PLANT SCIENCE TODAY
ISSN 2348-1900 (online)
Vol x(x): xx–xx
https://doi.org/10.14719/pst.7588

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RESEARCH ARTICLE

Performance of irrigation and fertigation levels on growth and yield potential of chia (*Salvia hispanica* L.) under drip system in the western zone of Tamil Nadu

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OPEN ACCESS

ARTICLE HISTORY
Received: 04 February 2025
Accepted: 08 March 2025
Available online
Version 1.0 : 06 May 2025

Check for updates

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

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CITE THIS ARTICLE
Umilsingh N, Pradeepkumar S, Latha HS, Priya MV, Jeevan N, Prasanna J, Vanathi J, Ammaiyappan A, Venkatesh B, Anushka AS. Performance of irrigation and fertigation levels on growth and yield potential of chia (*Salvia hispanica* L.) under drip system in the western zone of Tamil Nadu . Plant Science Today (Early Access).
https://doi.org/10.14719/pst.7588

Abstract

The field trial was conducted at the Tamil Nadu Agricultural University, Coimbatore, farm unit during the *Rabi* and *Kharif* seasons in 2022 and 2023, respectively. The objective was to evaluate the influence of various fertigation on the productivity of chia. The trial followed a randomized block design (RBD) consisted twelve treatments, duplicated thrice. The outcomes indicated that various irrigation and nutrient management practices substantially impacted chia performance. Plant height, branch counts, leaf area, dry matter production and yield variables (spikes count) were consistently greater in drip fertigation @ 75 % pan evaporation until 30 days after sowing + 100 % pan evaporation until 60 days after sowing + 125 % pan evaporation until 90 days after sowing with 125 % RDF (25 % as normal fertilizer + 75 % as water soluble fertilizer). In both research years (*Rabi* 2022 and *Kharif* 2023), the identical treatment resulted in a considerably greater seed yield of 842 and 772 kg ha^{-1} and biological yield of 3518 and 3159 kg ha^{-1}, respectively. However, when comparing the mean values of the two years, there was a notable reduction in the performance of chia in the second year. The changes detected were dose-dependent and supplement of drip fertigation @ 75 % pan evaporation until 30 days after sowing + 100 % pan evaporation until 60 days after sowing + 125 % pan evaporation until 90 days after sowing with 125 % RDF (25 % as normal fertilizer + 75 % as water soluble fertilizer) concluded better in the crop development and higher potential of yield, gross and net return in chia during both the season. On contrary returns per rupee invested (B: C ratio) was found superior in surface irrigation with soil application of 100 % RDF (T_{13}) in both the season.

Keywords

branches; dry weight; haulm; seed yield; spike counts; spike length

Introduction

Chia (*Salvia hispanica* L.) is a short day, pseudo-cereal herbaceous plant from the *Lamiaceae* family. It is widely sought after for its nutritional content and a dense seed that provides a rich source of omega-3 and omega-6 fatty acids, along with essential nutrients such as dietary fibre (25 %), protein (20 %) and oil

(35 %) (1). It is also packed with minerals, vitamins, antioxidants and amino acids, particularly lysine, crucial for human growth and development. Additionally, chia's nutritional properties contribute to the prevention and management of various diseases, highlighting its significant role in supporting human health and nutrition (2, 3). Chia plant is often grown in Bolivia, the United States, Peru, Colombia and northern Guatemala, despite being instigated in Southern-Mexico and north Guatemalan (4). Parts of the Indian states of Tamil Nadu, Kerala, Karnataka and Madhya Pradesh are used to cultivate the chia crop. However, fulfilling the growing demand for chia seeds, both as a nutritious food for human consumption and as an industrial raw material, presents a significant challenge, mainly when relying on the same cultivable land and limited resources (5). Expanding cultivable land for intensive food crop production is highly restricted. Thus, integrating industrial crops like chia into existing cropping systems with improved management can enhance overall productivity (6). Indian agriculture is characterized mainly by small and marginal farms with limited irrigation, primarily used for staple cereals, pulses, vegetables and commercial crops (7). In semi-arid regions, intercropping chia with locally significant crops could be a viable strategy, as it enhances diversity by incorporating plants with varying root structures, canopy sizes, growth durations and resource needs on the same land (8, 9).

Since the consumption of this crop is expected to reach 80.57 million metric tonnes by 2031, the existing international market for chia, as reported in 2021, was estimated to be worth USD 194.1 million (10). It has been consumed and domesticated as a staple food crop by Mesoamerican Indian Tribes since 2600 BC (11, 12). China and India are poised to witness a growth rate of 6.1 % and 8.9 %, in chia seed production by 2033 (13). The seeds are renowned for their therapeutic qualities, notably in treating cardiovascular diseases, diabetes and constipation. They contain about 30-35 % oil, making them the unlikeliest spring of omega-3 fatty acids, with a concentration exceeding 60 %. These seeds include essential polyunsaturated fatty acids (PUFAs), which are highly sought after for their market value and rich in protein and dietary fibre (14, 15). The fibre on the seed coat creates a mucilaginous substance that is highly viscous, hygroscopic and sticky and offers broad applicability in industries and medicine (16). Chia has been proposed as a suitable crop for semi-arid weather, however, the agronomic mark is limited. Though nothing is known about how much water chia needs, it is said to flourish in rainfed or irrigated environments. Throughout the growing period, chia growth reacts highly well to precipitation ranging from 300 to 1000 mm (17). The agronomic practices for producing chia in India are somewhat obscure, with few studies on its adaptability to Indian conditions. Due to the increasing demand for chia both domestically and internationally, it has the potential to become a viable crop for Indian soils and climate.

As a new entrant to the Indian agricultural landscape, evaluating the economic feasibility and suitability of chia cultivation, particularly in subtropical regions with limited irrigation access, is essential. This assessment is crucial for growers seeking sustainable production and financial benefits. While many areas of India possess appropriate soil and climate conditions for chia, there is a notable lack of information regarding its irrigation needs and the best agronomic practices, especially in water constraints. In todays' world, the rising cost of fertilizers necessitates implementing of agronomic techniques that efficiently utilize inputs. Sustainable agriculture requires the careful management of natural resources, particularly water, which is crucial for food security and accounts for nearly 80 % of total usage in farming. Limited access to quality irrigation increases crop vulnerability, often resulting in failures (18, 19). Chia seeds are highly sought after due to their rich content of α-linolenic acid and metabolites with industrial and pharmaceutical significance (20). As a result, their cultivation is expanding even into resource-constrained and less favourable agro-ecological regions. However, there is currently no available data on chia growth and productivity under different irrigation regimes or potential nutrient strategies in the semi-arid climate of the Deccan Plateau (Agro-Ecological Region-6) in India, where small and marginal farmers primarily rely on short-duration vegetable crops for their income (21). Consequently, the purpose is study aimed to understand better how fertigation and drip irrigation affect the development and production of chia.

Materials and Methods

A two-year field testing was done at the farm unit, Tamil Nadu Agricultural University, Coimbatore, located at latitude of 11° N and longitude of 77° E, 426.7 m altitude AMSL, during the *Rabi* season (August to December 2022) and the *Kharif* season (May to Sept 2023). The investigational site falls under the water insufficiency of the western zone of Tamil Nadu. The research site had a clayey texture, with 27.18 % sand, 12.56 % silt and 42.53 % clay, with somewhat alkaline pH (8.2), moderate level of organic carbon (0.65 %), diminished levels of accessible nitrogen (225 kg ha^{-1}), moderate levels of phosphorus (18.0 kg ha^{-1}) and elevated levels of accessible potassium (595 kg ha^{-1}). Also contains 37.3 % of the field capacity, 21.5 % permanent wilting point, 16.3 % of available water holding capacity and 1.3 % of soil bulk density. The weather parameters recorded at the Agro-Meteorological Observatory of the Agricultural College and Research Institute, Coimbatore, indicate that the average climatic conditions of Coimbatore, based on 50 years of weather data, show a mean annual rainfall of 672.4 mm occurring over 44.6 rainy days. In *rabi* 2022 and *kharif* 2023, rainfall totalled 359.1 mm and 94.9 mm, respectively. The average maximum (30.4° C and 32.9°C) and lowest temperature (22.3°C and 23.7°C) were registered in *Rabi* 2022 and *Kharif* 2023, respectively, with the average daily pan evaporation of 4.8 and 5.9 mm day^{-1} in both years (Fig. 1-2).

Experimental details

The field experiment included thirteen treatments distributed in a randomized block design, each reproduced thrice. The given treatments are given below in Table 1.

Installation of drip system and crop management

A drip irrigation system with one main line and three submain lines was installed, featuring laterals spaced 0.8 m apart and emitters having discharge frequency of 4 lph, positioned 0.3 m apart. Irrigations were scheduled once every three days based

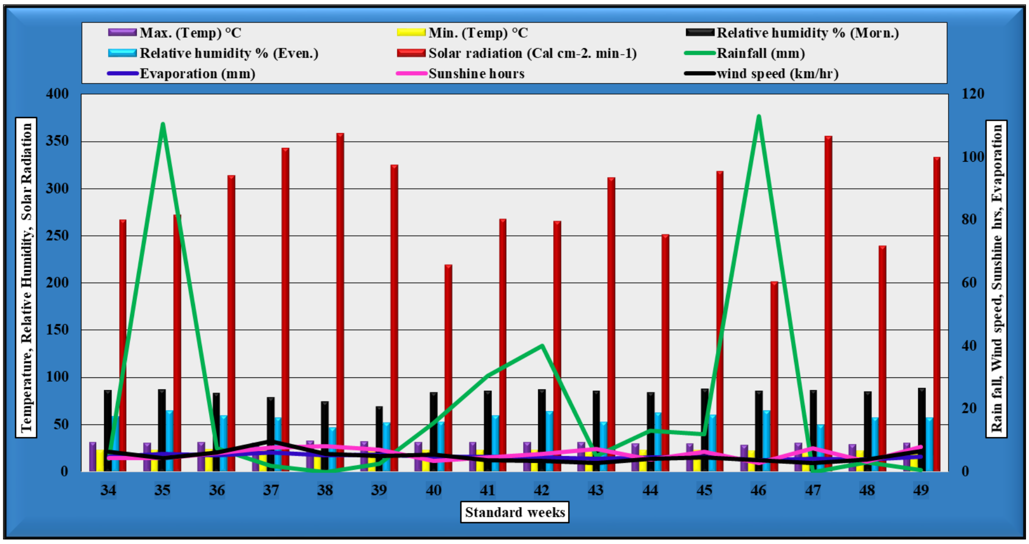

Fig. 1. Weather parameters prevailed during the cropping period of chia *Rabi* 2022.

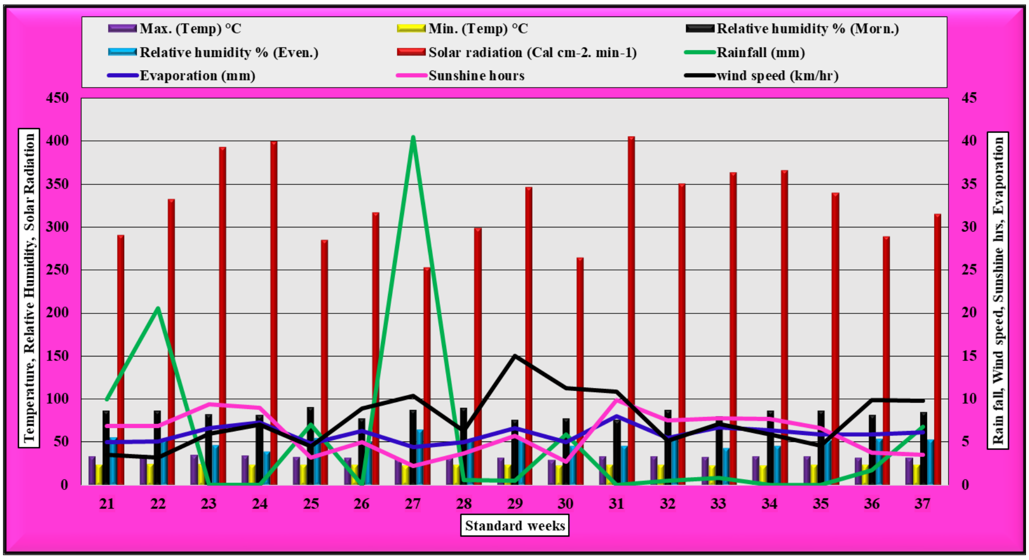

Fig. 2. Weather parameters prevailed during the cropping period of chia Kharif 2023.

Table 1. Treatments details of the chia experiment

Treatments		Treatment details
T_1	:	DF @ 25 % PE until 30 DAS + 50 % PE until 60 DAS + 75 % PE until 90 DAS with 75 % RDF (75 % as NF + 25 % as WSF)
T_2	:	DF @ 50 % PE until 30 DAS + 75 % PE until 60 DAS + 100 % PE until 90 DAS with 75 % RDF (50 % as NF + 50 % as WSF)
T_3	:	DF @ 75 % PE until 30 DAS + 100 % PE until 60 DAS + 125 % PE until 90 DAS with 75 % RDF (25 % as NF + 75 % as WSF
T_4	:	DF @ 25 % PE until 30 DAS + 50 % PE until 60 DAS + 75 % PE until 90 DAS with 100 % RDF (75 % as NF + 25 % as WSF)
T_5	:	DF @ 50 % PE until 30 DAS + 75 % PE until 60 DAS + 100% PE until 90 DAS with 100 % RDF (50 % as NF + 50 % as WSF)
T_6	:	DF @ 75 % PE until 30 DAS + 100 % PE until 60 DAS + 125 % PE until 90 DAS with 100 % RDF (25 % as NF + 75 % as WSF)
T_7	:	DF @ 25 % PE until 30 DAS + 50 % PE until 60 DAS + 75 % PE until 90 DAS with 125 % RDF (75 % as NF + 25 % as WSF)
T_8	:	DF @ 50 % PE until 30 DAS + 75 % PE until 60 DAS + 100 % PE until 90 DAS with 125 % RDF (50 % as NF + 50 % as WSF)
T_9	:	DF @ 75 % PE until 30 DAS + 100 % PE until 60 DAS + 125 % PE until 90 DAS with 125 % RDF (25 % as NF + 75 % as WSF)
T_{10}	:	DI @ 25 % PE until 30 DAS + 50 % PE until 60 DAS + 75 % PE until 90 DAS with 100 % RDF as soil application of conventional
T_{11}	:	DI @ 50 % PE until 30 DAS + 75 % PE until 60 DAS + 100 % PE until 90 DAS with 100 % RDF as soil application of conventional
T_{12}	:	DI @ 75 % PE until 30 DAS + 100 % PE until 60 DAS + 125 % PE until 90 DAS with 100 % RDF as soil application of conventional fertilizer
T_{13}	:	Surface watering and application of 100 % RDF (IW/CPE ratio of 1 with 5 cm deep of irrigation water)

DF: Drip fertigation; DI: Drip irrigation; PE: Pan evaporation; DAS: Days after sowing; RDF: Recommended dose of fertilizer; IW: Irrigation water; CPE: Cumulative pan evaporation; NF: Normal fertilizer; WSF: Water soluble fertilizer

on daily evaporation values (USWB-A open pan evaporimeter) till 90 DAS as required by treatments (T_1 to T_{12}). For surface irrigation (T_{13}), a 5.0 cm deep with an IW/CPE ratio 1.0 was used. Fertilizer applications, including 80:60:60 NPK kg ha^{-1}, were given by fertigation in all plots with equal amounts at 10 day intervals as required by treatments (T_1-T_9) till 90 DAS. Total P_2O_5 and K_2O and 50 % of N were utilized as basal and the lasting 50 % N split into times at 30 and 60 days after sowing for treatments T_{10} to T_{13}. For soil supplements, urea, di-ammonium phosphate and muriate of potash were used as standard fertilizers, while calcium ammonium nitrate, mono-ammonium phosphate and potassium nitrate were employed for fertigation to supply nitrogen, phosphorus and potassium, respectively. Two initial irrigations were uniformly applied after seeding to guarantee germination and establishment. The Chia cultivar GKVK Chiampion B-1 was planted with 40 × 30 cm spacing.

Economics

The total cost of cultivation was worked out based on prevailing market rates for various inputs and labour for different operations. The cost of a drip irrigation unit per season was computed by dividing the capital investment on the drip irrigation unit by its lifespan, which was assumed to be 7 years. Gross returns per hectare were calculated based on the local market price at harvest and net returns by subtracting the corresponding cost of cultivation from the respective gross returns. The net returns per rupee invested (B: C ratio) were calculated using the equation 1 (22).

$$\text{B:C ratio}=\frac{\text{Gross return (₹ha}^{-1})}{\text{Total cost of cultivation (₹ha}^{-1})} \quad \text{(Eqn.1)}$$

Data collection involved assessing five casually chosen plants from each plot. Statistical examination of the investigational data using the method of analysis of variance (ANOVA) in the SPSS software (Statistical Package for the Social Sciences) (23).

Results

During two years of experimentation (*Rabi* 2022 and *Kharif* 2023) amongst all the treatments drip fertigation @ 75 % PE until 30 DAS + 100 % PE until 60 DAS + 125 % PE until 90 DAS with 125 % RDF (25 % as NF + 75 % as WSF) shown the most significant improvements in plant growth, yield and yield determinants.

Growth attributes

The data on growth components of chia positively inclined by irrigation and fertigation levels (Table 2). The most effective treatment, among all tested, was found to be with DF @ 75 % PE until 30 DAS + 100 % PE until 60 DAS + 125 % PE until 90 DAS with 125 % RDF (25 % as NF + 75 % as WSF) (T_9). This treatment demonstrated significantly superior results, recorded enhanced taller plants, branch counts plant^{-1}, leaf area and dry matter accumulation (106.5 cm, 18.3, 4355 cm^2 and 109.2 g, respectively) during *Rabi* 2022 and *Kharif* 2023 (98.5 cm, 15.5, 3857 and 105.0 g, respectively) in chia. However, it was on par with treatment T_6 and T_8 concerning all the above growth metrics in both seasons. While, the T_1 tested plot noticed decreased plant height (68.1 and 63.6 cm), no. of branches plant^{-1} (10.1 and 9.4), leaf area (2117 and 1626 cm^2) and dry matter production plant^{-1}(80.2 and 75.4 g) during *Rabi* 2022 and *Kharif* 2023, respectively (Fig. 5-6).

Yield attributes

Table 3 shows that chia grown under drip irrigation and fertigation levels generated spikes in count/plant at all growth stages in both years. The crop that received T_9 irrigation had significantly more spikes counts per plant at 60, 90 DAS and harvest (9.6, 61.5 and 66.8 in *Rabi* 2022; 9.0, 56.1 and 62.3 in *Kharif* 2023, respectively). However, it showed significant variations with treatment T_6 and T_8followed by T_{12} at 60 DAS. Similarly, at 90 DAS and harvest stage, T_9 was statistically comparable to T_6 and T_8-. However, further irrigated treatment T_1 reduced spikes at 60, 90 DAS and harvest (4.8, 30.8 and 33.8 in first season; 3.8, 27.2 and 30.7 in the second season, respectively). Nevertheless, the inflorescence length ranged from 10.9 cm to 15.8 cm during *Rabi* 2022 and from 11.6 cm to 16.7 cm in *Kharif* 2023 and was failed to register significant difference (Fig. 7-8).

Yield

The productivity of chia was significantly affected by both fertigation and irrigating techniques (Table 4). Among other irrigation techniques, the greatest chia seed production of T_9 is about 842 and 772 kg ha^{-1} in *Rabi* 2022 and *Kharif* 2023, respectively. This was superior to other treatments and closely associated with T_6 (803 and 682 kg ha^{-1}) than came by T_8 (724 and 619 kg/ha). Likewise, the maximum haulm yield of 3518 and 3159 kg ha^{-1} was obtained with a similar treatment (T_9), it was statistically superior over other treatments and comparable with T_6, T_8, T_3 and T_{12} followed by T_{13} in *Rabi* 2022 and T_6, T_{12}, T_8 and T_3 in *Kharif* 2023. The *Rabi* 2022 crop yields were more significant than the *Kharif* 2023. This might be attributed to two factors: the crop received 359.1 mm of precipitation throughout its growth and was irrigated with lesser water. Conversely, lower seed and haulm yield values, about 382 and 2376 kg ha^{-1} during *Rabi* 2022; while 313 and 2108 kg ha^{-1} *Kharif* 2023 were recorded with treatment receiving T_1.

Table 2. Influence of drip irrigation and fertigation levels on growth parameters of chia during *Rabi* 2022 and *Kharif* 2023

Treatment	*Rabi* 2022				*Kharif* 2023			
	Plant height	No. of branches	Leaf area plant^{-1} (cm^2)	Dry matter production	Plant height (cm)	No. of branches	Leaf area plant^{-1} (cm^2)	Dry matter production
T_1	68.1 ± 4.5	10.1 ± 0.6	2117 ± 93	80.2 ± 3.5	63.6 ± 1.2	9.4 ± 0.3	1626 ± 53	75.4 ± 2.8
T_2	69.3 ± 1.5	10.7 ± 0.7	2287 ± 159	83.3 ± 0.4	65.2 ± 1.6	10.0 ± 0.1	1939 ± 4	77.4 ± 1.6
T_3	91.7 ± 1.6	14.6 ± 0.6	3446 ± 154	99.2 ± 6.9	87.3 ± 1.3	12.2 ± 0.8	2874 ± 163	94.5 ± 1.9
T_4	75.4 ± 3.4	11.9 ± 0.4	2390 ± 95	86.8 ± 0.5	70.2 ± 3.5	10.4 ± 0.5	2239 ± 12	81.5 ± 0.5
T_5	88.6 ± 6.3	14.0 ± 0.6	3222 ± 129	95.1 ± 5.8	84.5 ± 1.3	11.4 ± 0.6	2562 ± 92	90.9 ± 2.2
T_6	99.2 ± 2.9	17.5 ± 0.8	4074 ± 167	105.9 ± 1.3	92.8 ± 5.4	14.3 ± 0.5	3616 ± 80	101.6 ± 3.6
T_7	78.7 ± 4.5	12.4 ± 0.8	2700 ± 118	88.5 ± 3.3	72.6 ± 1.7	10.6 ± 0.8	2264 ± 12	84.0 ± 1.2
T_8	96.6 ± 4.6	16.6 ± 0.4	3755 ± 194	102.3 ± 3.7	90.6 ± 5.1	14.0 ± 0.6	3389 ± 249	98.3 ± 4.3
T_9	106.4 ± 3.7	18.3 ± 1.8	4355 ± 141	109.2 ± 1.1	98.5 ± 2.0	15.5 ± 0.6	3857 ± 242	105.0 ± 7.0
T_{10}	72.7 ± 4.3	11.5 ± 0.4	2215 ± 86	83.6 ± 5.4	67.6 ± 2.7	11.0 ± 1.0	2110 ± 93	79.9 ± 0.9
T_{11}	82.3 ± 2.1	12.9 ± 0.5	2884 ± 121	91.1 ± 0.8	75.1 ± 1.6	11.2 ± 0.6	2516 ± 145	88.3 ± 1.0
T_{12}	94.8 ± 0.8	15.5 ± 0.8	3551 ± 151	99.0 ± 3.9	88.0 ± 5.5	13.3 ± 0.7	3036 ± 189	97.1 ± 0.5
T_{13}	85.5 ± 4.8	13.3 ± 0.7	3096 ± 114	94.4 ± 0.6	82.0 ± 4.4	11.4 ± 0.7	2500 ± 141	89.7 ± 5.2
SE.m±	3.85	0.73	216	3.30	3.42	0.57	162	2.64
CD (P=0.05)	11.24	2.12	627	9.65	9.99	1.67	473	7.73

- Treatment details are given under Materials and Methods; *S-Significant; NS-Non significant
- The values represent the averages (±SE) of independent replicates, significantly different at P ≤ 0.05, according to Duncan's Multiple Range test.

Table 3. Influence of drip irrigation and fertigation levels on yield attributes of chia during *Rabi* 2022 and *Kharif* 2023

Treatments	*Rabi* 2022				*Kharif* 2023			
	Number of spikes plant^{-1}			Spike length (cm)	Number of spikes plant^{-1}			Spike length (cm)
	60 DAS	90 DAS	At harvest		60 DAS	90 DAS	At harvest	
T_1	4.8 ± 1.0	30.8 ± 3.3	33.8 ± 3.2	10.9 ± 0.9	3.8 ± 0.6	27.2 ± 2.5	30.7 ± 2.0	11.6 ± 1.6
T_2	5.2 ± 1.1	33.7 ± 3.4	38.4 ± 3.1	12.0 ± 1.2	4.4 ± 0.8	28.1 ± 2.2	32.5 ± 2.2	12.4 ± 1.8
T_3	8.1 ± 0.8	49.4 ± 3.8	53.4 ± 3.8	14.2 ± 1.9	7.5 ± 1.5	45.7 ± 3.4	50.5 ± 3.4	13.5 ± 0.8
T_4	6.3 ± 0.5	39.1 ± 2.6	44.8 ± 2.5	13.0 ± 1.1	5.5 ± 1.2	34.9 ± 3.7	38.9 ± 3.7	11.8 ± 1.2
T_5	7.8 ± 1.5	46.6 ± 3.6	49.9 ± 3.9	13.7 ± 1.0	7.1 ± 1.0	43.1 ± 3.5	46.5 ± 3.8	15.3 ± 1.7
T_6	9.3 ± 1.3	58.5 ± 3.2	63.5 ± 3.2	15.6 ± 1.0	8.4 ± 0.7	53.0 ± 3.4	57.8 ± 3.4	16.3 ± 1.3
T_7	6.9 ± 1.0	42.6 ± 2.9	48.6 ± 2.9	13.0 ± 1.2	6.1 ± 1.2	36.8 ± 4.2	40.3 ± 4.5	12.5 ± 1.4
T_8	8.8 ± 0.7	55.4 ± 4.0	60.1 ± 4.3	15.2 ± 0.8	7.8 ± 1.3	49.5 ± 3.6	54.5 ± 3.6	15.6 ± 1.8
T_9	9.6 ± 0.9	61.5 ± 5.2	66.8 ± 4.9	15.8 ± 0.6	9.0 ± 1.2	56.1 ± 2.5	62.3 ± 2.7	16.7 ± 1.1
T_{10}	5.8 ± 0.3	36.9 ± 1.7	40.9 ± 1.7	11.6 ± 0.7	4.9 ± 0.7	32.0 ± 3.4	36.1 ± 3.5	10.4 ± 1.2
T_{11}	7.5 ± 0.9	44.2 ± 2.1	47.8 ± 1.8	13.4 ± 0.5	6.6 ± 1.0	40.9 ± 2.5	44.1 ± 2.2	12.3 ± 1.1
T_{12}	8.4 ± 0.9	52.1 ± 3.3	58.0 ± 3.3	15.0 ± 0.9	7.7 ± 1.3	47.9 ± 3.3	53.0 ± 3.2	15.7 ± 1.6
T_{13}	7.5 ± 1.2	44.4 ± 3.9	48.4 ± 2.9	13.7 ± 0.7	6.6 ± 0.9	41.1 ± 3.0	46.5 ± 3.0	13.7 ± 1.8
SE.m±	**0.48**	**3.11**	**2.98**	**1.06**	**0.47**	**2.69**	**2.87**	**1.42**
CD (P=0.05)	**1.4**	**9.1**	**8.7**	**NS**	**1.38**	**7.84**	**8.35**	**NS**

- Treatment details are given under Materials and Methods; *S-Significant; NS-Non significant
- The values represent the averages (±SE) of independent replicates, significantly different at P ≤ 0.05, according to Duncan's Multiple Range test.

Table 4. Influence of drip irrigation and fertigation levels on yield (kg ha^{-1}) of chia during Rabi 2022 and Kharif 2023

Treatments	*Rabi* 2022			*Kharif* 2023		
	Seed yield (kg ha^{-1})	Haulm yield (kg ha^{-1})	Harvest index	Seed yield (kg ha^{-1})	Haulm yield (kg ha^{-1})	Harvest index
T_1	382 ± 56	2376 ± 67	0.14 ± 0.02	313 ± 58	2108 ± 70	0.13 ± 0.02
T_2	417 ± 11	2397 ± 47	0.15 ± 0	364 ± 60	2334 ± 83	0.14 ± 0.02
T_3	669 ± 49	3278 ± 165	0.17 ± 0.01	546 ± 31	2930 ± 124	0.16 ± 0
T_4	490 ± 26	3026 ± 24	0.14 ± 0.01	389 ± 55	2665 ± 101	0.13 ± 0.02
T_5	632 ± 49	3157 ± 58	0.17 ± 0.01	517 ± 52	2835 ± 74	0.15 ± 0.01
T_6	803 ± 37	3343 ± 38	0.19 ± 0.01	682 ± 31	2993 ± 111	0.19 ± 0.01
T_7	546 ± 52	3007 ± 188	0.16 ± 0.02	443 ± 60	2679 ± 147	0.14 ± 0.02
T_8	724 ± 39	3321 ± 164	0.18 ± 0.01	619 ± 46	2963 ± 110	0.17 ± 0.01
T_9	842 ± 25	3518 ± 89	0.19 ± 0.01	772 ± 51	3159 ± 68	0.2 ± 0.01
T_{10}	438 ± 29	2484 ± 93	0.15 ± 0.01	345 ± 49	2316 ± 199	0.13 ± 0.02
T_{11}	574 ± 75	3078 ± 162	0.16 ± 0.02	459 ± 63	2767 ± 36	0.14 ± 0.02
T_{12}	700 ± 67	3211 ± 154	0.18 ± 0.02	583 ± 52	2977 ± 67	0.16 ± 0.02
T_{13}	581 ± 40	3176 ± 57	0.15 ± 0.01	489 ± 48	2833 ± 91	0.15 ± 0.01
SE.m±	**48**	**119**	**0.01**	**53**	**109**	**0.02**
CD (P=0.05)	**140**	**348**	**NS**	**156**	**318**	**NS**

- Treatment details are given under Materials and Methods; *S-Significant; NS-Non significant
- The values represent the averages (±SE) of independent replicates, significantly different at P ≤ 0.05, according to Duncan's Multiple Range test.

Economics

Diverse levels of drip irrigation and fertigation showed significant variations on gross return, net return and B: C ratio during *Rabi* 2022 and *Kharif* 2023, as mentioned in Fig. 3-4. Significantly, the maximum amount of gross return (₹ 168455 and ₹ 154447 ha^{-1}) and net returns (₹ 94711 and 79853 ha^{-1}) was recorded under treatment T_9 during *Rabi* 2022 and *Kharif* 2023, respectively and on par with T_6 (₹ 160690 and ₹ 136398 ha^{-1}) and T_8 (₹ 144837 and ₹ 123736 ha^{-1}) in terms of gross returns and T_6 (₹ 92927 ha^{-1} and ₹ 67786 ha^{-1}) with T_{12} (₹ 83355 ha^{-1} and ₹ 59384 ha^{-1}) and with T_8 (₹ 78581 and 56630 ha^{-1}) in terms of net returns, respectively during *Rabi* 2022 and *Kharif* 2023, respectively. The least was in treatment T_1, recorded to the tune of ₹ 76,473 and ₹ 62,657 ha^{-1} gross return and ₹ 23,679 and 9,012 ha^{-1} net returns during both years. The benefit-cost ratio was registered higher under surface irrigation with soil application of 100 % RDF (T_{13}) (2.61 in *Rabi* 2022 and 2.09 in *Kharif* 2023) than others, which was statistically comparable with the ratio of 2.47, 2.37, 2.28, 2.19 and 2.16 under treatments of T_{12}, T_6, T_9, T_8 and T_3, correspondingly in *Rabi* 2022. Similar results were also obtained in *Kharif* 2023. The lowest B: C ratio was recorded with treatment T_1 (1.45 in 1st season and 1.17 in 2nd season).

Discussions

As the volume of irrigation water grew, so did the average values of the growth metrics. Across both experimental seasons, treatment T_9 consistently exhibited taller plants with more branches at harvest compared to other treatments (Fig. 5-6). A crops ability to absorb more nutrients and enhance photosynthesis may have been facilitated by optimal moisture in the rhizosphere. Consequently, photosynthates were more translocated to the growth regions, resulting in increased cell elongation and higher counts of branches per plant (24). Additionally, adding fertilizer that dissolves in water boosted the absorption and build-up of other nutrients like potassium and phosphorus (25, 26). Treatments with more branches and leaves effectively utilized available resources, resulting in a proportionately larger leaf area. In well-irrigated plants, the higher total dry weight is indicates increased photosynthesis due to the higher conductance of stomata, which is directly correlated to water supply and requirement for atmospheric evaporation (27). Similar, greater DMP can be caused by increased leaf area and leaf area index even during harvest because of optimal fertigation level (28). The significant reduction (T_1) might result from a plant response to water scarcity by shutting its stomata, which lowers carbon dioxide intake and consequently, reduces the carbon assimilation rate (29). Deficit irrigation

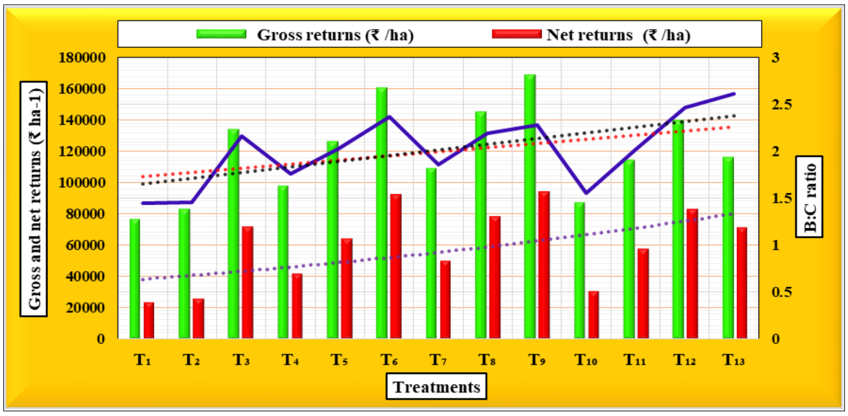

Fig. 3. Influence of drip fertigation on the economics of chia in Rabi 2022. This graph shows the treatments on the horizontal x-axis and gross and net returns on the primary and B:C ratio on the secondary y-axis vertically in Rabi 2022.

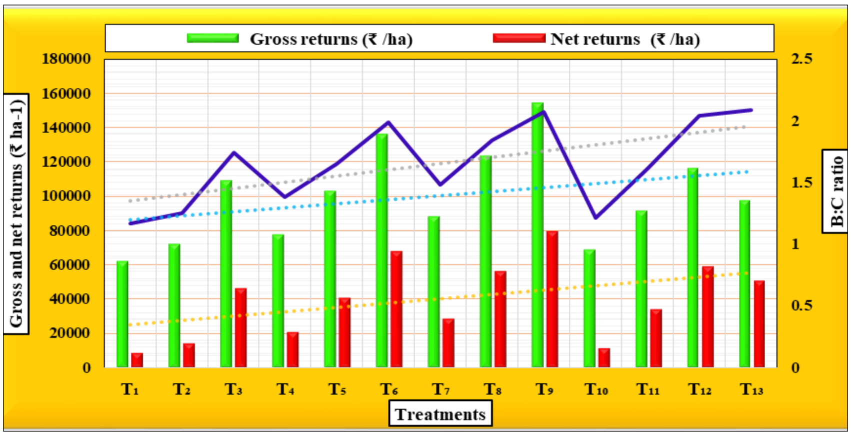

Fig. 4. Influence of drip fertigation on the economics of chia in Kharif 2023. This graph shows the treatments on the horizontal x-axis and gross and net returns on primary and B:C ratio on the secondary y-axis vertically in Kharif 2023.

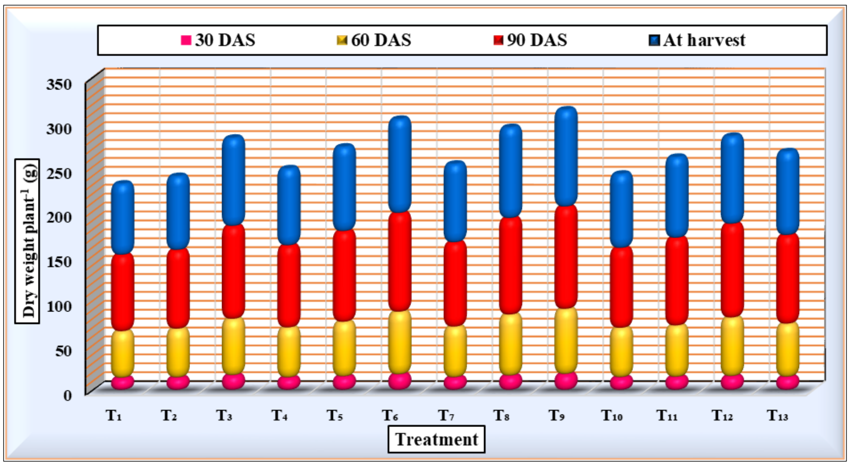

Fig. 5. Influence of drip fertigation on dry matter production (g plant^{-1}) of chia at various growth stages in *Rabi* 2022. This graph shows the treatments on the horizontal x-axis dry weight plant^{-1} (g) on the y-axis vertically in *Rabi* 2022.

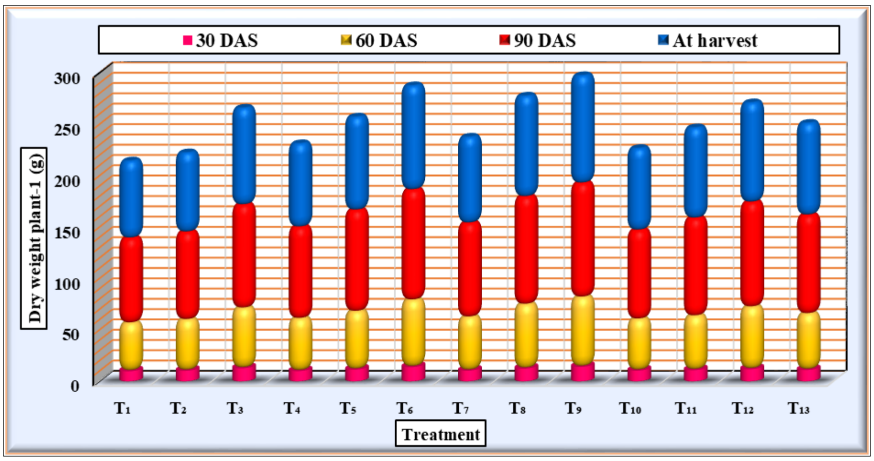

Fig. 6. Influence of drip fertigation on dry matter production (g plant^{-1}) of chia at various growth stages in Kharif 2023. This graph shows the treatments on the horizontal x-axis dry weight plant^{-1} (g) on the y-axis vertically in Kharif 2023.

reduced chia dry biomass, with non-irrigated chia plants showing a 31.8-38.3 % decrease compared to 100 % irrigated ones (30, 31). A 30-60 % deficiency irrigation impacted the transpiration and photosynthesis of chia, which may have inhibited the chia growth. These outcomes are consistent with previous conclusions (27, 32).

Higher yield attributes under drip fertigation were due to enhanced growth parameters and establishment of a better source-sink relationship (Fig. 7-8). This was because water-soluble fertilizers were more readily available and maintained optimal soil moisture near field capacity in the dynamic rhizosphere. This reduction in soil suction, improves water utilization, nutrient uptake and the maintenance of the soil-water-plant relationship compared to regular fertilizers. Divided application of fertilizers in drip irrigation coincided with the actual needs of the crop for up to eighty days and promoted good development and produced maximum yield variables (33, 34). The increased availability of soil nutrients through fertigation during the crop period likely contributed to the higher spike count/plant and length of spike (14, 35, 36). Lower yield components were primarily due to reduced growth attributes, leading to decreased nutrient absorption and a smaller photosynthetically active surface area, resulting in fewer spikes per plant (37, 38).

The higher yield levels are associated with higher yield attributes such as a several spikes and longer spikes. These outcomes supported the conclusions of (3), which found that chia productivity was enhanced by fertilizer applications up to 80:60:60 NPK kg ha^{-1}. The increased seed output might also be attributed to the high irrigation frequency, which kept the soil wet during the crops advancement (31, 39, 40). The main cause of this production loss in deficit irrigation was a decline in yield determinants such as harvest index, spike length and number of spikes/plant. In earlier research, the decreasing concentration of seed/spike under inadequate watering was linked to the decrease in chia yield (27). Various levels of fertigation were shown to have insignificant effects on the harvest index. However, the appreciable improvement of the harvest index with T_9 was mainly due to higher economic output (seed yield). The least harvest index was detected in unceasing stress imposed in T_1. Similar consequences were confined to the previous outcomes (28).

Drip fertigation with varied levels of water and nutrients registered a difference in gross, net returns and B: C ratio as compared to surface irrigation with soil application of 100 % RDF (Fig. 3-4). Higher gross and net income were worked out in both years with T_9. Lower gross income and net income were reported under T_1. The higher gross and net income per unit water consumption and net extra income over the surface irrigation method for either hectare basis or on equal water usage were more promising in drip irrigation (41). This was mainly because, these treatments out yielded in grain as compared to the rest of the treatments and also due to the lesser cost incurred for fertilizer in surface irrigation with soil application of 100 % RDF (T_{13}) as compared to other treatments and higher cost of water-soluble fertilizer involved in the case of all drip fertigated treatments during both years of experimentation (42).

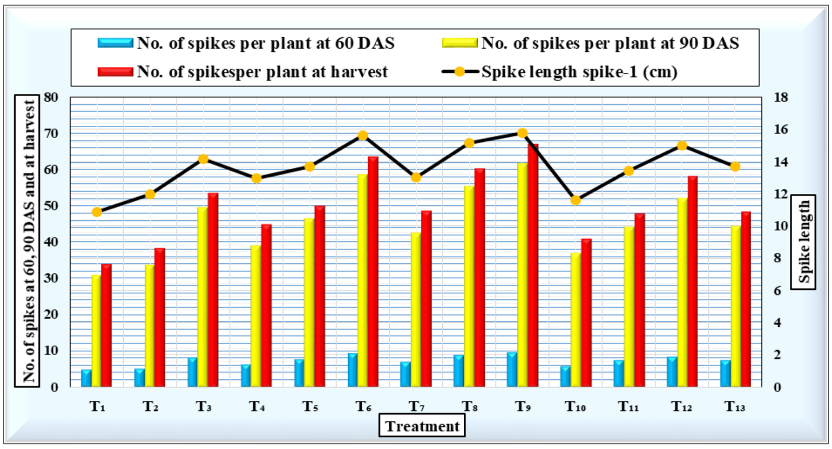

Fig. 7. Influence of drip fertigation on yield attributes of chia in *Rabi* 2022. This graph shown the treatments on the horizontal x-axis and no. of spikes $plant^{-1}$ (at 60, 90 DAS and Harvest) on primary and spikes length $spike^{-1}$ (cm) on the secondary y-axis vertically in *Rabi* 2022.

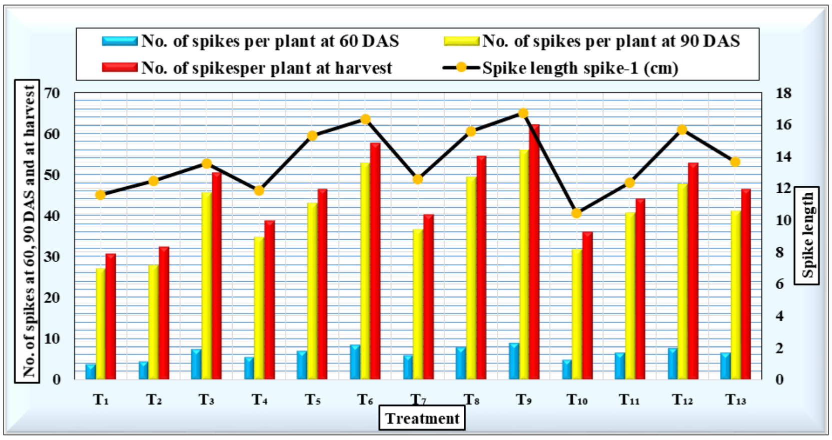

Fig. 8. Influence of drip fertigation on yield attributes of chia in Kharif 2023. Graph shown the treatments on the horizontal x-axis and no. of spikes $plant^{-1}$ (at 60, 90 DAS and Harvest) on primary and spikes length $spike^{-1}$ (cm) on the secondary y-axis vertically in Kharif 2023.

Conclusion

After 2 years of investigation, it was concluded that the treatment involving drip fertigation @ 75 % pan evaporation until 30 days after sowing + 100 % pan evaporation until 60 days after sowing + 125 % pan evaporation until 90 days after sowing with 125 % Recommended dose of fertilizer (25 % as normal fertilizer + 75 % as water soluble fertilizer) (T_9) demonstrated higher growth and yield components as well as yield and gross and net returns compared to alternative treatments. Furthermore, the same treatment exhibited statistically superior seed and haulm yield compared to the other treatments. On the contrary, in both the seasons found higher net returns per rupee invested (B: C ratio) in surface irrigation with soil application of 100 % RDF (T_{13}).

Further investigations are needed to optimize the drip fertigation parameters for chia, considering variations in climatic conditions, soil types and crop varieties. Explore the potential for tailoring fertigation strategies to enhance specific nutritional aspects of the crop.

Acknowledgements

The senior author expresses deep gratitude to the Ministry of Tribal Affairs, Government of India, for funding the research and farm and laboratory facilities at Tamil Nadu Agricultural University in Coimbatore for the research trials.

Authors' contributions

NU conducted the experiment, investigation, did formal data analysis and wrote the original draft. SP, HL and MP participated in the development of the concept, supervision and editing of the manuscript. NJ, JP and JV provided the resources, done writting the review, editing and provided the funding acquisition resources. AA, BV and AS developed the software, provided funding assistance and wrote and edited reviews.

Compliance with ethical standards

Conflict of interest: The authors have said there were no conflicts of interest.

Ethical approval: None

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