THE EFFECT OF IRRIGATION INTERVAL AND SOME ENVIRONMENTAL SUSTAINABILITY FACTORS ON GROWTH AND PRODUCTION OF COWPEA PLANTS

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ABSTRACT

This study was conducted during the spring season of 2023-2024 and the fall season of 2024-2025 at the fields of the College of Agricultural Engineering Sciences, University of Baghdad, to investigate effects of irrigation intervals I_1, I_2 (3 and 6 days) , soil amendment with zeolite at three concentrations Z_0 ,Z_1,Z_2 (0, 4, and 8 g. kg soil^{-1}), and foliar spraying with kaolin for three concentrations C_0,C_1,C_2 (0, 0.5, and 1 g .L^{-1}). The results revealed that the treatment $I_1Z_2C_2$ significantly excelled in leaf area, chlorophyll concentrations, and yield for both seasons, achieving 31.0 dm^2, 21.5 mg per 100 g fresh weight, and 1984.7 g in the first season, and 34.08 dm^2, 23.6 mg per 100 g fresh weight, and 2526.3 g in the second season. In contrast, the treatment $I_2Z_0C_0$ significantly outperformed others in proline concentration, peroxidase enzyme activity, and antioxidant capacity (DPPH), recording 45.5 mg g^{-1} dry weight, 1.09 absorption units g^{-1} protein, and 73.3% in the first season, and 101.80 mg g^{-1} dry weight, 4.400 absorption units g^{-1} protein, and 92.0% in the second season.

Keywords: zeolite, kaolin, electrolyte leakage, DPPH.

تأثير مدة الري وبعض عوامل الاستدامة البيئية في نمو وانتاج نبات اللوبيا

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المستخلص

نفذ البحث للموسمين الربيعي 2023- 2024 والموسم الخريفي 2024-2025 في الحقول التابعة لكلية علوم الهندسة الزراعية – جامعة بغداد، لدراسة تأثير فواصل الري 3و6 أيام رمز لها I_1 ,I_2 بالتتابع ،اما العامل الثاني فقد تضمن إضافة محسن التربة (الزيولايت) قبل الزراعة رمز لها Z_0 ,Z_1,Z_2 بالتتابع (0 و 4 و8 كغم . تربة$^{-1}$) والرش بالكاؤولين وبثلاث تراكيز رمز لها C_0,C_1,C_2 بالتتابع (0 و0.5 و1 غم.لتر) ، اشارت النتائج الى تفوق المعاملة $I_1Z_2C_2$ معنويا في المساحة الورقية ومحتوى الأوراق من الكلوروفيل والحاصل ولموسمي التجربة باعطائها (31.0دسم^2 ،21.5 ملغم .100 غم وزن رطب ،1984.7 غم) بالتتابع للموسم الأول و(34.08 دسم^2 ،23.6 ملغم .100 غم وزن رطب ،2526.3 غم) بالتتابع للموسم الثاني، تفوقت معاملة $I_2Z_0C_0$ معنويا وللموسمين في (تركيز البرولين ، فعالية انزيم البيروكسيديز، قوة مضادات الاكسدة DPPH) اذ أعطت (45.5 ملغم غم وزن جاف$^{-1}$ ،1.09 وحدة امتصاص غم $^{-1}$ بروتين،73.3 %) بالتتابع للموسم الأول ، فيما اعطت (101.80 ملغم غم وزن جاف$^{-1}$ ،4.400 وحدة امتصاص غم $^{-1}$ بروتين،92.0 %) بالتتابع للموسم الثاني.

الكلمات المفتاحية: الزيولايت، الكاؤولين، النضح الالكتروليتي، DPPH

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INTRODUCTION

The combination of population growth and climate change is expected to drive an increased demand for food production, posing significant economic challenges, particularly in agricultural activities, which are more vulnerable to environmental constraints compared to other production sectors (10, 12, 15). Therefore, attention to irrigation and the use of nutrients are crucial to achieving higher productivity levels, despite the associated increase in crop production costs (6, 11, 16). The importance of irrigation scheduling and water management has also emerged, focusing on determining the interval between irrigation events to provide the optimal water quantity needed for plants to complete their life cycle and achieve productivity at the lowest possible cost (1, 17 ,19, 24). Thus, producers are encouraged to explore new options, with a primary focus on improving irrigation water efficiency, as the water crisis poses a significant challenge to achieving food security (4, 7, 13, 20). Water importance a critical role in the supply and transport of nutrients, regulation of photosynthesis, and cell growth and division, all of which directly impact crop yield and quality. Cowpea *Vigna unguiculata* L. is recognized for its adaptability in drought-prone areas due to its resilience to water deficits (21, 25). Therefore, research has focused on studying the effects of water scarcity on this crop, emphasizing processes related to osmotic adjustment and antioxidant metabolism, which are critical for its adaptation and survival under such challenging conditions. There has been a growing trend toward using natural soil amendments that enhance soil moisture retention and improve cation exchange capacity, particularly zeolite (8, 26, 27, 28). Zeolite, a crystalline hydrated aluminosilicate of alkali and alkaline earth metals, possesses a high cation exchange capacity ranging between 200–400 meq/100 g (2, 29, 30). Torma *et al.,* (22) observed that adding zeolite to soil increased cucumber production by enhancing the number and size of fruits as well as plant height. This improvement was attributed to the enhancement of soil physical and chemical properties upon the addition of zeolite. The importance of kaolin clay lies in its role as a tool to enhance the plant's ability to withstand stress, thereby maintaining vital biological functions, particularly photosynthesis. It also contributes to improved plant growth and production quality (9). Based on this, the study aimed to achieve optimizing water use through extended irrigation intervals and irrigation scheduling, as well as mitigating drought stress through the application of soil amendments and Antitranspirants**.**

MATERIALS AND METHODS

This study was conducted during the spring season of 2023-2024 and the fall season of 2024-2025 at the fields of the College of Agricultural Engineering Sciences, University of Baghdad, Jadiriyah. Soil preparation involved plowing, leveling, and smoothing, followed by dividing the field into 2-meter-wide ridges. Cowpea seeds were sown on March 15, 2024, in two rows per ridge, with 30 cm spacing between plants. The experiment examined three factors and their interactions: irrigation intervals (every 3 and 6 days) as Their symbol $I_1$and I_2, soil amendment with zeolite at three concentrations (0, 4, and 8 g. kg soil^{-1}) applied before planting as Their symbol $\mathbf{Z_0}$,$\mathbf{Z_1}$**and** $\mathbf{Z_2}$ respectively, and foliar spraying with kaolin at three concentrations (0, 0.5, and 1 g. L^{-1}) as Their symbol $\mathbf{C_0}$,$\mathbf{C_1}$**and**$\mathbf{C_2}$ respectively . The experiment was designed as a factorial (2 × 3 × 3) within a nested design with three replicates. Data were analyzed statistically using Genstat software, and means were compared using the least significant difference (L.S.D.) test at a 5% probability level.

RESULTS AND DISCUSSION

Effect of irrigation interval, zeolite application, kaolin spraying, and their interactions on leaf area, chlorophyll concentrations , and yield of cowpea: Tables (1) and (2) demonstrate that the three-way interaction treatment $I_1Z_2C_2$ (irrigation every 3 days with the second concentration of both zeolite and kaolin) significantly outperformed other treatments in leaf area and chlorophyll concentrations across both seasons. It recorded 31.0 dm² and 21.5 mg per 100 g fresh weight in the first season and 34.08 dm² and 23.6 mg per 100 g fresh weight in the second season. The two-way interaction between irrigation every 3 days and the second concentration of zeolite achieved 26.6 dm² and 19.3 mg per 100 g fresh weight in the first

season, and 29.26 dm² and 21.2 mg per 100 g fresh weight in the second season. Similarly, the interaction between irrigation every 3 days and the second concentration of kaolin resulted in 17.1 dm² and 24.4 mg per 100 g fresh weight in the first season, and 26.87 dm² and 18.8 mg per 100 g fresh weight in the second season. The interaction between the second concentrations of zeolite and kaolin achieved 27.1 dm² and 18.4 mg per 100 g fresh weight in the first season, and 29.76 dm² and 20.3 mg per 100 g fresh weight in the second season. For the individual effects, irrigation every 3 days yielded the highest values, recording 22.8 dm² and 15.4 mg per 100 g fresh weight in the first season, and 25.66 dm² and 16.9 mg per 100 g fresh weight in the second season. The second concentration of zeolite recorded 24.6 dm² and 16.3 mg per 100 g fresh weight in the first season, and 27.04 dm² and 18.0 mg per 100 g fresh weight in the second season. Similarly, the second concentration of kaolin resulted in 22.8 dm² and 14.1 mg per 100 g fresh weight in the first season, and 25.13 dm² and 15.5 mg per 100 g fresh weight in the second season.

Table 1. Effect of irrigation interval, zeolite application, kaolin spraying, and their interactions on the leaf area(dm²) **of cowpea**

		First season				Second season			
Irrigation interval	**Zeolite Z**	**C kaolin**			**I * Z**	**C kaolin**			**I * Z**
		C0	**C1**	**C2**		**C0**	**C1**	**C2**	
3 days	**Z0**	**7.1**	**11.4**	**12.9**	**10.5**	**7.8**	**12.6**	**14.2**	**11.5**
I_1	**Z1**	**15.9**	**16.4**	**16.8**	**16.3**	**17.4**	**18.0**	**18.4**	**18.0**
	Z2	**17.1**	**19.3**	**21.5**	**19.3**	**18.8**	**21.2**	**23.6**	**21.2**
6 days	**Z0**	**6.0**	**6.9**	**7.1**	**6.7**	**6.6**	**7.6**	**7.8**	**7.3**
I_2	**Z1**	**7.2**	**8.1**	**11.2**	**8.8**	**7.9**	**8.9**	**12.3**	**9.7**
	Z2	**11.3**	**13.3**	**15.4**	**13.4**	**12.5**	**14.7**	**16.9**	**14.7**
LSD $_{I*Z*C}$			**0.85**		**0.57**			**0.934**	**0.631**
		I * C						**I * C**	
Irrigation interval		**C0**	**C1**	**C2**	**Mean Irrigation interval**	**C0**	**C1**	**C2**	**Mean Irrigation interval**
3 days		**13.3**	**15.7**	**17.1**	**15.4**	**14.7**	**17.3**	**18.8**	**16.9**
6 days		**8.2**	**9.4**	**11.2**	**9.6**	**9.0**	**10.4**	**12.3**	**10.6**
LSD $_{I*C}$			**0.57**		**0.57**		**0.631**		**0.631**
		Z * C						**Z * C**	
Zeolite		**C0**	**C1**	**C2**	**Mean Zeolite**	**C0**	**C1**	**C2**	**Mean Zeolite**
Z0		**6.5**	**9.2**	**10.0**	**8.6**	**7.2**	**10.1**	**11.0**	**9.4**
Z1		**11.5**	**12.2**	**14.0**	**12.6**	**12.7**	**13.5**	**15.4**	**13.8**
Z2		**14.2**	**16.3**	**18.4**	**16.3**	**15.6**	**17.9**	**20.3**	**18.0**
LSD $_{Z*C}$			**0.41**		**0.23**		**0.446**		**0.258**
		Kaolin						**Kaolin**	
kaolin		**C0**	**C1**	**C2**		**C0**	**C1**	**C2**	
Mean kaolin		**10.76**	**12.57**	**14.1**		**11.8**	**13.8**	**15.5**	
LSD $_{C}$			**0.23**				**0.258**		

Table 2. Effect of irrigation interval, zeolite application, kaolin spraying, and their interactions on the chlorophyll concentrations (mg per 100 g fresh weight) of cowpea leaves

Irrigation interval	Zeolite Z	First season C kaolin C0	C1	C2	I * Z	Second season C kaolin C0	C1	C2	I * Z
3 days	Z0	18.4	18.7	19.2	18.8	20.27	20.61	21.15	20.68
I_1	Z1	22.8	23.0	23.1	23.0	25.09	25.26	25.39	25.25
	Z2	23.7	25.1	31.0	26.6	26.10	27.62	34.08	29.26
6 days	Z0	14.9	15.9	18.5	16.5	16.43	17.50	20.37	18.10
I_2	Z1	21.9	22.0	22.1	22.0	24.04	24.16	24.33	24.18
	Z2	22.2	22.3	23.1	22.6	24.47	24.56	25.45	24.83
LSD_{I*Z*C}			0.118		0.052		0.131		0.057
		I * C						I * C	
Irrigation interval		C0	C1	C2	Mean Irrigation interval	C0	C1	C2	Mean Irrigation interval
3 days		21.7	22.3	24.4	22.8	23.82	24.50	26.87	25.06
6 days		19.7	20.1	21.3	20.3	21.65	22.07	23.38	22.37
LSD_{I*C}			0.52		0.52		0.057		0.057
		Z * C						Z * C	
Zeolite		C0	C1	C2	Mean Zeolite	C0	C1	C2	Mean Zeolite
Z0		16.7	17.3	18.9	17.6	18.35	19.05	20.76	19.39
Z1		22.3	22.5	22.6	22.5	24.57	24.71	24.86	24.71
Z2		23.0	23.7	27.1	24.6	25.28	26.09	29.76	27.04
LSD_{Z*C}			0.037		0.021		0.041		0.023
		kaolin						Kaolin	
kaolin		C0	C1	C2		C0	C1	C2	
Mean kaolin		20.67	21.17	22.8		22.73	23.28	25.13	
LSD_{C}			0.021				0.023		

The results of Table (3) show that the treatment I_1Z_2 showed significant superiority, achieving 1745.9 g and 2260.3 g, respectively. The treatment Z_2C_2 also showed significant superiority, recording 1847.0 g and 2342.0 g, respectively. For the individual effects, the treatment I_1 recorded the highest yields of 1439.6 g and 1710.6 g, respectively. The treatment Z_2 achieved 1591.4 g and 2108.8 g, while the treatment C_2recorded 1448.1 g and 1779.9 g, respectively.

Table 3. Effect of irrigation interval, zeolite application, kaolin spraying, and their interactions on the yield (g) of cowpea

Irrigation interval	Zeolite Z	First season C kaolin C0	C1	C2	I * Z	Second season C kaolin C0	C1	C2	I * Z
3 days	Z0	1031.7	1230.7	1296.0	1186.1	981.0	1203.3	1304.0	1162.8
I_1	Z1	1326.7	1359.0	1474.7	1386.8	1493.7	1727.7	1904.7	1708.7
	Z2	1576.0	1677.0	1984.7	1745.9	2061.0	2193.7	2526.3	2260.3
6 days	Z0	811.7	994.3	1043.0	949.7	876.0	1064.7	1223.0	1054.6
I_2	Z1	1099.3	1130.0	1180.7	1136.7	1335.3	1460.0	1563.7	1453.0
	Z2	1270.0	1331.7	1709.3	1437.0	1735.7	1978.3	2157.7	1957.2
LSD $_{I*Z*C}$			N.S		49.79		N.S		114.14
		I * C						I * C	
Irrigation interval		C0	C1	C2	Mean Irrigation interval	C0	C1	C2	Mean Irrigation interval
3 days		1311.4	1422.2	1585.1	1439.6	1511.9	1708.2	1911.7	1710.6
6 days		1060.3	1152.0	1311.0	1174.4	1315.7	1501.0	1648.1	1488.3
LSD $_{I*C}$			N.S		49.79		N.S		114.14
		Z * C						Z * C	
Zeolite		C0	C1	C2	Mean Zeolite	C0	C1	C2	Mean Zeolite
Z0		921.7	1112.5	1169.5	1067.9	928.5	1134.0	1263.5	1108.7
Z1		1213.0	1244.5	1327.7	1261.7	1414.5	1593.8	1734.2	1580.8
Z2		1423.0	1504.3	1847.0	1591.4	1898.3	2086.0	2342.0	2108.8
LSD $_{Z*C}$			35.21		20.33		80.71		46.60
		kaolin						Kaolin	
kaolin		C0	C1	C2		C0	C1	C2	
Mean kaolin		1185.9	1287.1	1448.1		1413.8	1604.6	1779.9	
LSD $_{C}$			20.33				46.60		

The reduction in vegetative growth indicators and yield under irrigation every 6 days may be attributed to the role of water stress in increasing the concentration of abscisic acid. This leads to thickening of the cell wall, which hinders cell expansion and elongation, negatively impacting growth and yield indicators. The effect of zeolite and kaolin can be attributed to their role in maintaining water potential and providing a continuous and controlled supply of nutrients. This ensures the availability of essential materials for chlorophyll synthesis. Additionally, zeolite supplies nitrogen in the form of ammonium, enhancing meristematic activity, which results in increased leaf area, improved photosynthesis, and carbohydrate production, ultimately boosting plant productivity.

Effect of irrigation interval, zeolite application, kaolin spraying, and their interactions on proline concentration, peroxidase enzyme activity, and antioxidant capacity (DPPH) in cowpea leaves

The results in Table (4) indicate that the treatment $I_2Z_0C_0$ significantly outperformed other treatments in proline concentration across both seasons, recording 54.5 mg g^{-1} dry weight and 101.80 mg g^{-1} dry weight, respectively. The treatment I_2Z_0 also showed significant superiority, achieving 44.9 mg g^{-1} dry weight and 95.50 mg g^{-1} dry weight, respectively. Similarly, the treatment I_2C_0 recorded 41.7 mg g^{-1} dry weight and 73.12 mg g^{-1} dry weight, respectively, while the treatment Z_0C_0 achieved 44.9 mg g^{-1} dry weight and 93.73 mg g^{-1} dry weight, respectively. For the individual effects, irrigation every 6 days (I_2) significantly increased proline concentration, recording 36.0 mg g^{-1} dry weight and 67.23 mg g^{-1} dry weight, respectively. The treatment Z_0 showed superiority with 39.3 mg g^{-1} dry weight and 87.08 mg g^{-1} dry weight, respectively. Additionally, the treatment C_0 recorded 35.6 mg g^{-1} dry weight and 64.61 mg g^{-1} dry weight, respectively.

Table 4. Effect of irrigation interval, zeolite application, kaolin spraying, and their interactions on proline concentration (mg g^{-1} dry weight) in cowpea leaves

		First season				Second season			
Irrigation interval	Zeolite Z	C kaolin C0	C1	C2	I * Z	C kaolin C0	C1	C2	I * Z
3 days	Z0	35.3	33.8	31.7	33.6	85.67	78.77	71.53	78.66
I_1	Z1	29.7	28.4	26.0	28.1	57.33	55.33	54.50	55.72
	Z2	23.6	21.3	19.3	21.4	25.27	16.93	12.80	18.33
6 days	Z0	54.5	41.4	38.9	44.9	101.80	96.43	88.27	95.50
I_2	Z1	37.7	36.5	35.3	36.5	65.50	64.00	61.43	63.64
	Z2	32.8	24.5	22.9	26.7	52.07	41.53	34.03	42.54
LSD $_{I*Z*C}$			1.46		0.61		2.37		1.02
		I * C				I * C			
Irrigation interval		C0	C1	C2	Mean Irrigation interval	C0	C1	C2	Mean Irrigation interval
3 days		29.5	27.8	25.7	27.7	56.09	50.34	46.28	50.90
6 days		41.7	34.1	32.3	36.0	73.12	67.32	61.24	67.23
LSD $_{I*C}$			0.61		0.61		1.02		1.02
		Z * C				Z * C			
Zeolite		C0	C1	C2	Mean	C0	C1	C2	Mean Zeolite
Z0		44.9	37.6	35.3	39.3	93.73	87.60	79.90	87.08
Z1		33.7	32.5	30.7	32.3	61.42	59.67	57.97	59.68
Z2		28.2	22.9	21.1	24.1	38.67	29.23	23.42	30.44
LSD $_{Z*C}$			0.43		0.25		0.72		0.42
		kaolin				Kaolin			
kaolin		C0	C1	C2		C0	C1	C2	
Mean kaolin		35.6	31	29.0		64.61	58.83	53.76	
LSD $_{C}$			0.25				0.42		

The results in Table (5) indicate that the treatment $I_2Z_0C_0$ achieved the highest peroxidase enzyme activity across both seasons, recording 1.09 and 4.400 absorption units g^{-1} protein, respectively, with no significant difference compared to other treatments in the first season. The two-way interaction I_2Z_0 significantly outperformed other treatments, recording 0.88 and 4.04 absorption units g^{-1} protein, respectively. Similarly, the treatment I_2C_0 showed significant superiority with values of 0.69 absorption units g^{-1} protein. Additionally, the treatment Z_0C_0 recorded 0.87 and 3.98 absorption units g^{-1} protein, respectively. For the individual effects, irrigation every 6 days (I_2) significantly outperformed irrigation every 3 days, recording 0.54 and 3.27 absorption units g^{-1} protein, respectively. The treatment Z_0 showed significant superiority, recording 0.76 and 3.54 absorption units g^{-1} protein, respectively, while the treatment C_0 achieved 0.52 and 3.14 absorption units g^{-1} protein, respectively.

Table 5. Effect of irrigation interval, zeolite application, kaolin spraying, and their interactions on peroxidase enzyme activity (absorption units g^{-1} protein) in cowpea leaves

		First season				Second season			
Irrigation interval	Zeolite Z	C kaolin C0	C1	C2	I * Z	C kaolin C0	C1	C2	I * Z
3 days	Z0	0.65	0.65	0.60	0.63	3.560	3.030	2.520	3.037
I_1	Z1	0.25	0.20	0.18	0.21	2.393	2.310	2.280	2.328
	Z2	0.17	0.14	0.11	0.14	2.130	1.987	0.877	1.664
6 days	Z0	1.09	0.90	0.66	0.88	4.400	4.057	3.687	4.048
I_2	Z1	0.63	0.51	0.45	0.53	3.610	3.457	2.987	3.351
	Z2	0.34	0.18	0.12	0.22	2.797	2.620	1.890	2.436
LSD $_{I*Z*C}$			N.S		0.084		0.272		0.215
		I * C					I * C		
Irrigation interval		C0	C1	C2	Mean Irrigation interval	C0	C1	C2	Mean Irrigation interval
3 days		0.36	0.33	0.30	0.33	2.694	2.442	1.892	2.343
6 days		0.69	0.53	0.41	0.54	3.602	3.378	2.854	3.278
LSD $_{I*C}$			0.084		0.029		N.S		0.215
		Z * C					Z * C		
Zeolite		C0	C1	C2	Mean Zeolite	C0	C1	C2	Mean Zeolite
Z0		0.87	0.78	0.63	0.76	3.980	3.543	3.103	3.542
Z1		0.44	0.36	0.31	0.37	3.002	2.883	2.633	2.839
Z2		0.26	0.16	0.12	0.18	2.463	2.303	1.383	2.050
LSD $_{Z*C}$			0.123		0.071		0.162		0.093
		kaolin					Kaolin		
kaolin		C0	C1	C2		C0	C1	C2	
Mean kaolin		0.52	0.43	0.35		3.148	2.910	2.373	
LSD $_{C}$			0.071				0.093		

The results in Table (6) show that the treatment $I_2Z_0C_0$ significantly outperformed others in antioxidant capacity (DPPH), recording 73.3% and 92.0% in the first and second seasons, respectively, with no significant difference compared to the treatment $I_2Z_0C_1$ in the first and second seasons, which recorded 71.6% and 90.3 respectively. The two-way interaction I_2Z_0 was also significantly superior, achieving 71.4% and 88.8% in the first and second seasons, respectively. Additionally, the treatment I_2C_0 significantly outperformed others in the second season, recording 77.8%.

The increase in proline concentration under irrigation every 6 days can be attributed to water stress enhancing protein degradation and activating amino acid-hydrolyzing enzymes, particularly Arginase, which converts the amino acid arginine into ornithine, subsequently transformed into proline. Conversely, the decrease in proline concentration with the addition of the soil amendment zeolite and kaolin spraying may be due to their role in maintaining osmotic balance between the vacuole and the cytoplasm of cells, thereby improving the plant's water relations and reducing the need for proline synthesis and accumulation (3). This could be attributed to increased oxidative stress due to drought, which stimulates plants to produce enzymatic antioxidants to mitigate the harmful effects of free radicals. Conversely, soil amendments caused a reduction in antioxidant activity, likely due to the role of zeolite in improving the plant's nutritional status, positively affecting biological processes and enhancing growth rates, as shown in Tables 1 and 2. Additionally, zeolite's ability to suppress the production of reactive oxygen species reduces the need for activating antioxidant production.

The results in Table 7 indicate that the treatment $I_2Z_0C_0$ significantly outperformed others in electrolyte leakage during the first season, recording 75.9%, with no significant difference compared to $I_2Z_0C_1$, which recorded 73.6%. The two-way interaction I_2Z_0 also showed significant superiority, achieving 73.3%, while I_2C_0 recorded 64.0%. The treatment Z_0C_0 demonstrated the highest value, recording 76.5%. For the individual effects, irrigation every 6 days (I_2) showed significant superiority, recording 58.2%. The treatment Z_0 recorded 70.0%, while C_0 achieved 58.9%. The results in Table 7 indicate that the three-way interaction $I_1Z_2C_2$ significantly outperformed others in membrane stability

index, recording 81.7%. Among the two-way interactions, I_1Z_2 showed superiority, achieving 73.8%, while I_1C_2 recorded 68.6%. The treatment Z_2C_2 also demonstrated significant superiority, achieving 78.7%. For the individual effects, irrigation every 3 days (I_1) showed significant superiority, recording 64.1%. The treatment Z_2 achieved 70.9%, while C_2 recorded 65.4%.

Table 6. Effect of irrigation interval, zeolite application, kaolin spraying, and their interactions on DPPH (%) in cowpea leaves

		First season				Second season			
Irrigation interval	Zeolite Z	C kaolin			I * Z	C kaolin			I * Z
		C0	C1	C2		C0	C1	C2	
3 days	Z0	71.3	67.3	59.8	66.1	83.2	78.5	76.2	79.3
I_1	Z1	53.2	50.8	49.3	51.1	73.6	68.4	62.0	68.0
	Z2	47.5	44.6	42.9	45.0	56.7	55.1	15.3	42.4
6 days	Z0	73.3	71.6	69.4	71.4	92.0	90.3	84.1	88.8
I_2	Z1	63.5	59.2	51.2	58.0	82.0	74.5	71.6	76.0
	Z2	46.6	43.7	41.4	43.9	59.3	55.7	51.6	55.5
LSD $_{I*Z*C}$			2.19		0.97		1.97		0.97
		I * C				I * C			
Irrigation interval		C0	C1	C2	Mean Irrigation interval	C0	C1	C2	Mean Irrigation interval
3 days		57.3	54.3	50.7	54.1	71.1	67.3	51.2	63.2
6 days		61.1	58.2	54.0	57.8	77.8	73.5	69.1	73.5
LSD $_{I*C}$			N.S		0.97		0.97		0.97
		Z * C				Z * C			
Zeolite		C0	C1	C2	Mean Zeolite	C0	C1	C2	Mean Zeolite
Z0		72.3	69.5	64.6	68.8	87.6	84.4	80.1	84.0
Z1		58.3	55.0	50.2	54.5	77.8	71.5	66.8	72.0
Z2		47.0	44.1	42.2	44.4	58.0	55.4	33.5	48.9
LSD $_{Z*C}$			0.68		0.40		0.56		0.32
		kaolin				Kaolin			
kaolin		C0	C1	C2		C0	C1	C2	
Mean kaolin		59.2	56.2	52.3		74.5	70.4	60.1	
LSD $_{C}$			0.40				0.32		

Table 7. Effect of irrigation interval, zeolite application, kaolin spraying, and their interactions on electrolyte leakage and membrane stability index (%) in cowpea plants

		First season- electrolyte leakage				First season- membrane stability index			
Irrigation Interval	Zeolite Z	C kaolin			I * Z	C kaolin			I * Z
		C0	C1	C2		C0	C1	C2	
3 days	Z0	77.1	72.1	50.6	66.6	52.4	54.1	59.9	55.5
I_1	Z1	49.0	47.2	38.0	44.7	61.6	63.0	64.3	63.0
	Z2	35.6	33.6	30.9	33.4	66.6	72.9	81.7	73.8
6 days	Z0	75.9	73.6	70.4	73.3	25.6	34.5	52.5	37.5
I_2	Z1	67.4	63.3	59.5	63.4	55.1	56.5	58.0	56.5
	Z2	48.6	38.2	26.4	37.7	62.2	66.0	75.7	68.0
LSD $_{I*Z*C}$			2.65		1.20		2.53		1.43
		I * C				I * C			
Irrigation interval		C0	C1	C2	Mean Irrigation interval	C0	C1	C2	Mean Irrigation interval
3 days		53.9	51.0	39.9	48.2	60.2	63.3	68.6	64.1
6 days		64.0	58.4	52.1	58.2	47.6	52.3	62.1	54.0
LSD $_{I*C}$			1.20		1.20		1.43		1.43
		Z * C				Z * C			
Zeolite		C0	C1	C2	Mean Zeolite	C0	C1	C2	Mean Zeolite
Z0		76.5	72.9	60.5	70.0	39.0	44.3	56.2	46.5
Z1		58.2	55.2	48.8	54.1	58.4	59.7	61.1	59.7
Z2		42.1	35.9	28.7	35.6	64.4	69.5	78.7	70.9
LSD $_{Z*C}$			0.85		0.49		1.01		0.58
		Kaolin				kaolin			
kaolin		C0	C1	C2		C0	C1	C2	
Mean kaolin		58.9	54.7	46.0		53.9	57.8	65.4	
LSD $_{C}$			0.49				0.58		

The reduction in membrane stability index under irrigation every 6 days can be attributed to stress-induced increases in ion leakage outside the cell and reduced ATPase activity. This results in damage to cellular membranes, leading to higher electrolyte leakage from the cytoplasm to the extracellular space. Additionally, oxidative damage to membrane lipids due to increased free radicals may enhance membrane permeability, further increasing electrolyte leakage. The effect of zeolite may be due to its calcium concentrations, which is a structural component of cellular membranes. Calcium contributes to protecting plants under stress conditions and helps maintain the integrity of phospholipids and proteins in cell membranes by binding them together. This maintains nutrient selectivity and reduces electrolyte leakage (23). The effect of kaolin can be attributed to its silicon concentrations, which protects cells by forming a mechanical barrier. Silicon binds to epidermal cells in the form of double layers, enhancing cell protection (5, 14).

CONCLUSION

Using irrigation intervals contributed to reducing water consumption, while soil amendments helped maintain soil moisture concentrations and mitigate the effects of drought stress. Additionally, the use of polymers improved the nutritional status of plants and enhanced antioxidant activity, positively reflecting on plant productivity.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

DECLARATION OF FUND

The authors declare that they have not received a fund.

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