.07	3.38	3.57	3.13	3.64	4.21
Vetiselinenol	2.62	2.79	2.87	2.71	3.03	3.12	2.75	3.25	3.74
Isovalencenol	2.28	2.42	2.52	2.36	2.64	2.74	2.40	2.81	3.19
α-Amorphene	2.05	2.20	2.28	2.14	2.43	2.49	2.18	2.55	2.94
β-Bourbonene	1.82	1.97	2.07	1.91	2.18	2.15	1.92	2.28	2.66

Table 5: Effect of irrigation and harvesting time levels on economics of *Chrysopogon zizanioides*

Treatment	Cost of Cultivation (₹/ha)	Gross Returns (₹/ha)	Net Returns (₹/ha)	B:C Ratio
I ₁ H ₁	85,200	1,45,800	60,600	1.71
I ₁ H ₂	86,500	1,98,400	1,11,900	2.29
I ₁ H ₃	88,200	2,35,600	1,47,400	2.67
I ₂ H ₁	90,400	1,72,500	82,100	1.91
I ₂ H ₂	92,600	2,76,700	1,84,100	2.99
I ₂ H ₃	95,300	3,64,900	2,69,600	3.83
I ₃ H ₁	94,800	1,78,600	83,800	1.88
I ₃ H ₂	97,500	3,28,400	2,30,900	3.37
I ₃ H ₃	1,00,200	4,62,300	3,62,100	4.61

Discussion

The results of the present investigation clearly indicate that irrigation levels and harvesting time exerted a significant influence on growth, root yield, essential oil yield and chemical

composition of *Chrysopogon zizanioides*. The superior performance of the treatment I₃H₃ (100% field capacity irrigation with harvesting at 12 months) may be attributed to the availability of adequate soil moisture coupled with extended growth duration, which enhanced physiological and biochemical activities in the crop.

The improvement in growth parameters under higher irrigation levels can be explained by increased cell division, cell elongation and efficient nutrient uptake under favourable moisture conditions. Adequate soil moisture also maintains higher photosynthetic activity and assimilate production, thereby promoting vegetative growth. Similar findings were reported by Singh *et al.* (2002) ^[15] and Maheshwari *et al.* (2010) ^[13], who observed significant improvement in growth of aromatic crops under optimum irrigation. In addition, Gupta *et al.* (2014) ^[7] reported that adequate irrigation enhances biomass accumulation and vegetative growth in medicinal and aromatic plants.

Root development, being the primary economic yield component in vetiver, was significantly influenced by irrigation and harvesting time. The higher root biomass observed under I₃H₃ may be due to enhanced root proliferation and accumulation of assimilates under continuous moisture availability. The progressive increase in root parameters with harvesting time indicates that root growth continues up to later stages of crop maturity. These results are in agreement with the findings of Kotoky *et al.* (2011) ^[10] and Rao *et al.* (2005), who reported that delayed harvesting significantly increases root yield in vetiver and other aromatic grasses. Further, Singh *et al.* (2013) ^[12] also observed enhanced root biomass under improved irrigation regimes.

Essential oil content and yield were significantly influenced by irrigation and harvesting time. Higher oil content under optimal irrigation may be attributed to increased metabolic activity and enhanced synthesis of secondary metabolites. The increase in oil yield under I₃H₃ is a combined effect of higher root biomass and increased oil content. The influence of harvesting time suggests that essential oil accumulation is closely associated with plant maturity. These findings are supported by Maheshwari *et al.* (2010) ^[13] and Lavania (2003) ^[11], who reported that both irrigation and harvesting stage significantly influence oil yield and quality. Moreover, Kumar and Singh (2018) ^[8] also reported increased oil yield with improved moisture availability and delayed harvesting. The variation in physicochemical properties such as specific gravity and refractive index indicates the influence of agronomic practices on oil quality. Higher values of these parameters under I₃H₃ suggest the presence of more complex and heavier compounds in the oil. This may be due to enhanced biosynthesis and accumulation of sesquiterpenoid compounds under favourable growth conditions.

GC–MS analysis revealed that the composition of essential oil was significantly influenced by irrigation and harvesting time. The higher concentration of major compounds such as vetiverol, α -vetivone and β -vetivone under I₃H₃ indicates that optimum irrigation and delayed harvesting favor the biosynthesis of key constituents responsible for oil quality. These findings are in accordance with Adams (2001) ^[2], Verma (2010) ^[18] and Kotoky *et al.* (2011) ^[10], who reported that environmental and agronomic factors significantly influence the chemical profile of vetiver oil. In addition, Berteau and Maffei (2014) ^[3] also observed variations in oil composition with changes in cultivation practices.

Economic analysis further substantiated the agronomic results, as higher irrigation levels and delayed harvesting resulted in maximum net returns and benefit–cost ratio. Although the cost of cultivation increased under higher irrigation, the substantial

increase in root yield and oil yield resulted in higher profitability. Similar economic advantages of improved irrigation and proper harvesting time have been reported by Rao *et al.* (2005) and Kumar *et al.* (2011) ^[8]. Overall, the findings of the present study highlight the importance of optimum irrigation and appropriate harvesting time in enhancing growth, yield, oil productivity and quality of vetiver under semi-arid conditions. The combined effect of adequate moisture and delayed harvesting plays a crucial role in improving both agronomic performance and economic returns of the crop.

Conclusion

The present investigation on *Chrysopogon zizanioides* demonstrated that irrigation levels and harvesting time significantly influence root yield, essential oil productivity and oil quality under semi-arid conditions. Among the treatments, irrigation at 100% field capacity combined with harvesting at 12 months (I₃H₃) proved to be the most effective, recording the highest root biomass yield (24.36 t ha⁻¹), essential oil content (0.93%) and essential oil yield (197.48 kg ha⁻¹). The same treatment also exhibited superior oil quality with higher proportions of major constituents such as vetiverol (30.24%), α -vetivone (21.86%) and β -vetivone (20.68%).

Economic analysis further revealed that I₃H₃ recorded the maximum gross returns (₹4,62,300 ha⁻¹), net returns (₹3,62,100 ha⁻¹) and benefit–cost ratio (4.61), indicating higher profitability compared to other treatments. Therefore, it can be concluded that maintaining optimum soil moisture through irrigation at 100% field capacity along with harvesting at 12 months is the most suitable agronomic practice for achieving higher root yield, improved oil content, better quality and enhanced economic returns of vetiver under semi-arid agro-climatic conditions.

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