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Interactive Effects of Water Stress and Foliar Application of Agrochemicals on Productivity and Profitability of Chia (*Salvia hispanica* L.) under Arid Conditions

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ABSTRACT

A field experiment was conducted during the *rabi* season of 2024-25 at the College of Agriculture, Agriculture University, Jodhpur (Rajasthan), to evaluate the effect of water stress and foliar application of agrochemicals on productivity and profitability of chia (*Salvia hispanica* L.). The experiment was carried out in a split plot design with three irrigation levels, recommended irrigation (I_0), one irrigation skip (I_1) and two irrigation skips (I_2), as main-plot treatments and four foliar-applied agrochemicals, control (C_0), thiourea @ 2% (C_1), potassium nitrate @ 100 ppm (C_2) and salicylic acid @ 100 ppm (C_3), as sub-plot treatments, replicated thrice. Results revealed that deficit irrigation significantly reduced growth and yield of chia. Recommended irrigation recorded the highest plant height, dry matter accumulation, yield attributes and seed yield (540.02 kg ha^{-1}). Among agrochemicals, foliar application of potassium nitrate proved most effective, producing maximum spikes per plant (13.28), spike length (11.28 cm), spike weight (12.28 g) and seed yield (507.25 kg ha^{-1}). Economic analysis showed the highest gross return (₹81,575 ha^{-1}), net return (₹48,302 ha^{-1}) and B:C ratio (2.45) under recommended irrigation, while potassium nitrate recorded maximum profitability among agrochemicals (B:C ratio 2.45). The study concludes that integration of adequate irrigation with foliar application of potassium nitrate is an effective strategy for enhancing productivity and profitability of chia under arid conditions.

Keywords Chia, Water stress, Agrochemicals, Yield, Economics.

INTRODUCTION

Global agricultural production systems are increasingly challenged by climate change, induced water scarcity, particularly in arid and semi-arid regions, where crop productivity and farm profitability are

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severely constrained. Efficient water management strategies that ensure both yield stability and economic sustainability are therefore essential for enhancing resilience of agricultural systems under such environments. In this context, identification of crops and management practices that can maintain productivity with reduced water inputs has become a major research priority.

Chia (*Salvia hispanica* L.), a member of the family *Lamiaceae*, has emerged as an important climate resilient crop owing to its moderate drought tolerance, low input requirement and exceptional nutritional value. Native to Central America, chia has gained global recognition as a functional food and superfood due to its high energy content, rich concentration of omega-3 fatty acids, proteins, dietary fiber, minerals and antioxidant compounds (Muñoz *et al.* 2012, USDA 2011). Owing to its expanding market demand, chia is increasingly being introduced into non-traditional growing regions, including India (Pravalika *et al.* 2024).

In India, particularly in the arid and semi-arid regions of Western Rajasthan, chia offers promising potential as an alternative high-value crop. Previous studies have reported seed yields ranging from 600 to 2500 kg ha^{-1} depending on climatic conditions, irrigation management and agronomic practices (Coates 2011, Bilalis *et al.* 2016). Despite being classified as a drought-tolerant species, chia exhibits considerable sensitivity to water stress, especially during reproductive stages. Moisture deficit adversely affects chlorophyll content, leaf water status, stomatal conductance and photosynthetic efficiency, leading to reduced biomass accumulation and seed yield (Herman *et al.* 2016, Choukri *et al.* 2025). Prolonged or severe drought conditions may therefore result in substantial yield penalties and reduced economic returns. However, plants employ several adaptive mechanisms to withstand drought stress, including osmotic adjustment, enhanced antioxidant activity, accumulation of compatible solutes and improved stomatal regulation (Herman *et al.* 2016).

In recent years, foliar application of stress-mitigating agrochemicals such as potassium nitrate, salicylic acid and thiourea has gained attention as an effective approach to enhance drought tolerance. Potassium nitrate improves nutrient uptake, osmotic regulation and enzyme activation, thereby sustaining photosynthesis and assimilate translocation under stress. Salicylic acid functions as a signaling molecule that regulates antioxidant defense, hormonal balance and membrane stability, while thiourea acts as an osmoprotectant and metabolic regulator (Fouad *et al.* 2018, Singh *et al.* 2022). Several studies have demonstrated the beneficial effects of these compounds in mitigating drought-induced yield losses in chia and other crops (Harisha *et al.* 2023, Salama 2023).

MATERIALS AND METHODS

The experiment was conducted during *rabi* 2024-25 at the Instructional Farm, College of Agriculture, Jodhpur (Rajasthan). Geographically, the site lies between 26°15' N to 26°45' N latitude and 73°00' E to 73°29' E longitude, at an elevation of 231 meters above mean sea level (MSL). The area falls within Rajasthan's agro-climatic zone IA, known as the Arid Western Plains Zone. The experimental soil was sandy loam in texture, slightly alkaline (pH 8.31) and non-saline (EC 0.40 dS m^{-1}). It was low in organic carbon (0.17%) and available nitrogen (150.53 kg ha^{-1}), while available phosphorus (20.50 kg P_2O_5 ha^{-1}) and potassium (319.65 kg K_2O ha^{-1}) were in the medium range. The experiment was laid out in split plot design (SPD), comprising 12 treatment combinations and replicated three times. The main plot included three irrigation levels (recommended irrigation: I_0, one irrigation skips: I_1 and two irrigations skip: I_2). The subplots comprised foliar application of four different agrochemicals, including thiourea @ 2% (C_1), potassium nitrate @ 100 ppm (C_2), salicylic acid @ 100 ppm (C_3) and water spray as control (C_0). The chia variety used for the study was JC^{-1}.

The observations on different growth parameters and yield and yield attributes were recorded from five selected tagged plants from each plot. Growth parameters were recorded after 40 and 75 DAS. Yield and yield attributes were recorded at harvest. Economics of treatments was worked out by considering the prevailing prices of inputs and produce. The cost of cultivation (₹/ha) was calculated treatment-wise based on inputs used. Gross returns (₹/ha) were estimated by multiplying economic yield with the market price of chia seed. Net returns (₹/ha) were obtained by subtracting cost of cultivation from gross returns. The benefit–cost (B:C) ratio was computed as the ratio of gross returns to cost of cultivation. All the experimental data were subjected to statistical analysis using analysis of variance (ANOVA) appropriate for the split plot design as described by Panse and Sukhatme (1984). The statistical analysis was performed using Microsoft Excel for testing the significance of variation in experimental result. Wherever, the F value was found significant at 5% level of significance, the critical difference (CD) value was computed for making comparison among the treatment means.

RESULTS AND DISCUSSION

Effect on growth attributes

Water stress significantly influenced plant height and dry matter accumulation of chia at both 40 and 75 DAS (Table 1). Recommended irrigation (I_0) recorded the maximum plant height (11.96 cm at 40 DAS and 76.86 cm at 75 DAS) and dry matter accumulation (4.85 g/m row and 83.95 g/m row), which were significantly superior to one and two irrigation skips. Two irrigations skipped (I_2) resulted in the lowest plant height (10.13 cm at 40 DAS and 65.08 cm at 75 DAS) and dry matter accumulation (4.20 g/m row and 65.53 g/m row). These findings align with Fouad *et al.* (2018), who reported higher chia yields under full irrigation. Karam *et al.* (2006) similarly demonstrated in cereals and pseudocereals that reduced water availability limits carbohydrate synthesis, resulting in shorter, lighter spikes. Harisha *et al.* (2023) also confirmed severe yield losses under water stress in semi-arid regions. Thus, adequate irrigation is vital during reproductive stages to ensure optimal yield in chia.

Among stress-mitigating agrochemicals, foliar

Table 1. Effect of irrigation and agrochemicals on growth attributes of chia.

Treatments	Plant height (cm) 40 DAS	Plant height (cm) 75 DAS	Dry matter accumulation ($g\ m^{-1}$ row) 40 DAS	Dry matter accumulation ($g\ m^{-1}$ row) 75 DAS
Irrigation levels				
I_0 : Recommended irrigations	11.96	76.86	4.85	83.95
I_1 : One irrigation skip	10.19	71.34	4.21	75.01
I_2 : Two irrigations skip	10.13	65.08	4.20	65.53
SEm±	0.36	0.70	0.14	0.76
CD at 5%	1.41	2.73	0.53	2.99
Agrochemicals (stress mitigating)				
C_0 : Control	10.01	67.38	3.87	70.01
C_1 : Thiourea	11.05	71.79	4.16	72.47
C_2 : KNO_3	11.38	74.03	4.86	79.24
C_3 : Salicylic acid	10.61	71.16	4.78	77.60
SEm±	0.31	0.56	0.13	0.56
CD at 5%	0.92	1.65	0.37	1.68
Irrigation × Agrochemicals (stress mitigating)				
SEm±	0.54	0.96	0.22	0.98
CD at 5%	NS	2.86	NS	2.91

Table 2. Effect of irrigation and agrochemicals on yield parameters of chia.

Treatments	Yield parameters: Spikes/plant (no.)	Spike length (cm)	Spike weight (g)	Seed yield ($kg\ ha^{-1}$)
Irrigation				
I_0: Recommended irrigations	13.68	11.57	12.73	540.02
I_1: One irrigation skip	12.61	10.51	11.61	463.62
I_2: Two irrigations skip	9.81	8.61	9.88	399.83
SEm±	0.37	0.22	0.33	10.77
CD at 5%	1.45	0.86	1.29	42.29
Agrochemicals (stress mitigating)				
C_0: Control	10.93	8.63	10.51	425.00
C_1: Thiourea	11.51	9.96	11.06	457.74
C_2: KNO_3	13.28	11.28	12.28	507.25
C_3: Salicylic acid	12.39	11.05	11.78	481.31
SEm±	0.29	0.11	0.14	7.94
CD at 5%	0.87	0.34	0.41	23.60
Irrigation × Agrochemicals (stress mitigating)				
SEm±	0.51	0.20	0.24	13.76
CD at 5%	1.51	0.59	0.70	40.88

Table 3. Effect of irrigation and agrochemicals on economics of Chia.

Treatments	Cost of cultivation (₹ ha^{-1})	Gross return (₹ ha^{-1})	Netreturn (₹ ha^{-1})	B:C ratio
Irrigation				
I_0: Recommended irrigations	33,273	81,575	48,302	2.45
I_1: One irrigation skip	32,187	70,091	37,904	2.18
I_2: Two irrigations skip	31,101	60,492	29,391	1.95
Agrochemicals (stress mitigating)				
C_0: Control	30,668	64,278	33,610	2.1
C_1: Thiourea	35,254	69,204	33,950	1.96
C_2: KNO_3	31,334	76,647	45,313	2.45
C_3: Salicylic acid	31,492	72,749	41,257	2.31

application of KNO_3 (C_2) produced the tallest plants (11.38 cm at 40 DAS and 74.03 cm at 75 DAS) and the highest dry matter accumulation (4.86 g/m row and 79.24 g/m row), followed by salicylic acid (C_3) and thiourea (C_1), while the control (C_0) recorded the lowest values (Table 1). Our results are corroborated by Reddy *et al.* 2020 and Kumar 2023.

Effect on yield parameters

Yield parameters of chia were significantly influenced by irrigation levels and stress-mitigating agrochemicals (Table 2). Recommended irrigation (I_0) recorded the highest number of spikes per plant (13.68), spike length (11.57 cm), spike weight (12.73 g) and seed yield (540.02 kg/ha), which were significantly superior to one and two irrigation skips. Skipping two irrigations (I_2) resulted in the lowest spikes per plant (9.81), spike length (8.61 cm), spike weight (9.88 g) and seed yield (399.83 kg/ha), indicating the adverse effect of moisture stress on reproductive development and yield formation. Similar results were also reported by Baginsky *et al.* 2016; Zahoor *et al.* 2017 and Herman *et al.* 2016.

Among stress-mitigating agrochemicals, foliar application of potassium nitrate (C_2) produced significantly higher yield attributes, recording the maximum spikes per plant (13.28), spike length (11.28 cm), spike weight (12.28 g) and seed yield (507.25 kg/ha), followed by salicylic acid (C_3) and thiourea (C_1). The control treatment (C_0) recorded the lowest values for all yield parameters, with a seed yield of 425.00 kg/ha (Table 2). These improvements are attributed to enhanced nutrient uptake, osmotic adjustment and improved hormonal and antioxidant signalling, crucial for spike initiation, development and seed filling under moisture stress. Supporting studies by Singh *et al.* (2022) and Kumar (2023) in chia confirm that foliar KNO_3 enhances nitrogen assimilation and stomatal conductance, improving reproductive performance.

Effect on economics

Economic analysis revealed that irrigation levels and stress-mitigating agrochemicals markedly influenced the profitability of Chia cultivation (Table 3). Among irrigation treatments, recommended irrigation (I_0) recorded the highest gross return (₹81,575 ha^{-1}), net return (₹48,302 ha^{-1}) and benefit cost (B:C) ratio (2.45), owing to superior seed yield despite higher cultivation cost. Net returns declined progressively under one irrigation skipped (I1: ₹37,904 ha^{-1}) and two irrigations skipped (I2: ₹29,391 ha^{-1}), primarily due to reduced yield under moisture stress.

Among agrochemical treatments, potassium nitrate (C_2) resulted in the highest gross return (₹76,647 ha^{-1}), net return (₹45,313 ha^{-1}) and B:C ratio (2.45), followed by salicylic acid (C_3). Although thiourea (C_1) improved yield over control, its higher cost of application resulted in comparatively lower net return and B:C ratio. The control treatment recorded the lowest economic returns, reflecting yield losses under stress without mitigation.

The superior economic performance of potassium nitrate can be attributed to substantial yield enhancement relative to its additional input cost, making it the most economically efficient stress-mitigation strategy. Similar economic advantages of potassium nitrate and salicylic acid under deficit irrigation have been reported by Dhillon *et al.* (2021), Reddy *et al.* (2020) and Harisha *et al.* (2023).

Interaction effect

The interaction between irrigation levels and foliar application of stress-mitigating agrochemicals ex-

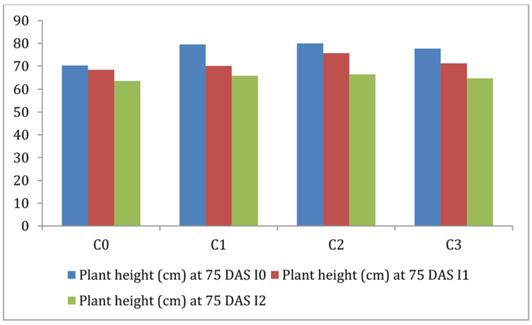

Fig. 1. Interaction effect of irrigation and agrochemicals on plant height (cm) at 75 DAS in chia.

erted a significant influence on plant height and dry matter accumulation at 75 DAS (Table 1). The combination of recommended irrigation with potassium nitrate (I_0C_2) recorded the maximum plant height (Fig. 1) and dry matter accumulation (Fig. 2), indicating synergistic effects of adequate moisture availability and enhanced nutrient assimilation. At 75 DAS, the maximum plant height (79.97 cm) was recorded with recommended irrigations plus potassium nitrate (I_0C_2), which was statistically at par with thiourea (I_0C_1) and salicylic acid (I_0C_3) and significantly superior to the control (I_0C_0). Under one irrigation skip (I_1), potassium nitrate (I_1C_2) resulted in the highest plant height (75.71 cm), while the control showed the lowest value. With two irrigation skips (I_2), plant height declined across treatments, though potassium nitrate (I_2C_2) remained superior, whereas the control (I_2C_0) recorded the minimum height (Fig. 1).

The interaction between irrigation levels and stress-mitigating agrochemicals on dry matter accumulation was non-significant at 40 DAS, indicating no differential effect during early growth. However, at 75 DAS, the interaction was significant, reflecting a pronounced influence during later growth stages. The highest dry matter accumulation was recorded with potassium nitrate under recommended irrigation (I_0C_2), which was statistically at par with salicylic acid (I_0C_3) and thiourea (I_0C_1), while the control (I_0C_0) recorded the lowest value. Under one irrigation skip (I_1), potassium nitrate (I_1C_2) and salicylic acid (I_1C_3) produced higher dry matter compared to the control. With two irrigation skips (I_2), dry matter accumulation declined across treatments, however, potassium nitrate (I_2C_2) and salicylic acid (I_2C_3) remained superior to the control (Fig. 2). The similar trend was reported by Harisha *et al.* (2023), where untreated, water-stressed chia plants suffered major declines in both yield and quality.

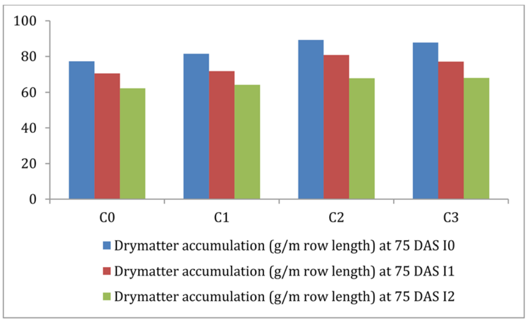

Fig. 2. Interaction effect of irrigation and agrochemicals on Dry matter accumulation (g m^{-1} row length) in chia.

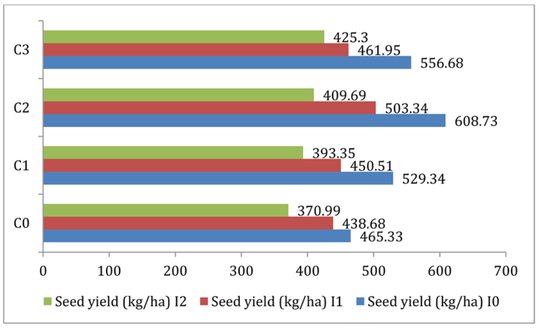

Fig. 3. Interaction effect of irrigation levels and agrochemicals on seed yield (kg ha^{-1}) of Chia.

The interaction effect on seed yield (Fig. 3) revealed that the combination of recommended irrigation with potassium nitrate (I_0C_2) recorded the maximum seed yield (608.73 kg ha^{-1}), which was significantly superior to all other treatment combinations. Under one irrigation skipped (I_1), foliar application of potassium nitrate (503.34 kg ha^{-1}) and salicylic acid (461.95 kg ha^{-1}) significantly mitigated yield losses compared to the control (438.68 kg ha^{-1}). Even under severe moisture stress (I_2), potassium nitrate (409.69 kg ha^{-1}) and salicylic acid (425.30 kg ha^{-1}) maintained higher seed yield than the control (370.99 kg ha^{-1}), indicating their effectiveness in alleviating drought stress. These results indicate that foliar application of potassium nitrate and salicylic acid can partially compensate for moisture stress by improving physiological efficiency, osmotic adjustment and assimilate production, thereby maintaining vegetative growth under deficit irrigation. Similar interactive responses between irrigation levels and foliar-applied agrochemicals have been reported in chia and other crops by Fouad *et al.* (2018), Harisha *et al.* (2023) and Singh *et al.* (2022).

CONCLUSION

It is concluded that adequate irrigation is crucial for achieving optimum growth and yield of chia, as recommended irrigation recorded the highest plant height, dry matter accumulation, yield attributes and seed yield. Moisture stress caused by skipping irrigations markedly reduced vegetative growth, spike development and seed yield. However, foliar application of stress-mitigating agrochemicals, particularly potassium nitrate, effectively alleviated the adverse effects of water stress by improving growth and yield parameters. Therefore, the integration of moderate deficit irrigation with foliar application of potassium nitrate emerged as the most profitable and resource-efficient management strategy for chia cultivation under arid conditions.

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