Interactive Effects of Supplementary Irrigation with Plastic Mulch Colors Strategies on Guar Production in Rain-Fed Area of Tharparkar

Chetan, Rajesh Kumar Soothar, Mashooque Ali Talpur, Altaf Ali Siyal
Faculty of Agricultural Engineering and Technology, Sindh Agriculture University, Tandojam, Pakistan
*** Correspondence:** rksoothar@sau.edu.pk
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Tharparkar boasts significant underground water potential, serving as a crucial source for guar production and ecosystem requirements. Guar crops thrive in desert areas with sandy textured soil, requiring well-drained conditions. Yet the mechanisms underlying the improved yield and crop water productivity of guar crops under supplementary irrigation remain unclear. The field trials were conducted during the guar growing seasons at the Mr. Dharam Das Agricultural Farm, Village Bewato, Mithi, Pakistan in 2022-23. The experiment design was based on the split plot in randomized complete block design including three different factors, supplementary irrigation water, plastic mulch color, and soil texture under conventional cultivation practice along with three replications. Factor-A: Irrigation water = 05 (No irrigation (CK), rainwater (R), rainwater and groundwater (R+G), groundwater and rainwater (G+R), and groundwater (G) at sequential vegetative and reproductive stage of guar. Factor B: Plastic film mulch = 03 (Black and white color plastic film mulch, and without plastic film mulch (control)). Factor-C: Soil textures = 02 (sandy loam (S1) and (sandy clay loam (S2). The results showed that the different supplementary irrigation and plastic film mulching significantly affected plant height, dry biomass, seed yield and crop water productivity of guar at sites. Across the irrigation treatments, the rainwater treatment could highly significantly enhance biomass production by 39 % and seed yield by 52.9 % as compared to CK treatment. Across the plastic film mulching, by improving the plant and soil micro-climatic condition, mulched plots increased significantly seeds yield by 9 % in black-colored film mulched plots and 5 % in white plastic film mulched plots because of less soil water depletion as compared to non-mulch plots. Across the soil types, S2 soil type increased highly significantly ($p>0.01$ in 2022 and $p>0.001$ in 2023) dry biomass by 70 % and seeds yield by 82 % as compared to S1. The supplementary saline and rainwater irrigation (G+R) can be applied at sequential vegetative and reproductive stages without any more negative impact on yield compared to R treatment. Tharparkar region, using saline groundwater water during the vegetative stage and rainwater during the reproductive stage is recommended for achieving optimal guar yields while conserving water.
Keywords: Rain and groundwater, Irrigation, Mulching, Plant growth, Guar yield

Introduction:

Water is a vital resource essential for life on Earth, playing a crucial role in sustaining ecosystems and societies. It is critical for a wide range of human activities, including drinking, domestic use, and various economic functions. Agriculture is the largest consumer of water, utilizing over 85% of the total water used by humans [1]. With the remaining freshwater supply being limited, it is vital to prioritize conservation and promote efficient water use to meet the needs of people, animals, and plants. Climate change exacerbates this issue, causing erratic rainfall patterns in regions like Tharparkar, making sustainable water management crucial. The World Water Development Report highlights the severity of the problem, with over two billion people facing water scarcity, and predicts that nearly half of the global population will experience high water stress by 2050 [2]. This underscores the urgent need for water-efficient agricultural practices to ensure sustainable food production and mitigate the impacts of water scarcity.

The Thar Desert, located in southeastern Pakistan, is a harsh and arid region characterized by scarce and irregular rainfall. As a result, guar crops, which are harvested in early November, cannot efficiently utilize rainfall [3][4]. During the peak dry season, underground water is essential for crop cultivation. In this region, agriculture relies solely on rainfall, supplemented by groundwater when rainfall is scarce [5][6]. Tharparkar has significant potential for saline groundwater, which can be harnessed for guar production and ecosystem needs. However, the region faces severe water scarcity, exacerbated by rapid water losses due to coarse soils and high temperatures. To promote sustainable agriculture, effective land and water conservation management strategies are crucial. Moreover, improper water management in agriculture can exacerbate water scarcity.

According to author[7], the water management sector has not fully benefited from innovations in water efficiency. In Pakistan, farmers are often considered a major factor in inefficient water use; however, they face limited access to resources needed to assess current on-farm water conservation practices and often rely on outdated or inappropriate irrigation methods [8]. As a result, water efficiency remains inadequate. To promote sustainable agriculture effectively, it is essential to implement improved land and water conservation management techniques. Additionally, due to improper water management, agriculture may be the cause of water scarcity.

Water scarcity hurts crop production, and mulches have in water-strapped settings, there is good potential to boost soil moisture retention. The mulching technique is also a cost-effective and superior management technique for preserving soil moisture. However, this modification can be maintained through crop residues, live tree canopies, and plastic film sheets, which can reduce evaporation rates and weed growth, compared to bare soil surfaces [6][9]. Mulching materials can be classified into two categories: organic and inorganic. Inorganic mulch, particularly plastic film mulch, is widely used for its efficiency in controlling weeds and initially cultivating crops. In rain-fed regions, the use of dark-colored plastic film mulch has proven to be particularly beneficial, as it helps modify the soil microclimate, minimize evaporation, enhance water retention, and stabilize soil temperature [10][11]. The use of plastic film mulching, especially black plastic films, has been found to increase crop yield components compared to bare fields, likely due to stimulated root growth caused by increased soil temperature and moisture [12]. Mulching has also been shown to improve soil moisture retention under water-limited conditions, reducing the negative impact of water shortages on crop production [13][14].

While existing studies provide indirect evidence in favor of using supplementary alternate irrigation with rainwater and saline groundwater [15][16], there is still a need for comprehensive research to assess its practical effectiveness during different crop growth stages, particularly in the unique environmental conditions of Tharparkar, Sindh. Groundwater is the only source of supplementary irrigation for crops in this region, and its quality is mostly saline. Cluster bean is a suitable option as it is moderately salt-tolerant. Pakistan is the second-largest producer of guar seeds, accounting for about 15% of global production. Guar crops thrive in desert areas with sandy soils and can grow well in drained soil. Plastic film mulching has also been shown to significantly increase the growth and seed yield of cluster beans [17]. The sustainability of dry land agriculture is threatened by the inefficient use of available water, coupled with drought and heat stress during the cropping season [18]. To address these challenges, new technologies have been developed to enhance precipitation water use efficiency and increase crop yields. These technologies include different color plastic film mulching, rainwater harvesting, and supplemental irrigation with groundwater resources [19]. On the other hand, Crop and irrigation models are valuable tools for generating quantitative predictions of crop yields under a range of environmental and non-environmental stressors. These factors include soil properties, farming practices, water management strategies, water quality, and the use of mulch technologies. Yet the mechanisms underlying the improved yield and crop water productivity of guar crops under supplementary irrigation remain unclear.

Objectives:

The aim of this study is to examine the yield responses of guar subjected to supplementary irrigation with plastic mulch color strategies under different soil types in the rain-fed area of Tharparkar.

Materials and Methods:

Study Area:

The field trials were conducted on guar crops during the 2022-2023 cropping seasons at the Mr. Dharam Das Agricultural Farm, Village Bewato, Mithi, Sindh Province, Pakistan. It is located on Google position between 24°42'44.45" N and 69°42'01.40" E at an elevation of about 30 m above mean sea level (Figure 1). The study site lies in a typical continental monsoon climate zone (Figure 2), with adequate light and, an average rainfall of 274 mm (range between 137-448 mm) from August to November, and seasonal and inter-annual distribution [3]. The total area of the experimental station is 54 hectares, situated approximately 11 kilometers from Mithi city in the Tharparkar region.

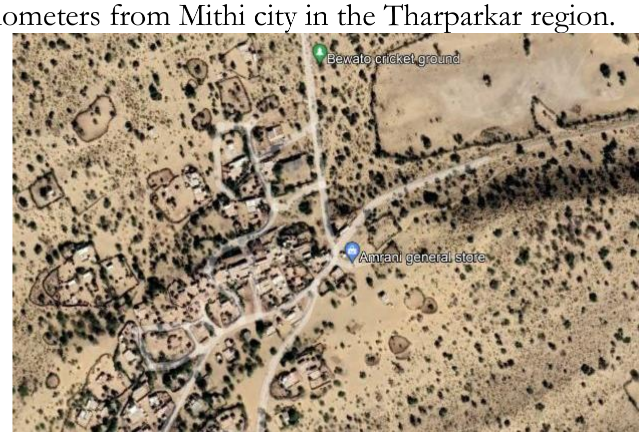

Figure 1. Satellite image view of the experimental area

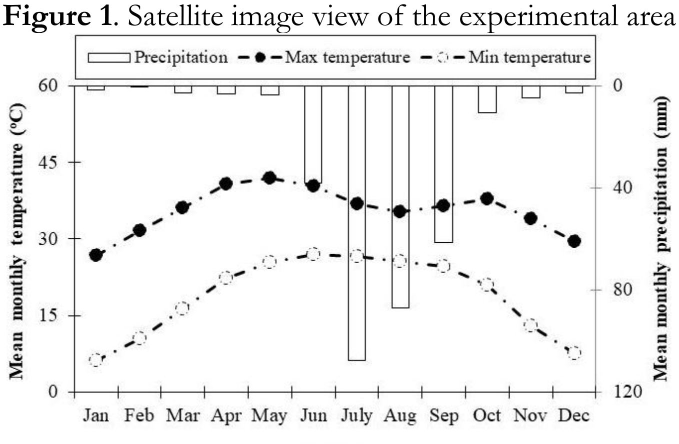

Figure 2. Mean monthly maximum and minimum temperatures and precipitation near the experimental area at Mithi from January to December (Reference: Pakistan Meteorological Department, University Road Karachi-75270)

Experimental Treatments:

The field research was conducted using a split-plot design within a randomized complete block design (RCBD), incorporating three key factors: supplementary irrigation sources, plastic mulch colors, and soil textures. The study followed conventional cultivation practices and included three replications for each treatment combination. The factor-A includes five irrigation water (1) no irrigation water applied during whole crop period (CK); (2) Irrigation water applied at sequential vegetative and reproductive stage with rainwater (R); (3) irrigation water applied at sequential vegetative and reproductive stage with rainwater and groundwater, respectively (R+G); (4) irrigation water applied at sequential vegetative and reproductive stage with groundwater and rainwater, respectively (G+R), (5) irrigation water applied at sequential vegetative and reproductive stage with local groundwater, respectively (G). Factor B includes (1) Black color plastic film mulch (BPFM); (2) white color plastic film mulch (WPFM), and without plastic film mulch (control, CK). Factor-C includes (1) sandy loam soil (S1), and sandy clay loam soil (S2). A total area of 2,112 m² was designated for the experiment and systematically divided into two equal main plots. Guar seeds of the selected genotype were sown at around the end of July 2022 and the same as the next experimental year (2023) through hand drill in prepared plots (4 m × 4 m) after receiving the first rainfall. The different rainwater harvesting techniques were (rooftop techniques) used and stored that water in the storage tank, and then used for supplementary irrigation. Similarly, saline groundwater was collected from a local open well and a well already functional at the experimental site. To assess soil properties, composite soil samples were collected from depths of 0–20, 20–40, 40–60, 60–80, and 80–100 cm at three representative locations across all replications of the experiment. Therefore, before the experiment, a total of 30 soil samples were collected and after the experiment 450 samples were taken and these composed soil samples were taken from the experimental field and analyzed in the laboratory. All soil parameters were evaluated using established standard methods before the start of the experiment, and their mean values are shown in Table 1.

Irrigation Delivery Scheme:

Soil moisture is taken up by field crops through their roots. The irrigation scheduling is based on the soil moisture depletion and each irrigation application was applied at 76 mm per acre according to the local irrigation guidance for non-saline irrigated soil exclude control treatment [3][6]. The depth of water was calculated using the following equation;

$$D = \frac{\theta_v \times d_s}{100}$$

Where;

D = Depth of water (mm), θ_v = Volumetric soil moisture (%), d_s = Depth of soil sample (mm)

Soil moisture is the amount of water available in the soil. In order to determine, soil moisture storage before and after each irrigation application, the composite soil samples were collected up to 0-100 cm soil depth from all the plots. Initially, weighed, and then after drying at 105 °C for 24 hrs in the oven was measured using the gravimetric method. After determining soil moisture storage on a gravimetric (weight) basis, it was converted to a volumetric basis. The corresponding water depth was then calculated using the following formula:

$$\theta_v = \theta_d \times \frac{B}{g_w}$$

Where;

θ_v = Volumetric soil moisture (%), θ_d = Soil moisture (%), B = Bulk density (g/cm³), g_w = Specific weight of water (g/cm³)

Table 1. Pre-Experiment Soil Properties of the Experimental Site Upto 100 cm soil Depth

Soil Layer (cm)	Soil properties					
	S1			S2		
	Soil porosity	Dry bulk density	Field capacity	Soil porosity	Dry bulk density	Field capacity
0–20	0.41	1.49	0.18	0.39	1.39	0.27
20–40	0.42	1.48	0.19	0.38	1.42	0.26
40–60	0.44	1.51	0.21	0.39	1.43	0.29
60–80	0.43	1.50	0.20	0.40	1.40	0.30
80–100	0.42	1.47	0.19	0.36	1.41	0.29

Sampling, Measurement, and Analysis:

The experimental sites were visited every second day to monitor crop growth, with measurements taken on various growth parameters at different intervals after seed sowing. Plants were selected and tagged under each designated treatment for consistent observation. The harvested plants from each replication were carefully labeled and kept separate to ensure accurate data recording and analysis. Similarly, five guar plants were selected from each replication. Harvested pods were sun-dried until moisture content reached the recommended level, after which the seed yield was recorded. According to author[20] (2023), crop water productivity was computed as total seed yield divided by the total amount of water consumption. The volume of irrigation water applied and rainfall readings during the experimental period are presented in Figure 3. In order to determine crop water productivity (CWP) for all designed treatments was calculated by following the relationship:

$$CWP = \frac{Y}{WR}$$

Where; CWP = Crop water productivity (Kg/m³), Y = Yield of crop (Kg/ha), WR = Total water consumed for crop yield (m³/ha)

Statistical Analysis:

The data collected from the field were statistically analyzed using Microsoft Excel spreadsheets and the SPSS software package (version 20.0, SPSS Inc., USA). Duncan's Multiple Range Test (DMRT) was conducted to evaluate significant differences between treatments at the 0.05 probability level ($p \leq 0.05$).

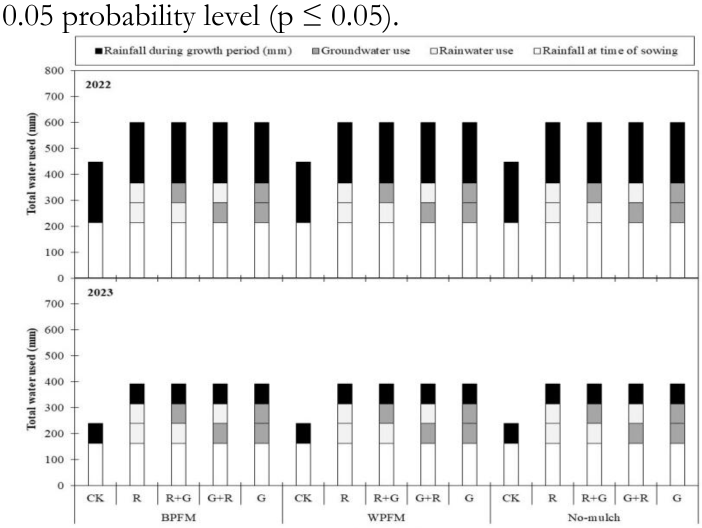

Figure 3. Rainfall before seeds sowing, volume of irrigation water applied at different growth stages, and rainfall during the experimental period in the treatment plots during the base period of guar crop (2022-23)

Results:

Plant height of guar under different factors:

The height of the gaur plant was measured three times on 39, 64, and 86th days after sowing (DAS) during both experimental years. Guar crop was irrigated with rain water at the vegetative stage, it had the highest plant height after 39 days of sowing**.** The average plant height of the guar crop was significantly influenced at various growth stages in the rain-fed area by the type of supplementary irrigation water and plastic film mulching, across different soil textural classes throughout the cropping period as indicated by Figure 4 and Figure 5. Under supplementary irrigation water and plastic film mulch, S2 soil produced significantly greater plant height compared to the S1 soil during the 2022 cropping season, and a similar trend was observed in the cropping season 2023. At the harvesting stage, among the five supplementary irrigation treatments, the tallest guar plants were observed under rainwater irrigation compared to other supplementary sources and the rain-fed (no irrigation) condition, specifically under the S1 soil type (Figure 4). Similarly, the different supplementary irrigation practices significantly increased the plant of the plant up to 13.6, 7.8, 9.5 and 9.9% in the R, R+G, G+R, and G water treatments, respectively, as compared to CK treatment (rain-fed cultivation) during both seasons. However, the highest plant of guar was recorded in the R+G treatment (irrigation with rainwater at the vegetative stage and groundwater at the reproductive) as compared to other irrigation water treatments under the S2 soil type (Figure 5). Similarly, the various supplementary irrigation practices significantly increased the average plant height by 8.1%, 10.9%, 8.2%, and 8.9% under the R, R+G, G+R, and G water treatments, respectively, when compared to the CK treatment (rain-fed cultivation). Across the mulching practice treatments in the S1 soil type, black and white color plastic film mulched plants showed significantly higher guar height as compared to no-mulch treatment. However, mulched practices significantly increased the plant height up to 17.8 in the black plastic film mulch and 12.1% in the white plastic film mulch as compared to the no-mulch treatment during experimental periods. Similarly, in the S2 soil type, the plant height of guar increased significantly by up to 25.3% with black plastic film mulch and 16.6% with white plastic film mulch, compared to the no-mulch treatment during the experimental period. Overall, in the no-mulch plots under supplementary irrigation and plastic film mulch conditions, plant height was reduced by 10% in S1 soil and 27% in S2 soil compared to the mulched plots. In terms of interactions between factors included in Table 2, the supplementary irrigation x plastic film mulching, supplementary irrigation x soil texture, and supplementary irrigation x plastic film mulching x soil texture were highly significant (p = 0.001) on crop height of guar at harvesting stage plastic. Plastic film mulching x soil texture was significant at the 0.01 level of probability.

Table 2. The ANOVA output for the effect of supplementary irrigation (SI), plastic film mulch (MFP), and soil texture (ST) on plant height of seed guar on different days after sowing (DAS). *, ** and *** indicate the significant differences among the treatments according to Duncan's multiple range test at $p \leq 0.05$, 0.01, and 0.001 level

Factor	Days after sowing		
	39	64	86
Supplementary Irrigation (SI)	***	***	***
Plastic Film Mulch (PFM)	***	***	***
Soil Texture (ST)	***	***	***
SI x PFM	***	***	***
SI x ST	***	***	***

PFM x ST	*	**	**
SI x PFM x ST	***	***	***
SI x PFM x ST x Y	ns	ns	ns

Note: Y is experimental years.

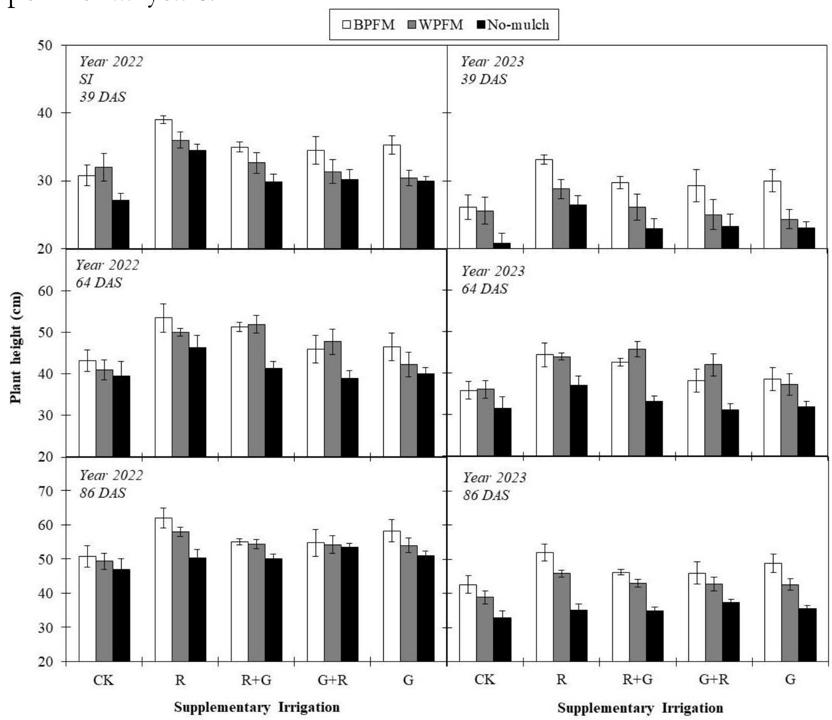

Figure 4 Plant height of seed guar crop as affected by supplementary irrigation (SI), plastic film mulch (MFP) under S1 (sandy loam soil) throughout the growing season during 2022-2023. The values are means ± SE (n=15). The small bars are standard errors.

Biomass, seed yield, and crop harvest index of guar:

The dry biomass of the guar crop at harvest was significantly influenced ($p \leq 0.001$) by supplementary irrigation and plastic film mulching across different soil textures during the 2022 and 2023 cropping seasons, as shown in Table 3. The data indicated that the highest plant dry biomass was recorded in the R treatment (irrigation with rainwater during the vegetative and reproductive stages), with average biomass values of 2124.8±1265 kg ha^{-1} in 2022 and 1595.0±949 kg ha^{-1} in 2023, outperforming other supplementary treatments.

The mean plant dry biomass increased by 39%, 31%, 26%, and 34% under the R, R+G, G+R, and G water treatments, respectively, when compared to the CK treatment (rain-fed cultivation). However, no significant differences were observed in dry biomass among the R, R+G, and G treatments. In terms of plastic film mulching practices, a highly significant decrease in plant dry biomass ($p \leq 0.05$) was noted in the no-mulch (control) treatment. During the study periods, the plant dry biomass for each treatment was ranked as the BPFM > WPFM > No-mulch treatment. Regarding soil types, both S1 and S2 soil classes significantly enhanced plant dry biomass. In the 2022 cropping season, biomass increased from 832.7 to 2782.2 kg ha^{-1} in S1 soil, and from 633.8 to 2116.2 kg ha^{-1} in S2 soil. A similar trend was observed during the 2023 season.

Experimental results indicated that the highest seed yield of guar was noted in the R treatment; the average biomass observed was 1040.1±784 and 780.6±588 Kg ha^{-1} in the 2022 and 2023 cropping seasons, respectively, as compared to compared to supplementary water treatments and CK (Table 3). Similarly, the average seed yield of guar increased by 52.8%, 48.4%, 40.0%, and 48.4% under the R, R+G, G+R, and G supplementary irrigation treatments, respectively, when compared to the CK treatment (rain-fed cultivation). The overall average of both years, seeds yield for each treatment was ranked as the R > R+G > G > G+R > CK water treatment. In plastic film mulching practices, seed yield increased highly significantly ($p \leq 0.05$) under treatment of mulching (BPFM and WPFM practices). Black plastic film mulching resulted in the highest seed yield increase (9%), followed by white plastic film mulching with a moderate increase (4.9%), while the lowest yield was recorded under the no-mulch treatment. During the study periods, the plant dry biomass for each treatment was ranked as the BPFM > WPFM > No-mulch treatment. In the case of soil types, the S1 and S2 soil classes significantly increased seeds of guar crop from 255.9 to 1443.1 Kg ha^{-1}, and 194.4 to 1096.5 Kg ha^{-1} in the 2022 and 2023 cropping seasons, respectively. The factors interaction of supplementary irrigation x plastic film mulching, supplementary irrigation x soil texture, and supplementary irrigation x plastic film mulching x soil texture was significant at the 0.001 level of probability. However, the interaction between plastic film mulching and soil textures was significant at the 0.05 level of probability in the cropping year 2022, and in the 2023 cropping season, it was significant at the 0.01 level of probability.

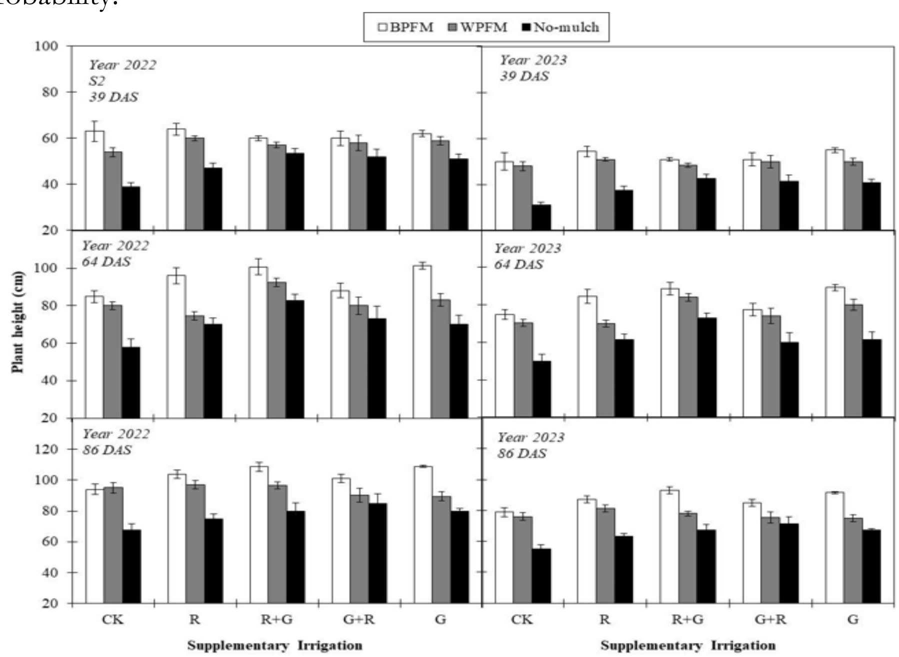

Figure 5 Plant height of seed guar crop as affected by supplementary irrigation (SI), plastic film mulch (MFP) under S2 (sandy clay loam soil) throughout the growing season during 2022-2023. The values are means ± SE (n=15). The small bars are standard errors.

The crop harvest index (CHI) of the guar crop at the harvesting stage was significantly affected by supplementary irrigation under different soil textures, and not by plastic film mulching during the cropping seasons of 2022 and 2023, as shown in Table 3. The result clearly shows that the maximum crop harvest index (CHI) of guar crop was recorded under the G treatment (irrigation with saline water at the vegetative and reproductive stage of guar); the average crop harvest index (CHI) observed was 0.44±0.15 in the cropping seasons of 2022 as compared to compared to other supplementary treatments. However, a different trend was observed during the 2023 cropping season. The crop harvest index (CHI) of the guar crop was highest under the R+G water treatment, where rainwater was applied during the vegetative stage and saline water during the reproductive stage. In comparison, the average CHI recorded during the 2022 season was 0.44 ± 0.11. In plastic film mulching practices, crop harvest index (CHI) is non-significant under all plastic film mulch and treatment of no-mulch. However, the no-mulch treatment had the highest crop harvest index (CHI), intermediate under black plastic film mulching, and the lowest under white plastic film mulching treatment. During the study periods, the crop harvest index (CHI) for each treatment was ranked as the No-mulch > BPFM > WPFM treatment. In the case of soil types, the S1 and S2 soil classes significantly increased plant dry biomass from 0.29±0.13 to 0.53±0.09, and 0.31±0.04 to 0.51±0.07 (unit-less) in 2022 and 2023 cropping seasons, respectively. In addition, the factors interaction of supplementary irrigation x soil texture, plastic film mulching x soil texture, and supplementary irrigation x plastic film mulching x soil texture were significant at the 0.01 level of probability.

Crop water productivity:

In experimental periods, the guar crop was irrigated with supplementary water at two different growth stages such as the vegetative and reproductive stages during 2022 and 2023.

For crop water productivity (CWP), the results indicated significant differences among the treatments during both the 2022 and 2023 cropping seasons (Figure 6). Among the supplementary irrigation water treatments, the two-year average crop water productivity (CWP) was highest under the R+G treatment,where rainwater was applied at the vegetative stage and saline water at the reproductive stage combined with white plastic mulching, compared to other water treatments under the S1 soil type. Besides in S2, in both years average CWP was highest recorded in the irrigation with rainwater applied at both growth stages when compared to other supplementary irrigation and no irrigation. Similarly, in S1, the different supplementary irrigation practices significantly decreased the CWP of guar crop up to 35.2, 18.5 and 13.6% in CK, G+R, and G treatments and increased 1.1% in the R+G water treatments, respectively, as compared to R treatment (rainwater applied at both select stages) during 2022 and 2023 cropping seasons. In the S2 soil type, the different supplementary irrigation practices significantly decreased the CWP up to 55.0, 11.0, 25.7 and 8.3% in the CK, R+G, G+R, and G water treatments, respectively, as compared to R treatment in both experimental years. However, the S1 soil still had significantly decreased CWP as compared with the S2 soil during the 2022 and 2023 cropping seasons. However, the water productivity of guar increased in 2023 as compared to the cropping season in 2022, but data trends were similar during both experimental years. It is revealed that the different supplementary water and soil types significantly increased CWP in this experiment as compared to rainwater treatment.

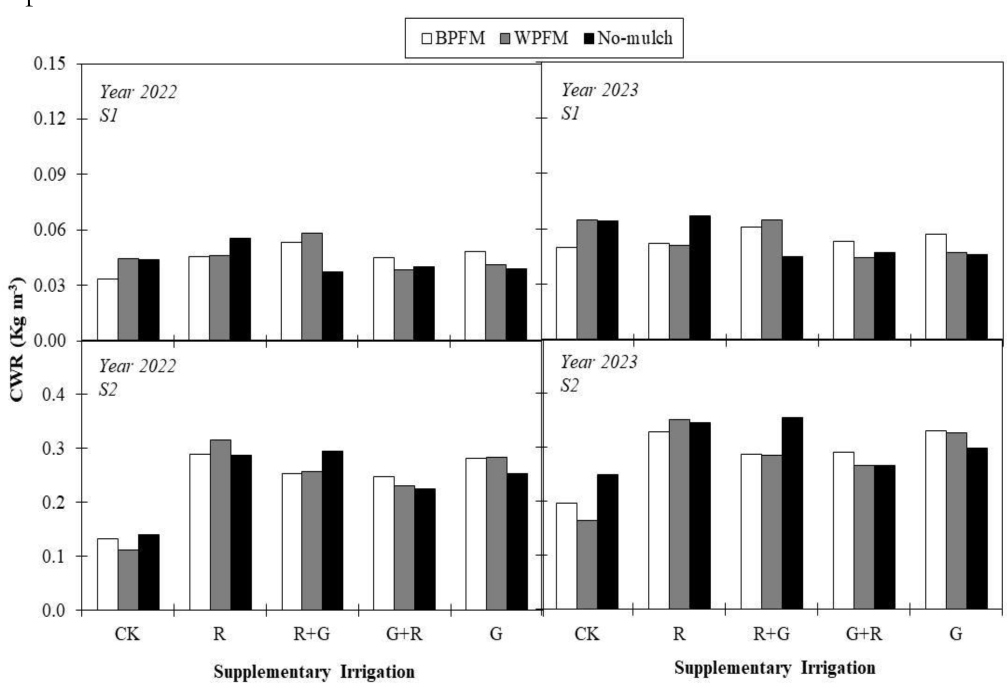

Figure 6 Crop water productivity (CWR) of guar crop as affected by supplementary irrigation (SI), plastic film mulch (MFP) under S1 (sandy soil texture), and S2 (clay soil texture) throughout the growing season during 2022-2023. The values are means ± SE (n=03)

Table 3. Main factor effects and interactions of supplementary irrigation (SI), plastic film mulch (MFP), and soil texture (ST) on plant dry biomass, seed yield, and crop harvest Index (CHI) during cropping season 2022 and 2023

Factor levels/interactions	Plant dry biomass (Kg ha^{-1})		Seed yield (Kg ha^{-1})		CHI (unitless)	
	2022	2023	2022	2023	2022	2023
Supplementary irrigations (SI)						
CK	1274.4±771[c]	1001.9±602[c]	481.6±394[d]	378.6±308[d]	0.33±0.07[b]	0.34±0.76[b]
R	2124.8±1265[a]	1595.0±949[a]	1040.1±784[a]	780.6±588[a]	0.42±0.12[a]	0.43±0.13[a]
R+G	1948.0±1124[a]	1363.5±847[a]	952.1±680[a]	715.5±516[ab]	0.43±0.12[a]	0.44±0.11[a]
G+R	1733.6±1017[b]	1323.6±774[b]	826.6±606[c]	631.3±463[c]	0.43±0.09[a]	0.42±0.12[a]
G	1951.6±1135[a]	1491.0±868[a]	945.0±717[a]	721.6±547[ab]	0.44±0.15[a]	0.42±0.14[a]
Significance	***	***	***	***	***	***
Plastic film mulch						
BPFM	1862.7±1119[a]	1449.7±869[a]	884.9±682[a]	688.8±530[a]	0.44±0.13	0.41±0.10
WPFM	1801.4±1076[a]	1338.9±788[b]	862.3±681[a]	650.7±493[b]	0.42±0.12	0.40±0.13
Non-mulch	1758.3±1123[b]	1136.4±841[b]	831.3±656[b]	607.1±501[b]	0.40±0.10	0.42±0.12
Significance	*	*	*	**	ns	ns
Soil texture						
S1	832.7±174	633.8±124	255.9±62	194.4±44	0.29±0.13	0.31±0.04
S2	2782.2±671	2116.2±491	1443.1±417	1096.5±503	0.53±0.09	0.51±0.07
Significance	**	***	***	***	***	***
Interactions						
SI x MFP	**	**	***	***	ns	ns
SI x ST	***	***	***	***	**	**
MFP x ST	ns	ns	*	**	**	**
SI x MFP x ST	**	**	***	***	**	**
SI x MFP x ST x Year	ns	ns	ns	ns	ns	ns

Note: All means within a column followed by the same letters are not different at the 5% level of significance using LSD; ns = Not significant, * = Significant at the 0.05 level, ** = Significant at the 0.01% level, and *** = Significant at the 0.001% level. The values are means ± SD (n=18 for irrigation treatments, n=30 for mulching treatments and n=45 for soil texture treatments)

Correlation analysis between different parameters of guar crop:

The correlation analysis between various parameters;including plant height, yield, biomass response, and water productivity of the guar crop showed high significance at both the 0.05 and 0.01 probability levels under different treatment factors. The corresponding r2r^2r2 values are presented in Table 4. The data indicates that the crop harvest Index was strongly positively and significantly correlated with plant height at harvesting. Additionally, the analyzed data revealed that seed yield was positively and significantly correlated with both plant height at harvest and the crop harvest index. The data indicate that dry biomass was strongly and positively significantly correlated with plant height at harvest, crop harvest index, and seed yield. These results showed that the significant increase in the r^2 value between dry biomass and different growth parameters has led to an improvement in the grain yield of guar.

Table 4. Correlation analysis between various growth parameters of guar under supplementary irrigation (SI), plastic film mulch (MFP), and soil texture (ST)

	PH	CHI	SY	DB
PH	1			
CHI	0.745**	1		
SY	0.807**	0.911**	1	
DB	0.816**	0.823**	0.978**	1

** Correlation is significant at the 0.01 level (2-tailed) and * Correlation is significant at the 0.05 level (2-tailed). PH = Plant height, CHI = Crop harvest Index, SY = Seed yield, and DB = Dry biomass

Discussion:

The experimental area is located in an arid and hot region in the southeastern part of Pakistan, characterized by low and unevenly distributed rainfall. Consequently, guar cannot effectively utilize rainfall, particularly since it is harvested in early November. In the previous studies, plant responses to drought and salinity are often similar, since both stresses induce soil water stress that leads to a delay in plant growth, a decrease in stomata aperture, and a nutrient deficiency [15][21][22][23][24].

Experimental results show that the plant height of the guar crop was highly significantly affected at various growth stages in rain-fed areas among the supplementary irrigation water and plastic film mulching under different soil textural classes throughout the cropping periods (Figure 4 and Figure 5).

These results indicate that plant height responses were significantly higher under black and white plastic film mulching treatments compared to the control (CK) treatment. Furthermore, S2 soil still had a significantly greater plant height compared with the S1 soil during the 2022 cropping season under supplementary irrigation water and plastic film mulch, and similar trends were observed in the cropping season 2023 (Table 2). The treatments receiving rainwater at the stem elongation stage of guar had the highest plant height, whereas the lowest plant height was noted in the CK treatment at both experimental sites. Previous studies reported that, if fresh water was available during initial crop stages for better plant height and growth, the saline water irrigation could be more effectively applied at other crop development stages of guar crop during peak dry period [16][25][26][27]. In general, for the no-mulch plots under supplementary irrigation and plastic film mulch, plant height in cm was reduced by 10% and 27% in the S1 and S2 Soil types, respectively. Previous research studies have shown that the number of pods per plant is a vital seed yield-attributing parameter for the guar crop, especially under water stress conditions in rain-fed regions [6][27]. Guar plant dry biomass, seeds yield, and crop harvest index (CHI) were significantly affected by main factors, and CHI was non-significantly affected by plastic film mulching treatments, as shown in Table 3. The data indicates that the crop harvest Index was strongly positively and significantly correlated with plant height at harvesting. Besides, the analyzed data showed that the seed yield was positively significantly correlated with plant height at harvesting, and crop harvest Index [4][28]. These results are also in agreement with the findings of author[29], author[30], and author[31], who reported that the alternate or supplementary use of saline and fresh water for irrigation has positive effects on crop growth and yield. The result clearly shows that the maximum plant dry biomass of guar crop was recorded under the R treatment; the average biomass observed was 2124.8 and 1595.0 Kg ha^{-1} in the 2022 and 2023 cropping seasons, respectively, as compared to compared to other supplementary treatments. In the case of soil types, the S1 and S2 soil classes significantly increased plant dry biomass. These results showed that the significant increase in the r^2 value between dry biomass and different growth parameters has led to an improvement in the grain yield of guar. The overall average of both years, seeds yield for each treatment was ranked as the R > R+G > G > G+R > CK water treatment. Supplementary irrigation with saline water produced the lowest seed yield compared with other water treatments [4][16][32][33]. If rainwater was applied during the initial stages for better vegetative guar growth, supplementary saline irrigation can be implemented during other stages of plant development. Several studies have established that guar can tolerate saline water irrigation up to a threshold level of 8.8 dS/m [4][34][35]. Researchers have noted the beneficial impact of supplementary saline irrigation on guar production in the rain-fed regions of Pakistan. Additionally, black plastic film mulching resulted in the highest seed yield, increasing it by 9%, while white plastic film mulching led to an intermediate yield increase of 4.9%, and no-mulch treatment produced the lowest yield. Our results are similar to author[36], who reported that the 30% yield increased under plastic mulching practice as followed by control. Our results also concise with author[37], observed that the soybean yield significantly under mulching practices. Similarly, a non-significant difference was observed in the CHI under all supplementary water treatments except CK treatment.

In experimental periods, the results show that the CWP was significant among the treatments during the 2022 and 2023 cropping seasons (Figure 6). We observed that the total amount of rainfall that occurred during the growth period of guar was not similar in 2022 and 2023, a higher CWP of guar was noted even when the amount of rainfall was lower in 2023 than in 2022. This could potentially be due to the distribution and pattern of rainfall, and the availability of sufficient volumes of saline or harvested rainwater at regular intervals. According to authors[38][4], supplementary regular irrigation was most efficient for guar seed production. Field water productivity is a key indicator that reflects the relationship between water usage and seed yield [39].Several studies have highlighted that plastic film mulching can significantly enhance water use efficiency [31][40][41].

Conclusions:

In rain-fed areas, soil water status, temperature of upper soil layers, and other growth parameters are the restricting factors in guar production. Across the supplementary saline and rainwater irrigation treatments to guar crop, irrigation water applied at sequential vegetative and reproductive stages with rainwater could highly significantly enhance dry biomass production by 39 % and seeds yield by 52.9 % as compared to CK treatment. Similarly, there is no significant differences were found between R+G and G supplementary saline and rainwater treatments. Across the plastic film mulching treatments, by improving the plant and soil micro-climatic condition, mulched plots increased significantly seed yield by 9 % in black-colored film mulched plots and 5 % in white plastic film mulched plots because less soil water depletion as compared to non-mulch plots during both cropping seasons at both experimental sites. Across the soil types, due to soil properties, the S2 soil type increased highly significantly dry biomass by 70 % and seeds yield by 82 % as compared to S1, S2 has more filed capacity as followed by S1. The Supplementary saline irrigation (G treatment), and alternate saline and rainwater irrigation (G+R treatment) can be applied at sequential vegetative and reproductive stages without any more negative impact on the seed yield of guar compared to other supplementary irrigation treatments. In supplementary irrigation water treatments, the two-year results also showed that the CWP was highest found in the irrigation with rainwater and lowest in G+R water treatment under plastic film mulching practice and soil textural classes when compared to other water treatments, except rain-fed cultivation.

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