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Strategies for Improving Resilience against Abiotic Stresses in Summer Groundnut

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

A study was conducted during the summer of 2022 and 2023 at the Instructional farm of Junagadh Agricultural University, India, to assess various irrigation techniques (drip and surface irrigation), residue mulching and stress-mitigating chemicals (salicylic acid, potassium nitrate, and kaolin) in combating environmental stress on summer groundnut. The findings indicated that the

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implementation of drip irrigation at a 0.8 PEF led to enhanced growth, yield, physiological traits, water use efficiency and economics of summer groundnut led to enhanced soil water loss. The mulch rate of 5 t ha^{-1} was determined to be the most effective for growth, yield, physiological traits, water use efficiency and economics. Different chemical compounds for reducing stress also had a significant impact on these factors. During this study, combining drip irrigation at 0.8 PEF, mulching with 5 t ha^{-1} of residue and applying salicylic acid (foliar) at 100 ppm during 45 and 60 days after sowing enhanced the growth, yield and physiological traits, water use efficiency and economics of summer groundnut in areas with limited irrigation.

Keywords: Abiotic stress; irrigation; residue mulching; stress mitigation chemicals.

1. INTRODUCTION

Abiotic stresses play a crucial role in determining the productivity, sustainability and resilience of Indian agriculture, with diverse agro-climatic zones making the country susceptible to a range of challenges. From droughts and erratic rainfall to extreme temperatures and soil-related issues, these stresses significantly impact crop yields, threatening food security. Climate change-induced stresses can result in a drastic reduction of up to 70% crop yield, while edaphic stresses like nutrient deficiencies and salinity further compound challenges in crop production.

Peanut serves as an important oilseed crop, comprising 44-56% oil and 22-30% protein based on a dry seed analysis. Groundnut plants have developed different physiological characteristics to endure harsh conditions in order to cope with the adverse effects of abiotic stress. Research indicates that the application of diverse irrigation methods, residue mulching and stress mitigation chemicals can greatly improve crop growth, yield, physiological traits and water use efficiency in summer groundnut while managing abiotic stress.

Studies show that drip irrigation significantly enhances pod and haulm yield, water and fertilizer savings, and net returns compared to traditional surface irrigation methods [1]. Mulching, particularly with crop residue, positively impacts yield attributes and economic returns by conserving soil moisture and improving nutrient uptake [2]. Stress mitigating chemicals such as Salicylic acid, potassium nitrate and kaoline enhance physiological parameters like relative water content, photosynthetic rate, and membrane stability index under stress conditions, providing effective solutions for managing water stress in groundnut [3].

This study investigates the management of abiotic stress in the cultivation of summer groundnuts. It evaluates various stress factors, such as extreme temperatures and insufficient moisture. The objective of the study is to comprehend the impacts of these stressors on growth, yield, physiological traits, water use efficiency and economics. Additionally, it investigates adaptive strategies, such as irrigation management techniques combined with mulching practices and foliar application of stress mitigation chemicals. The findings could contribute to sustainable agricultural practices for enhancing productivity and resilience profitability under abiotic stress conditions.

2. METHODOLOGY

2.1 Site Characterization

Field trials were conducted in medium black clay soil under irrigated conditions at the Instructional farm of the Junagadh Agricultural University, in summer 2022 and 2023. South Saurashtra Agro-climatic region of Gujarat state has a tropical wet and dry climate, with three distinct seasons observed, a mild winter sets in the month of November and continues till the month of February. December and January are the coldest month of winter. Summer season commences during the second fortnight of February and ends by middle of June and a monsoon from July to October. Junagadh faces adverse climatic conditions in the summer months with the temperature ranging from 28 ºC to 38 ºC. April and May are the hottest months of summer. In the winter months, the temperature ranges from 10 ºC to 25 ºC. Various factors such as its close proximity to the sea influence the weather of Junagadh. The latent winds from the sea affect the climatic conditions in the region Chinchorkar et al. [4].

The soil is classified as Vertic Ustochrept, medium black, clayey, shallow (15-20 cm depth) and highly calcareous in nature. The soil contains moderate available nitrogen, medium available phosphorus and high in available potassium.

List 1. Physicochemical properties of experimental site

pH	7.9
EC	0.41 ds m^{-1}
Organic carbon	0.58 %
Available nitrogen	257 kg ha^{-1}
Available phosphorus	37.68 kg ha^{-1}
Available potassium	276.8 kg ha^{-1}
Bulk density	1.33 g cm^{-3}
Field capacity	27.63 % - 28.37 %
Permanent wilting point	13.39 % - 14.21 %

2.2 Crop Management

The variety of summer groundnut used in this study was Gujarat Junagadh Groundnut-31. The crop was sown on 15th and 10th February in 2022 and 2023, respectively. Seed rate and spacing of growing the crop were 120 kg ha^{-1} and 30 cm * 10 cm.

The gap filling operation was conducted between 12 to 15 Days After Sowing (DAS) in each row to ensure an appropriate plant-to-plant spacing of 10 cm. The total amount of fertilizers were applied at the time of sowing. For effective weed management, pre-emergence application of Pendimethalin at 1.0 kg *a.i*. ha^{-1} was used. Two common irrigation was applied for uniform germination. After proper germination drip installation and residue mulching treatment was applied in respected plot. Threshing of the crop was done on 19th June, 2022 and 16th June, 2023. Respectively.

2.3 Treatment

The experiment was laid out in a split split plot design having three replications. Main plot comprised of three of irrigation methods and scheduling on the basis of IW/CPE ratio and PEF *viz*. surface irrigation at 1.0 IW/ CPE and drip irrigation at 0.6 and 0.8 PEF, different mulching i.e. residue mulch 5 t ha^{-1} and no mulch were taken at sub-plots. While different stress mitigation chemicals foliar application at 45 and 60 DAS *viz*. Control, Salicylic acid at spray @ 100 ppm, Potassium nitrate spray @ 2% and Kaolin spray @ 6% were taken at sub sub-plots treatments. Thus, the experiment was comprised of total 24 treatment combinations.

Performance of drip irrigation was evaluated based on the uniformity coefficient, distribution uniformity and emission uniformity by measuring the discharge from first, middle and end laterals for 5 minutes and then converted into the lph. The hydraulic performance of drip system is as summarized in Table 1. The system was made to run at fixed pressure (1 kg cm^{-2}) throughout the period of experiment. The maximum discharge observed as 3.52, 3.48 and 3.46 lph at starting point of the lateral in middle, first and last lateral respectively. Minimum discharge was occurred at first lateral then followed by last and middle lateral respectively. The average discharge of first, middle and last lateral was 3.23, 3.35 and 3.23 respectively, with overall average discharge of system was 3.27 lph which was 81.75 % of manufacturer discharge (4 lph). As such this is considered as a good discharge. Also Uniformity coefficient (%), Distribution Uniformity (%) and Emission Uniformity (%) are 96.22%, 96.90% and 96.92%, respectively. Which indicates excellent performance of drip irrigation [5].

Table 1. Evaluation of hydraulic performance of drip irrigation system

Variation	First Lateral	Middle Lateral	Last Lateral	Average
Maximum Discharge (lph)	3.48	3.52	3.46	3.49
Minimum Discharge (lph)	2.98	3.17	3.00	3.05
Average of Discharge (lph)	3.23	3.35	3.23	3.27
Average of 1/4 the lowest emitter discharge (lph)	3.14	3.22	3.14	3.17
Standard deviation (SD)	0.14	0.10	0.13	0.12
Coefficient of variation (Q_{var})	0.04	0.03	0.04	0.04
Uniformity coefficient (%)	95.67	97.01	95.98	96.22
Distribution Uniformity (%)	97.21	96.26	97.21	96.90
Emission Uniformity (%)	98.04	94.67	98.04	96.92

A common irrigation was applied at sowing and 7 DAS to ensure proper germination as well as establishment of the crop irrespective of cumulative pan evaporation readings. Afterward, irrigations were given as per irrigation treatment. This is a climatological approach of scheduling irrigation. In this approach a known amount of Irrigation Water (IW) is applied when cumulative pan evaporation CPE reaches a predetermined level. Pan evaporation denoted the water loss because of evaporation from an open pan evaporimeter. The total amount of Irrigation Water (IW) was applied in each irrigation was 50 mm per irrigation during both the years. Therefore, the cumulative pan evaporation value was 50 mm at 1.0 IW/CPE ratio. Irrigation frequency was varied at same level of IW/CPE ratio due to variation in rainfall in crop duration. While in drip irrigation alternate day irrigation was given at different pan evaporation fraction. Sowing of seeds in plot was done in 9 rows having spacing of 30 cm row-row and 10 cm plant-plant. Crop residue at 5000 kg ha^{-1} was applied under mulching treatment after both common irrigation and drip installation, while, under no-mulch no crop residue was applied. Mulch was uniformly spread in between the rows of crop. Application of different stress mitigation chemicals was given at 45 DAS and 60 DAS *via.* foliar spray.

2.4 Growth Parameters, Yield Attributes and Yield

Plant height, number of branches and dry matter production at harvest by selecting random 5 plant sample per plot and mean data were analysis. Various yield attributes like number and weight of pod per plant as well as yield like pod, haulm and kernel yield were recorded per plot.

2.5 Physiological Traits

The SPAD meter readings were obtained at 90 Days After Sowing (DAS) as well as at the time of harvest, utilizing the chlorophyll meter (Minolta SPAD-502). Observations were taken from 4 to 5 upper leaves of five designated plants, and the results were averaged to ensure accuracy. These measurements were documented as SPAD values.

Relative water content (RWC) was assessed according to Barrs and Weatherly [6] method with the following formula,

$$\mathbf{RWC}\,(\%) = \frac{Fresh\ weight\ (g) - Dry\ weight\ (g)}{Turgid\ weight\ (g) - Dry\ weight\ (g)} \times 100$$

Membrane Stability Index (MSI) was calculated by taking the electrical conductivity of leaf leachates in double distilled water at 40 and 100°C by following the method of Sairam [7].

$$\text{Membrane stability index (MSI)} = \left(1 - \frac{C1}{C2}\right) x\ 100$$

Mature leaf was cut into small pieces and then taken (0.5 g) in test tubes having 10 ml. of double distilled water in two sets. One set was kept at 40ºC for 30 min and another set at 100ºC in boiling water bath for 15 min and their respective electric conductivity's C_1 and C_2 were measured by conductivity meter.

2.6 Water Use Efficiency (kg ha^{-1} mm^{-1})

The response of pod yield per unit of irrigation water applied at varying levels of irrigation was worked out by dividing per hectare pod yield of groundnut crop obtained under various treatments with the total quantity of irrigation water applied (mm) which was worked out by the following formula [8].

$$\text{WUE (Kg ha}^{-1}\text{mm}^{-1}) = \frac{\text{Pod yield (Kg ha}^{-1})}{\text{Water applied (mm)}}$$

2.7 Data Analysis

Standard analysis of variance was used to do the statistical analysis of the data [9] & Panse and Sukhatme [10] The F-test was used to assess the treatment effects' significance. Using the Least Significant Difference (LSD) at the 5% probability level, the significance of the difference between the means of the different treatments was examined.

3. RESULTS AND DISCUSSION

The analysis of variance (ANOVA) for different parameters tested in this experiment exhibited that the main effects of various irrigation, residue mulching and stress mitigation chemicals were significant for almost all the parameters like growth, yield, physiological traits, water use efficiency and economics *etc*. during both the years of experiment (Tables 2, 3 & 4). The interaction effects between irrigation with residue mulch (I*M), Irrigation with stress mitigation chemicals (I*S), residue mulching combined with stress mitigation chemicals (M*S) and irrigation, residue mulching and stress mitigation chemicals (I*M*S) were significant during both the years of study as well as pooled results (Figs. 1&2).

Table 2. Effect of resilient strategies on growth parameters, yield attribute and yield of summer groundnut

Treatment		Plant Height (cm)	Number of Branches	Dry Matter Production (g plant^{-1})	Number of Pod Per Plant	Pod Yield (q ha^{-1})	Haulm Yield (q ha^{-1})
Irrigation (I)							
I_1		20.07	4.13	25.44	10.13	31.00	46.30
I_2		23.33	4.65	26.66	10.68	32.64	48.39
I_3		26.92	5.31	32.40	13.40	40.73	59.74
SEM		0.38	0.06	0.45	0.17	0.51	0.90
CD 5%		1.25	0.20	1.47	0.56	1.67	2.94
CV %		11.32	9.14	11.10	10.51	10.18	12.11
Residue Mulch (M)							
M_0		22.39	4.46	26.72	10.78	32.95	48.83
M_1		24.49	4.94	29.62	12.02	36.63	54.12
SEM		0.26	0.05	0.32	0.13	0.38	0.60
CD 5%		0.79	0.14	0.99	0.40	1.17	1.86
CV %		9.25	8.24	9.66	9.57	9.25	9.96
Stress Mitigation chemicals (S)							
S_0		21.44	4.31	26.17	10.48	32.07	47.68
S_1		24.83	5.04	29.56	12.05	36.71	54.13
S_2		23.07	4.78	28.72	11.62	35.44	52.46
S_3		24.42	4.66	28.23	11.45	34.95	51.64
SEM		0.32	0.06	0.37	0.16	0.46	0.68
CD 5%		0.90	0.17	1.04	0.44	1.29	1.93
CV %		8.20	7.49	7.88	8.17	7.90	7.97
I X M	**SEM**	0.44	0.08	0.56	0.22	0.66	1.05
	CD 5%	1.36	0.24	1.71	0.69	2.02	3.22
I X S	**SEM**	0.56	0.10	0.64	0.27	0.79	1.18
	CD 5%	1.56	0.29	1.81	0.76	2.24	3.34
M X S	**SEM**	0.45	0.08	0.52	0.22	0.65	0.97
	CD 5%	1.28	0.23	1.47	0.62	1.83	2.73
I X M X S	**SEM**	0.78	0.14	0.91	0.38	1.12	1.68
	CD 5%	2.21	0.40	2.55	1.07	3.16	4.72
Y	**SEM**	0.31	0.05	0.37	0.14	0.42	0.73
	CD 5%	NS	NS	NS	NS	NS	NS

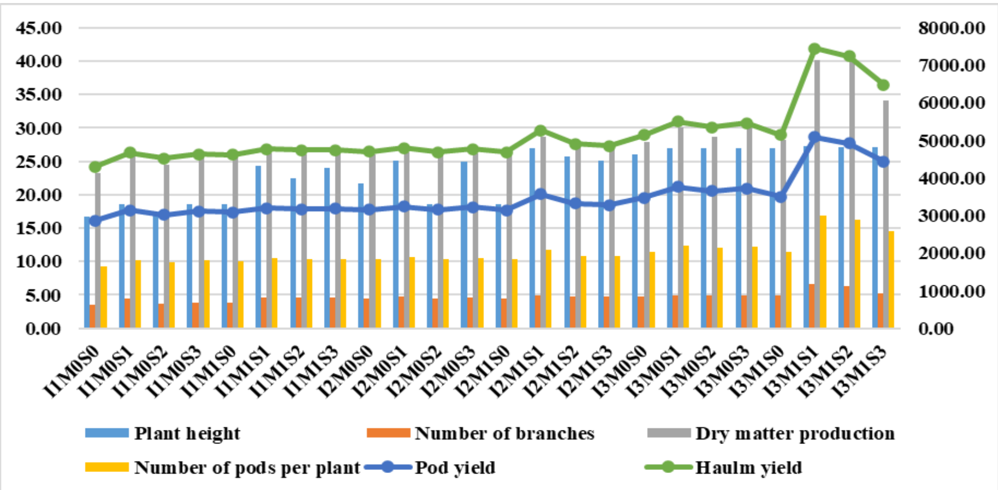

Fig. 1. Interaction effect of resilient strategies on plant height, number of branches per plant, dry matter production, number of pods per plant, pod and haulm yield of summer groundnut (pooled)

Table 3. Effect of resilient strategies on physiological traits and water use efficiency of summer groundnut

Treatment		SPAD Meter Value		RWC (%)		MSI		WUE (kg ha^{-1} mm^{-1})
		90 DAS	At Harvest	90 DAS	At Harvest	90 DAS	At Harvest	
Irrigation (I)								
I_1		33.14	34.87	66.15	68.15	68.85	61.16	3.42
I_2		39.02	41.62	77.25	78.82	81.12	72.36	5.59
I_3		43.06	45.93	85.45	86.70	89.61	82.53	5.47
SEM		0.66	0.67	1.18	1.13	1.30	1.16	0.06
CD 5%		2.15	2.20	3.85	3.70	4.23	3.78	0.20
CV %		11.88	11.45	10.73	10.10	11.25	11.14	8.94
Residue Mulch (M)								
M_0		36.68	38.87	72.87	74.61	76.26	68.31	4.58
M_1		40.13	42.74	79.70	81.17	83.46	75.72	5.08
SEM		0.40	0.50	0.80	0.77	0.89	0.77	0.06
CD 5%		1.24	1.54	2.48	2.38	2.75	2.36	0.17
CV %		8.87	10.37	8.95	8.42	9.48	9.03	9.90
Stress Mitigation chemicals (S)								
S_0		35.15	37.06	69.96	71.81	73.08	65.95	4.46
S_1		40.89	43.60	81.17	82.59	85.12	77.14	5.10
S_2		37.53	39.73	74.60	76.27	78.01	70.48	4.91
S_3		40.06	42.82	79.40	80.89	83.24	74.50	4.84
SEM		0.48	0.56	0.98	0.94	1.01	0.91	0.07
CD 5%		1.36	1.59	2.76	2.65	2.84	2.56	0.19
CV %		7.51	8.28	7.70	7.25	7.57	7.57	8.21
I X M	**SEM**	0.70	0.86	1.39	1.34	1.55	1.33	0.10
	CD 5%	2.14	2.66	4.29	4.13	4.76	4.09	0.30
I X S	**SEM**	0.83	0.98	1.70	1.63	1.74	1.57	0.11
	CD 5%	2.35	2.75	4.78	4.60	4.92	4.43	0.32
M X S	**SEM**	0.68	0.80	1.38	1.33	1.42	1.28	0.09
	CD 5%	1.92	2.25	3.90	3.75	4.01	3.62	0.26
I X M X S	**SEM**	1.18	1.38	2.40	2.31	2.47	2.22	0.16
	CD 5%	3.32	3.89	6.76	6.50	6.95	6.27	0.46
Y	**SEM**	0.54	0.55	0.96	0.93	1.06	0.95	0.05
	CD 5%	NS	NS	NS	NS	NS	NS	NS

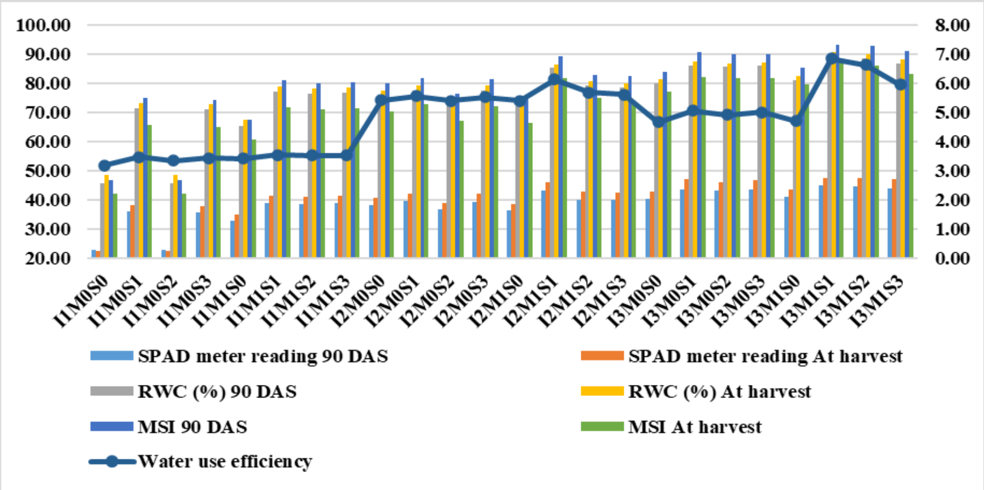

Fig. 2. Interaction effect of resilient strategies on physiological traits at 90 DAS & harvest and water use efficiency of summer groundnut (pooled)

Table 4. Effect of resilient strategies on economics of summer groundnut

Treatment	Cost of Cultivation (₹ ha^{-1})		Gross return (₹ ha^{-1})		Net return (₹ ha^{-1})		Benefit Cost Ratio	
	2022	2023	2022	2023	2022	2023	2022	2023
$I_1M_0S_0$	173855	194894	69880	68578	103974	126317	2.49	2.84
$I_1M_0S_1$	192587	210754	69996	68694	122591	142061	2.75	3.07
$I_1M_0S_2$	182179	206191	74212	72910	107967	133281	2.45	2.83
$I_1M_0S_3$	191071	208593	95872	94570	95199	114023	1.99	2.21
$I_1M_1S_0$	190893	206419	78145	76843	112747	129576	2.44	2.69
$I_1M_1S_1$	196825	215067	78261	76959	118564	138108	2.51	2.79
$I_1M_1S_2$	195855	212466	82477	81175	113378	131291	2.37	2.62
$I_1M_1S_3$	196285	213028	104137	102835	92147	110193	1.88	2.07
$I_2M_0S_0$	193826	212155	67101	66530	126725	145626	2.89	3.19
$I_2M_0S_1$	198462	218213	67217	66645	131244	151568	2.95	3.27
$I_2M_0S_2$	193631	211630	71433	70862	122198	140769	2.71	2.99
$I_2M_0S_3$	198398	216093	93093	92522	105305	123571	2.13	2.34
$I_2M_1S_0$	192761	211356	75366	74795	117394	136562	2.56	2.83
$I_2M_1S_1$	216026	243567	75482	74910	140544	168657	2.86	3.25
$I_2M_1S_2$	205296	221094	79698	79127	125598	141968	2.58	2.79
$I_2M_1S_3$	202347	219008	101358	100787	100989	118222	2.00	2.17
$I_3M_0S_0$	211762	235020	68946	68162	142817	166858	3.07	3.45
$I_3M_0S_1$	227094	255927	69061	68278	158033	187649	3.29	3.75
$I_3M_0S_2$	221863	247667	73278	72494	148585	175173	3.03	3.42
$I_3M_0S_3$	226595	251844	94938	94154	131657	157690	2.39	2.67
$I_3M_1S_0$	212371	236955	77211	76427	135160	160528	2.75	3.10
$I_3M_1S_1$	314853	338966	77326	76543	237526	262423	4.07	4.43
$I_3M_1S_2$	297180	336277	81543	80759	215638	255518	3.64	4.16
$I_3M_1S_3$	267757	302007	103203	102419	164555	199588	2.59	2.95
Pod price = 58 ₹ kg^{-1} (2022) & 63 ₹ kg^{-1} (2023)					**Haulm price = 2.5 ₹ kg^{-1}**			

Drip irrigation with 0.8 PEF had much better growth parameters, yield attributes and yield over surface irrigation with 1.0 IW/CPE. The plant did very well under the stressful water conditions with proper irrigation at 0.8 PEF, which helped improve cell division and expansion to bear on a stronger plant. If there is a constant feed of adequate soil moisture to the plant, it will achieve its full genetic potential by growing taller, with an increased number of branches and dry matter for photosynthesis simultaneously. The results were in coherence with the research published by Ranjitha et al. [11] and Chandini et al. [12] Higher pod yield per plant under drip irrigation at 0.8 PFE was obtained because of sufficient moisture coupled with improved nutrient uptake, resulting in better yield attributed to more metabolites produced from photosynthates. Enough watering at the right time and quantity during the reproduction phase of the plants enhances the pegging process and sets up a favourable soil condition for pod development, thereby increasing the number of pods per plant. More water is loss due to surface irrigation, which puts stress on the plants at their reproductive stage. Hence, there will be a reduction in pegs and a reduced number of pods per plant. The results obtained are supported by Eman et al. [13] and Harini et al. [14]. Almost all growth and yield features in this investigation had a positive strong relationship with the pod and haulm yield of the groundnut. Results agreed with those reported by Solanke et al. [15], Kumar et al. [16], Metin et al. [17] and Vaghasia et al. [1].

Residue mulching at 5 tons per hectare had a significant effect on summer groundnut. This may be due to the fact that the continued growth trend of the plants that were mulched during harvest was perhaps due to the beneficial effects of the mulch on soil moisture retention and temperature control. This showed a carry-over effect of mulch on vigorous growth and for resistance to stresses like drought and extreme temperatures in plants. Probably this is because of exposure of the plants to more moisture during its growing period, favouring increased physiological and metabolic processes. This forms conditions that better cell elongation, cell turgidity, opening of stomata and finally distribution of photosynthesis efficiently to the sink. In the absence of mulch, higher water stress may prevail during the critical water requirement stage, reducing the plant growth parameters. Similar findings have been reported by Mathukia et al. [18], Taufiq et al. [19] and Kaur et al. [20] The high yield and yield per plant with residue mulch were mainly due to increased moisture in the root zone, which improved nutrient uptake, leading to an improvement in physiological effects that increased net assimilation and promoted the translocation of photosynthates from source to sink. Evaporation is reduced through crop residue mulching, which thus helps in the retention of soil moisture at critical factor during the hot summer season. This finding is in agreement with earlier studies of Maurya et al. [21], Bhattarai et al. [22] and Chaudhary et al. [23].

Among the various stress mitigating chemicals tested, salicylic acid at 100 ppm applied at 45 and 60 DAS was superior, although potassium nitrate at 2% and kaolin at 6% showed almost comparable results in summer groundnut. Salicylic acid enhances photosynthesis, reduces oxidative stress, increased plant height, dry matter production and overall crop growth by stimulating cell division, cell elongation and metabolic activity. Potassium nitrate supplies vital potassium and nitrogen for vegetative growth, which raises the height of plants, makes them more branched out and increases dry matter accumulation as a result of increased availability of nutrients and greater root growth. Kaolin helps in reducing heat stress and conserving water by reflecting excess sunlight and lowering leaf temperature, thus maintaining turgor pressure and promoting overall growth. These plant stress reducing chemicals improved plant height, branching, and dry matter production and even growth rates under challenging conditions. The results obtained are in agreement with the findings of Muthulakshmi and Lingakumar, [24], Nkrumah et al. [25] and Singh et al. [26] Salicylic acid is known to promote plant growth and productivity under stressful conditions, since it induces systemic acquired resistance via the expression of defence-related enzymes. It thus provided better stress tolerance and reproductive growth, hence superior yield characteristics than the control. It must have enhanced the ability of the plant to cope with the non-living stress factors more than the other treatments did. Even though potassium nitrate and kaolin are both useful, they act in different ways. Potassium nitrate provides nutritional support and may cause some stress tolerance but was less effective than salicylic acid in improving the reproductive properties. Kaolin works mainly as a physical shade, reflecting sunlight thus reducing heat stress. It doesn't affect the internal physiological activities like salicylic acid does. The similarity of the results obtained following the application of 2% potassium nitrate spray and 6% kaolin spray indicate that these two chemicals alleviate stress by reducing transpiration and promoting the uptake of nutrients. However, the higher yielding parameters obtained with salicylic acid applications are likely due to its higher impact on the internal induction of defence pathways and promotion of general plant health as compared to potassium nitrate and kaolin. The results obtained are in proximity to the findings shown by Meena et al. [27], Thombare et al. [28] and Raviteja et al. [29].

The results from the present investigation clearly indicated that physiological traits *viz*, SPAD meter reading, relative water content and membrane stability index as well as water use efficiency of summer groundnut were significantly influenced by irrigation with residue mulch and stress mitigation chemicals during cropping period compared (Table 3).

Drip irrigation is significantly positively correlated with physiological traits and water use efficiency. More frequent and profound water applications by drip irrigation may provide better soil moisture conditions, an essential criterion for optimal photosynthetic activity and chlorophyll development in groundnut leaves. The uniform distribution of water and nutrients due to drip irrigation may cause more uniform crop growth and development, resulting in a consistent SPAD reading across the field compared to surface irrigation. Drip irrigation can reduce the negative impact of water deficit an abiotic stress that reduced leaf chlorophyll in groundnut. Better management of available water under drip will enhance resilience in a groundnut crop by maintaining higher RWC levels required for plant health and resilience to abiotic stresses. Drip irrigation was established as a better strategy for improving crop resilience. The membrane stability index measures the capacity of the plant to bear stress; the greater the MSI, the healthier the plants. These results are in conformity with the findings of Chomsang et al. [30], Singh and Singh [31] and Dong et al. [32]. In drip irrigation, the water is applied directly at the roots of the plants, so it supplies the required amount of water continuously without wasting it. In the case of surface irrigation, the water will flood the soil, and perhaps there may be non-uniform distribution or even waterlogging conditions in the roots. These advantages of drip irrigation add to improved water-use efficiency, good soil moisture conditions, consistency in temperature, control of salts and availability of nutrients. Higher WUE under 0.6 PEF (I_2) might be on account of less quantity of irrigation water application. Higher yield under 0.8 PEF (I_3) due to the increase in moisture regimes increased the production of pods in proportion to the consumptive use of water. Rathore et al. [33], Ramanjaneyulu et al. [34] and Kumar et al. [16] showed almost similar effects of irrigation on consumptive use of water and water-use efficiency.

Mulch helps retain soil moisture by decreasing evaporation, thus keeping the leaves' relative water content and SPAD meter reading higher. The reason for this is that mulch acts as an insulator, reducing temperature changes to prevent excessive heat that harms the cell membrane and therefore enhancing the membrane stability index. These results corroborate the research outcomes of Kannan et al. [35], Pradhan et al. [36] and Das et al. [37]. It is likely that there was an increase in water use efficiency from high pod yield after applying residue mulch, as it requires minimal to moderate water consumption while still producing a high pod yield. These results align with the ones documented by Maurya et al. [38], Das et al. [37] and Minh et al. [39].

The findings in Table 3 show that using stress mitigation chemicals, like salicylic acid at 100 ppm and kaolin at 6%, greatly enhanced leaf SPAD meter reading, relative water content and membrane stability index in summer groundnut at 90 DAS and at harvest when compared to just spraying water as a control treatment. In particular, Salicylic acid showed the strongest physiological characteristics at 90 DAS and at harvest in both years and in the combined analysis. The results indicate that salicylic acid and kaolin helped alleviate abiotic stresses in summer groundnut by boosting photosynthetic efficiency and increasing leaf chlorophyll content, ultimately enhancing the crop's resilience to environmental challenges. The decreased physiological traits seen in the water spray treatment show lower physiological traits than the stress-relieving chemicals. This indicates that water spray did not work well in reducing abiotic stresses in summer groundnut plants, whereas salicylic acid and kaolin were successful in keeping chlorophyll levels and photosynthetic efficiency high during all stages of crop growth. The findings back the idea that salicylic acid and kaolin have the ability to alleviate stress and improve groundnut tolerance to abiotic stresses. These results align with the results presented by Khavari et al. [40], Meena et al. [41] and Elshamly et al. [42].

WUE was maximum at 100 ppm salicylic acid applied at both 45 and 60 DAS, having values of 4.78, 5.41, and 5.10 kg ha^{-1} mm^{-1} for 2022 and 2023 and combined data, respectively. The increase was due to the action of salicylic acid, which enhances plants' ability to counteract stress by controlling physiological processes, like stomatal regulation and antioxidant activity, in order to improve water retention and use. Also, the 2% application of potassium nitrate repeated at frequent intervals showed similar results, probably due to its osmotic regulation and nutrient absorption properties making the plants use more water when under stress. Even a 6% kaolin spray reduced the leaf temperature and evapotranspiration to retain soil moisture. On the other hand, water spray showed the lowest WUE and hence was ineffective in protecting the plants from stress. The results thus proved that salicylic acid and potassium nitrate treatments are an effective means of improving WUE. This finding agrees with the work provided by Krishna et al. [43] and Alotaibi *et al* [44].

The interaction of I × M × S were significant, thus indicating that a combination of drip irrigation at 0.8 PEF and mulching at 5 t ha^{-1} with salicylic acid spray at 100 ppm performed well due to the creation of favourable conditions for plant growth enhancement over individual treatment. This consistent trend of higher pod quantity per plant and crop output through enhancement of physiological traits and water usage efficiency remained constant over the two years and in the combined data. A synergistic effect of the mixture is generated, improving several parameters of the growth environment simultaneously. Drip irrigation provides a constant supply of water, while mulching does the same in increasing water-holding capacity by reducing evaporation and salicylic acid will help the plant cope more effectively with stress and enhance resistance to diseases. This complex approach will provide plants with a more stable and preferred medium for growth, thereby enhancing crop yields. This comprehensive plan explains the scientific rationale for using a combination of irrigation, residue mulching and stress mitigation chemicals in improving and sustaining crop productivity in agro-ecological setups in summer season groundnut cultivation. Above results presented are in tandem with those reported by Yeganehpoor et al. [45], Sharma et al. [46] and Maurya et al. [2].

3.1 Economic Analysis

The assessment of the yield and cost-effectiveness of irrigation, residue mulching, and stress mitigation chemicals was conducted to ascertain the feasibility of increasing groundnut production. By analysing crop yield and market prices, net realization returns and benefit-cost ratios were calculated to evaluate the economic viability.

The highest economic returns and B:C ratios were obtained with drip irrigation at 0.8 PEF, application of residue mulch at 5 t ha^{-1} and spraying of salicylic acid at 100 ppm ($I_3M_1S_1$), which exhibited the synergism of combined treatments of these three. During 2022, $I_3M_1S_1$ recorded an gross realizations of ₹3,14,853 ha^{-1} and net realizations of ₹2,37,526 ha^{-1} with a B:C ratio of 4.07. Gross realisations in 2023 increased to ₹3,38,966 ha^{-1} and net realisations to ₹2,62,423 ha^{-1} with a B:C ratio of 4.43. The results therefore brought out that for economizing on gains and efficient use of resources in summer groundnut cultivation, there is every need to incorporate comprehensive management strategies. This could be because the improved gains from these treatments were also brought about by the increased yields of summer groundnut pods and stalks. The findings were in conformity with the investigations conducted by Kachhadiya et al. [47], Kadu et al. [48], Dass and Bhattacharyya, [49] and Gajera et al. [50].

4. CONCLUSION

Based on the findings from the two-year field study conducted it can be concluded that effective profitable production in summer groundnut can be obtained by application of two common surface irrigation (first immediately after sowing and second 5-6 days after first irrigation) each of 50 mm depth followed by scheduling drip irrigation at 0.8 PEF (operating pressure: 1.2 kg cm^{-2} and lateral spacing: 90 cm) at alternate day with residue mulch @ 5 t ha^{-1} Additionally, the foliar application of stress mitigation chemicals, such as salicylic acid at 100 ppm or potassium nitrate at 2%, should be administered at 45 and 60 days after sowing, specifically in the medium black calcareous soil of saurashtra region.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

We hereby declare that no generative AI technologies such as Large Language Models (ChatGPT, COPILOT, *etc*) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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