

The Impact of Sustainable Farming Techniques (Irrigation, Mulching, and Kaolin) on Pomegranate Fruit Quality, Productivity, and Physiological Disorders Reduction.

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Abstract

This study aimed to enhance the productivity, quality and reduction of sunburn incidence in pomegranate fruits (*Punica granatum* L., CV. Wonderful) grown under desert and semi desert environments. The experiment was conducted at the desert farm in Karbala during the 2024-2025 season. three main sustainable strategies were evaluated to improve the physiological traits and fruit quality: irrigation levels (I1: 1 hour, 65 L tree⁻¹ day⁻¹; I2:0.5-hour, 32.5 L tree⁻¹ day⁻¹), soil mulching (CO: no mulch; C1: spent mushroom compost substrate SMC; C2: straw mulch), and foliar application of kaolin (KO: no spray, K2: 2 g tree⁻¹; K4: 4 g tree⁻¹). The Results showed that all studied parameters were significantly affected by the three factors and their two-way and three-way interactions. The combination of watering for an hour with SMC substrate mulching and foliar kaolin application at 4 g tree⁻¹ produced the best results in terms of fruit size, juice percentage, leaf calcium concentration, and reduced sunburn incidence. Meanwhile, Watering for an hour, with no mulch and kaolin at 4 g tree⁻¹ increased peel thickness. Watering for half an hour combined with straw mulching and kaolin at 4 g tree⁻¹ resulted in the highest fruit weight, while half irrigation with mushroom spent substrate mulching and kaolin at 4 g tree⁻¹ led to the highest boron concentration in the leaves.

Keywords: pomegranate, irrigation management, soil mulching, kaolin, fruit quality, sunburn, nutrient

Introduction

Pomegranate (*Punica granatum* L.) is considered one of the most economically and important fruit crops in tropical and subtropical regions around the world, and it is widely cultivated in warm and dry areas. It is a popular and widespread fruit its originally in native to Central Asia, from northern India to the Himalayas and Iran the cultivar Wonderful is among the most important commercial varieties due to its good adaptation to arid

environments. It first developed in Florida and later Exported to the world and countries across the world after being widely accepted by farmers (28). Pomegranate generally needs a hot summer weather or semi-arid and also long summers Iraq provides suitable and a lot of great conditions for cultivating several pomegranate cultivars however the harsh and hard climatic conditions in most regions often result in poor-quality fruits suffering from physiological disorders such as fruit cracking and sunburns These disorders significantly reduce the marketable yield and the economic

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losses. Since fruit development and ripening extend through the hot summer and early autumn, the trees are exposed to high temperatures, intense solar radiation, and low relative humidity. Although pomegranate trees are relatively drought tolerant, fruit quality is markedly reduced under such stress. Optimum production is usually achieved under regular irrigation throughout the growing season (23)(28). Many crops grown in warm regions are affected by a physiological disorder known as sunburn, which is mainly caused by photodamage resulting from excessive solar radiation (visible and UV) combined with high temperatures (23)(19). Ghasemi-Soloklui et al. (2023) reported that climate change in the native habitats of pomegranate may negatively affect fruit quality traits such as fruit color, weight, seed weight, peel thickness, and edible portion (12). Pomegranate fruits are particularly sensitive to physiological disorders such as sunburn, especially under hot and dry climates with high solar radiation. Symptoms typically appear as brown area patches on the peel of the fruit, which later expand leading to cracking of the fruit skin and discoloration of the internal membranes. These changes negatively affect juice quality, making the fruit unmarketable. Porras-Jorge et al. (2025) indicated that reducing irrigation levels to 50% significantly decreased both total and marketable yield by reducing fruit size and weight, while increasing the physiologically damaged fruits of inferior quality (27). Efficient water resource management, particularly through proper irrigation scheduling and water quality management represents the proper strategy to enhance growth yield and fruit quality under current environmental conditions (26). The problem of declining pomegranate quality due to sunburn and cracking is becoming more acute with the worsening of negative climate changes as is the case in most areas of central Iraq, which used to be fertile ground for fruit production. However, climate change, desertification, drought, and the severe shortage of natural water resources are causing

the problem (11). This has led to the need to find sustainable strategic solutions to this problem as although pomegranate is relatively resistant to drought under such conditions the tree and its fruits must be protected from the sun's rays in the summer so it must be planted under trees (16) and the trend towards using some sustainable methods to address such challenges to increase pomegranate production, improve fruit quality and reduce sunburn including mulching the soil around trees, using organic materials such as plant waste including wheat straw and mushroom mulch (SMC). Mulching the soil reduces water loss and evaporation from the soil surface and improves soil fertility which provides a suitable environment conducive to root growth. It also contributes to providing the essential nutrients necessary for plant growth through the continuous decomposition of organic compounds, regulates temperature and helps protect the environment (14). Pomegranate fruits are borne terminally on the branches and the leaves are small so the fruits are highly exposed to intense solar radiation, which leads to sunburn. To reduce the intensity of radiation, as well as reduce transpiration and maintain a balanced water content in the tissues, it is possible to use some sustainable natural compounds such as kaolin, which is a natural clay used as a natural anti-transpirant that works to reflect the sun's rays and thus reduce the temperature which leads to a decrease in transpiration, which is reflected in the quality of the fruits and the rationalization of water consumption. A number of researchers indicated that fruits treated with kaolin were more effective in reducing sunburn (25)(19)(14)(4). Ahmed and Gaber (2022)(1) also noted that foliar kaolin sprays significantly improved yield and quality of 'Manfalouty' pomegranates under harsh conditions, compared with untreated fruits, which exhibited up to 30% sunburn incidence (1). Therefore, this study aimed to improve the quality, and reduce sunburn incidence, of pomegranate cv. Wonderful, cultivated under the harsh desert environment of Karbala, Iraq,

through sustainable practices including irrigation management, soil mulching, and foliar kaolin application . Material and Methods

The experiment was conducted during the 2024 growing season, starting from March 1, 2024 until January 2025, in one of the orchards belonging to the Ministry of Agriculture, Department of Agricultural Extension and Training / Agricultural Training Extension Center in Holy Karbala / Desert Extension Farm (32°32'25.1"N 44°01'19.8"E), on nine-year-old wonderful pomegranate trees planted under date palms. The aim of this study was to evaluate the effects of irrigation regulation, soil mulching, and foliar application of kaolin as sustainable agricultural practices intended to enhance tree performance under arid conditions and achieve optimal efficiency in the use of limited water resources. The research plan was implemented with the following factors:

Irrigation Levels: The pomegranate trees were irrigated by drip irrigation after determining the soil moisture content, it was irrigated with two levels of water (operating the pump daily at 4:00 AM exactly for one hour, and half an hour), as follows:

- The first level, symbolized as I1
, the trees were irrigated with 65 liters of water per tree.
- The second level, symbolized as I2 the trees were irrigated with 32.5 liters of water per tree.

mulching: The soil around the trees was mulched in a circle with a diameter of 1.5 meters with mulching materials that include:

- Without mulching, symbolized as C0.

mulched with (SMC) spent mushroom compost, symbolized as C1.

mulched with wheat straw, symbolized

- as C2.

Foliar Spray with Kaolin (natural anti-transpirant) at three concentrations:

- Foliar spray with water, symbolized as K0.
- Foliar spray with kaolin at a concentration of 2 g L⁻¹, symbolized as k2.
- Foliar spray with kaolin at a concentration of 4 g L⁻¹, symbolized as k4.

Spraying with kaolin began after fruit set, every month throughout the growing season.

The experiment was carried out according to a Nested-Factorial Experiment design. The following traits were studied (10) (11) (27) (31):

Sunburned fruit percentage (%), Fruit weight (g), Fruit size (cm³), Juice percentage in fruits (%), Peel thickness(mm), Calcium concentration in leaves (%), Boron concentration in leaves (%).

while the maximum production was found in the I2K0 this treatment gave values of (26.14 %). The lowest Sunburned fruit percentage fruits in the interaction of soil mulch and kaolin spraying was in the C1K4, respectively gave (7.00%), and the highest was C0K0 treatment gave (37.31%).

Results and Discussion

Sunburned fruit percentage (%):

The results in Table 1 the effect of individual factors, with the highest in the I2 treatment gave (22.65%) and the lowest in the I1 level gave (13.03%). Soil mulch had a significant effect on Sunburned fruit percentage; with the maximum being observed under (C0) it gave (24.79%) and the minimum under residue removal (C1) gave (11.85%). The effect of kaolin was also statistical significantly, the his value of K 0 (26.12%) were higher than lower his value observed in K4 (11.17%). The results of the combined effect of irrigation and mulch level (Table 1) revealed that the combination I2C0 it gave (29.93 %), while the lowest was obtained from I1C1 this treatment gave values of (6.58 %).

the data showed that irrigation levels and kaolin spraying, was in the minimal were observed in I1K4 treatment gave (3.45%)

The data clearly show that Table (1) indicate that the interaction of the research factors significantly affected the Sunburned fruit percentage fruits. the minimal production was found in the I1C1K4 this treatment gave values of (0 %). Conversely, the maximum was observed in I1C0K0 it gives (40.00).

Table 1. Effect of irrigation level, soil mulching, kaolin spraying, and interaction between them on Sunburn (%).

I	C	K			I*C	Mean I
		K0	K2	K4		
I1	C0	40.00	10.92	8.02	19.64	13.08
	C1	12.73	7.00	0	6.58	
	C2	25.54	11.15	2.34	13.01	
I2	C0	34.61	34.10	21.07	29.93	22.65
	C1	18.82	18.52	14.01	17.12	
	C2	25.00	19.27	18.43	20.9	
LSD 0.05		I=0.107	I*C =0.320	I*C*K		

K x I				
I1	26.09	9.69	3.45	LSD: I*K = 0.312
I2	26.14	23.96	17.84	
K x C				
C0	37.31	22.51	14.55	24.79
C1	15.78	12.76	7.00	11.85
C2	25.27	15.21	10.39	16.96
LSD	LSD: C*K = 0.448			LSD: C = 0.261
Mean K	26.12	16.31	11.17	
LSD	LSD: K = 0.254			

Fruit weight (g):

There is clear evidence that Table 2 show effect of individual factors, with the highest Fruit weight in the I2 treatment 165.1 and the lowest in the I1 level gave 107.8. Mulching had a significant effect on Fruit weight; with the maximum being observed under (C2) gave 193.3 and the minimum under residue removal (C0) gave 81.1. The effect of kaolin was also statistical significantly, the his value of K2 were higher giving 152.3 than lower his value observed in K0 gave 109.8.

it was found that irrigation levels and kaolin spraying, was in the maximum Fruit weight were observed in I2K4 treatment gave 186.6, while the minimal production was

found in the I1K0 gave 97.0. The highest Fruit weight in the interaction of soil mulch and kaolin spraying was in the C2K4 220.8, respectively, and the lowest was C0K0 treatment gave 33.5.

The results in Table (2) indicate that the interaction of the research factors significantly affected the Fruit weight. The maximum Fruit weight were observed in I2C2K4 it gave 203.9. Conversely, the minimal production was found in the I1C0K0 35.8. The results of the combined effect of irrigation and mulch level (Table 2) revealed that the combination I2C2 gave 216.1, while the lowest was obtained from I1C0 it gave 49.5.

Table 2. Effect of irrigation level, soil mulching, kaolin spraying, and interaction between them on Fruit weight (g) .

I	C	K			I*C	Mean I
		K0	K2	K4		
	C0	35.8	54.8	58.1	49.5	107.8
I1	C1	117.5	98.3	94.7	103.5	
	C2	137.7	202.5	171.2	170.5	
	C0	31.1	167.4	139.4	112.6	165.1
I2	C1	163.1	187.1	149.9	166.7	
	C2	173.8	203.9	270.4	216.1	
LSD 0.05		I=5.19	I*C =7.56	I*C*K =		
K x I						
I1		97.0	118.5	108.0	LSD: I*K =7.15	
I2		122.7	186.1	186.6		
K x C					Mean C	
C0		33.5	111.1	98.7	81.1	
C1		140.3	142.7	122.3	135.1	
C2		155.7	203.2	220.8	193.3	
LSD		LSD: C*K =7.98			LSD: C =4.77	

Mean K	109.8	152.3	147.3
LSD	LSD: K = 4.27		

Fruit size (cm³):

The results in Table 3 show the effect of individual factors, with the highest Fruit size in the I2 treatment and the lowest in the I1 level. Soil mulch had a significant effect on Fruit size; with the maximum being observed under (C2) gave 51.07 and the minimum under residue removal (C0) gave 40.29. The effect of kaolin was also statistical significantly, the his value of K4 were higher it gave 49.05 than lower his value observed in K0 it gave 41.93.

The results of the combined effect of irrigation and mulch level (Table 3) revealed that the combination I1C2 was gave 52.10, while the lowest was obtained from I1C0 gave 36.06.

results indicated that irrigation levels and kaolin spraying, was in the maximum Fruit size were observed in I2K4 treatment it gave 51.74, while the minimal production was found in the I2K0 gave 40.92. The highest Fruit size in the interaction of soil mulch and kaolin spraying was in the C1K4 it gave 55.97, respectively, and the lowest was C0K0 treatment gave 34.03.

The results in Table (3) indicate that the interaction of the research factors significantly affected the Fruit size. The maximum Fruit size were observed in I1C1K4 was 56.97. Conversely, the minimal production was found in the I1C0K0 it gave 27.20.

Table 3. Effect of irrigation level, soil mulching, kaolin spraying, and interaction between them on Fruit size (cm³).

I	C	K			I*C	Mean I
		K0	K2	K4		
I1	C0	27.20	38.53	42.43	36.06	44.27
	C1	46.17	53.17	56.97	52.10	
	C2	55.43	38.87	39.67	44.66	
I2	C0	40.87	44.17	48.53	44.52	46.54
	C1	41.17	53.97	54.97	50.03	
	C2	40.73	42.73	51.73	45.07	
LSD 0.05		I=0.192	I*C = 0.459	I*C*K =		
K x I						
I1		42.93	43.52	46.36	LSD: I*K = 0.593	
I2		40.92	46.96	51.74		
K x C						
C0		34.03	41.35	45.48	Mean C	
C1		43.67	53.57	55.97	40.29	
C2		48.08	40.80	45.70	51.07	
LSD		LSD: C*K = 0.705			LSD: C = 0.361	
Mean K		41.93	45.24	49.05		
LSD		LSD: K = 0.486				

Juice percentage in fruits (%):

It appears clearly that Table 4 show the effect of individual factors, with the highest Juice percentage in fruits in the I 1 treatment gave 10.23 and the lowest in the I 2 level gave 5.70. Soil mulch had a significant effect on Juice content of arils; with the maximum being observed under (C1) gave 10.70 and the minimum under residue removal (C0) gave 5.75. The effect of kaolin was also statistical significantly, the his value of K4 were higher it was giving 11.08 than lower his value observed in K0 gave 4.73. The results of the combined effect of irrigation and mulch level (Table 4) revealed that the combination I1C 113.73 while the lowest was obtained from I2C0 gave 3.29.

the data showed that irrigation levels and kaolin spraying, was in the maximum Juice content of arils were observed in I1K4 treatment it gave 14.59, while the minimal production was found in the I2K0 gave 3.89. The highest Juice content of arils in the interaction of soil mulch and kaolin spraying was in the C1K4 was gave 16.73, respectively, and the lowest was C0K0 treatment gave 4.07. The results in Table (4) indicate that the interaction of the research factors significantly affected the Juice content of arils. The maximum Juice percentage in fruits were observed in I1C1K4 it gave 22.36. Conversely, the minimal production was found in the I2C0K0 gave 2.61.

Table 4. Effect of irrigation level, soil mulching, kaolin spraying, and interaction between them on juice percentage (%).

I	C	K				
		K0	K2	K4	I*C	Mean I
	C0	5.54	9.39	9.72	8.21	10.23
I1	C1	6.07	12.77	22.36	13.73	
	C2	5.15	9.45	11.68	8.76	
	C0	2.61	3.23	4.05	3.29	5.70
I2	C1	4.98	6.91	11.11	7.66	
	C2	4.08	6.80	7.60	6.16	
LSD 0.05		I= 0.493	I*C =0.655	I*C*K =		
K x I						
	I1	5.58	10.53	14.59	LSD: I*K =0.549	
	I2	3.89	5.64	7.58		
K x C						Mean C
	C0	4.07	6.31	6.88	5.75	
	C1	5.52	9.84	16.73	10.70	
	C2	4.61	8.12	9.64	7.46	
LSD		LSD: C*K =0.720			LSD: C =0.467	
Mean K		4.73	8.09	11.08		
LSD		LSD: K = 0.344				

Peel thickness(mm):

There is clear evidence that Table 5 show effect of individual factors, with the highest Peel thickness in the I 2 treatment gave 4.01 and the lowest in the I 1 level gave 3.11. Soil mulch had a significant effect on Peel thickness; with the maximum being observed under (C0) it gave 4.60 and the minimum under residue removal (C1) it gave 2.72. The effect of kaolin was also statistical significantly, the his value of K 0 were higher it gave 4.14 than lower his value observed in K 4 gave 3.06.

The results of the combined effect of irrigation and mulch level (Table 5) revealed that the combination I2C 0 gave 5.05, while the lowest was obtained from I1C 1 gave 2.30.

the analysis showed that irrigation levels and kaolin spraying, was in the maximum Peel thickness were observed in

Table 5. Effect of irrigation level, soil mulching, kaolin spraying, and interaction between them on peel thickness (mm).

I	C	K			I*C	Mean I
		K0	K2	K4		
I1	C0	4.54	4.35	3.56	4.15	3.11
	C1	3.01	2.23	1.66	2.30	
	C2	3.92	2.56	2.22	2.90	
I2	C0	5.21	5.06	4.88	5.05	4.01
	C1	3.29	3.18	2.95	3.14	
	C2	4.88	3.58	3.12	3.86	
LSD 0.05		I= 0.139	I*C =0.137	I*C*K =		
K x I					LSD: I*K = 0.1414	
I1		3.82	3.04	2.48		
I2		4.46	3.94	3.65		
K x C					Mean C	
C0		4.87	4.70	4.22	4.60	
C1		3.15	2.70	2.30	2.72	
C2		4.40	3.07	2.67	3.06	
LSD		LSD: C*K = 0.096			LSD: C = 0.052	
Mean K		4.14	3.49	3.06		
LSD		LSD: K = 0.069				

Calcium concentration in leaves (%):

The data clearly show that Table 6 show effect of individual factors, with the highest Calcium concentration in leaves in the I1 treatment it gave 1.80 and the lowest in the I2 level gave 1.65. Soil mulch had a significant effect on Calcium concentration in leaves; with the maximum being observed under (C1) it gave 2.07 and the minimum under residue removal (C0) it gave 1.41. The effect of kaolin was also statistical significantly, the his value of K4 were higher was gave 1.94 than lower his value observed in K0 it gave 1.53.

The results of the combined effect of irrigation and mulch level (Table 6) revealed that the combination I1C1 gave 2.34, while the lowest was obtained from I1C0 gave 1.24.

analytical results revealed that irrigation levels and kaolin spraying, was in the maximum Calcium concentration in leaves were observed in I1K4 treatment it gave 2.04, while the minimal production was found in the I2K0 gave 1.50. The highest Calcium concentration in leaves in the interaction of soil mulch and kaolin spraying was in the C1K4 gave 2.37, respectively, and the lowest was C0K0 treatment it gave 1.41.

The results in Table (6) indicate that the interaction of the research factors significantly affected the Calcium concentration in leaves. The maximum Calcium concentration in leaves were observed in I1C1K4 gave 2.87. Conversely, the minimal production was found in the I1C0K0 gave 1.24.

Table 6. Effect of irrigation level, soil mulching, kaolin spraying, and interaction between them on Ca (%).

I	C	K				
		K0	K2	K4	I*C	Mean I
	C0	1.15	1.23	1.36	1.24	1.80
I1	C1	1.80	2.35	2.87	2.34	
	C2	1.75	1.85	1.91	1.83	
	C0	1.31	1.51	1.91	1.57	1.65
I2	C1	1.75	1.82	1.87	1.81	
	C2	1.45	1.52	1.75	1.57	
LSD 0.05		I=0.017	I*C =0.025	I*C*K		
K x I						
	I1	1.57	1.81	2.04	LSD: I*K =0.033	
	I2	1.50	1.61	1.84		
K x C						
	C0	1.23	1.37	1.63	Mean C	1.41
	C1	1.78	2.08	2.37		2.07
	C2	1.60	1.68	1.83		1.70
LSD		LSD: C*K =0.036			LSD: C =0.018	
Mean K		1.53	1.71	1.94		
LSD		LSD: K = 0.027				

Boron concentration in leaves (%):

The results in Table 7 show the effect of individual factors, with the highest Calcium concentration in leaves in the I 1 treatment gave 55.49 and the lowest in the I 2 level gave 47.23. Soil mulch had a significant effect on Calcium concentration in leaves; with the maximum being observed under (C1) gave 71.71 and the minimum under residue removal (C0) gave 35.94. The effect of kaolin was also statistical significantly, the his value of K4 gave 56.93 were higher than lower his value observed in K0 gave 46.04. The results of the combined effect of irrigation and mulch level (Table 7) revealed that the combination I2C 1 gave 72.05, while the lowest was obtained from I2C0 gave 34.20.

In the interaction of irrigation levels and kaolin spraying, was in the maximum

Calcium concentration in leaves were observed in I1K 2 treatment it gave 58.02, while the minimal production was found in the I2K0 gave 40.10. The highest Calcium concentration in leaves in the interaction of soil mulch and kaolin spraying was in the C1K4 gave 84.75, respectively, and the lowest was C0K 4 treatment it gave 35.05. The results in Table (7) indicate that the interaction of the research factors significantly affected the Calcium concentration in leaves. The maximum Calcium concentration in leaves were observed in I2C1K4 gave 84.75. Conversely, the minimal production was found in the I2C0K0 gave 31.16.

Table 7. Effect of irrigation level, soil mulching, kaolin spraying, and interaction between them on Boron (%).

I	C	K			I*C	Mean I
		K0	K2	K4		
I1	C0	41.20	39.70	35.05	37.68	55.49
	C1	60.23	75.60	84.75	71.37	
	C2	54.53	58.76	58.96	57.42	
I2	C0	31.16	33.50	37.93	34.20	47.23
	C1	57.73	67.22	91.20	72.05	
	C2	31.40	31.90	43.03	35.44	
LSD 0.05		I= 0.459	I*C =0.563	I*C*K		
K x I						
I1		51.98	58.02	56.47	LSD: I*K = 0.596	
I2		40.10	44.20	57.38		
K x C					Mean C	
C0		36.18	36.60	35.05	35.94	
C1		58.98	71.41	84.75	71.71	
C2		42.96	45.33	51.00	46.43	
LSD		LSD: C*K =0.657			LSD: C = 0.381	
Mean K		46.04	51.11	56.93		
LSD		LSD: K = 0.435				

Discussion

The results of this study clearly demonstrated that one-hour irrigation significantly enhanced vegetative growth and improved the nutritional quality of pomegranate plants. Irrigation, increased the concentrations of essential nutrients such as nitrogen, phosphorus, potassium, which impacted growth, higher yields and superior fruit quality. Fruit yield, quality parameters, were strongly influenced by Irrigation water quantities in contrast, inadequate irrigation reduced nutrient uptake from the soil, leading to a decline in fruit quality. Conversely, trees irrigated for one hour exhibited vigorous growth and higher leaf water content, findings consistent with those of El-Bolok (7) and El-Salhy (9). Fruit quality attributes—including size, firmness, color, sugar concentration, titratable acidity, sugar:acid ratio, and dry matter content were strongly influenced by water stress in arid and semi-arid environments. Water deficit often increased soluble solids in fruits, likely due to the accumulation of dry matter, although it negatively affected vegetative growth and yield, as reported by Gomez-Bellot (13).

The reduction in sunburn damage following kaolin foliar sprays can be attributed to its reflective properties against solar radiation (Ahmed and Gaber, 1). Similarly, soil mulching with organic materials improved fruit quality and minimized sunburn damage by conserving root-zone moisture, enhancing nutrient availability, and creating suitable conditions for growth. These findings are consistent with Meshram (21) and 23. Lokesha (20), who reported that mulching improves the microclimate, promotes nutrient uptake, conserves soil water, and suppresses weeds, ultimately increasing fruit size through enhanced cell division and elongation. Organic mulches such as wheat straw and spent mushroom compost (SMC) further improved fruit yield and quality by supplying nutrients and stimulating physiological and biochemical processes, including carbohydrate

and protein metabolism. This practice also reduced fruits sunburn, in agreement with earlier studies that highlighted the synergistic effect of irrigation and mulching on productivity under harsh conditions (Nasrabadi, 24). Beelagi (5) emphasized that organic mulches represent eco-friendly and sustainable alternatives to plastic mulches, as they not only conserve soil moisture but also enhance fruit quality through the gradual release of nutrients during decomposition. Kaolin foliar sprays also proved effective as natural anti-transpirants, reducing fruit sunburn, enhancing fruit quality, and increasing sugars and anthocyanin levels, these improvements were attributed to the maintenance of cell turgor and reduced water loss, as supported by Al-Hayani (3). Thus, the combined use of organic mulching and kaolin sprays represents a sustainable strategy to enhance pomegranate productivity and fruit quality under desert conditions.

Calcium (Ca) concentrations increased under organic matter application, likely due to improved soil conditions, reduced leaching, and enhanced nutrient availability. This facilitated greater Ca uptake, strengthening tissues and improving fruit firmness. These findings align with Mohamed (22), Kochakinezhad (18), Khalil, (17), and Kadiri (15), who confirmed the role of calcium in reducing fruit sunburn and enhancing fruit structural integrity. Micronutrients, particularly iron and boron, also played essential roles in regulating plant physiology. Boron was reported to promote cell elongation, nucleic acid synthesis, hormone regulation, and membrane function (Shelp, 29). Boron stimulated meristematic tissue growth, nucleic acid biosynthesis, sugar transport, and potassium uptake (Al-Dulaimi, 2). Singh (30) further emphasized boron's role in converting amino acids into sugars and their derivatives through specific metabolic pathways, findings consistent with the present results. Similarly, Sutanu (31) confirmed that

boron application enhanced vegetative growth, fruit set, total soluble solids (TSS), and juice content. Taken together, these results suggest that integrating efficient irrigation with

organic mulching represents a promising strategy for improving pomegranate growth and productivity under semi-arid conditions.

Conclusion

This study highlights the importance of sustainable orchard management for pomegranate cultivation under semi-arid conditions characterized by limited water resources, high temperatures, and sandy soils. The results demonstrate that combining efficient irrigation practices with organic mulching and kaolin foliar sprays can enhance

fruit yield and quality, reduce physiological disorders such as sunburn and fruit cracking, and improve nutrient uptake efficiency. These sustainable practices not only improve fruit quality and marketability but also provide environmentally friendly solutions that ensure long-term orchard productivity and resilience under challenging environmental conditions.

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