



Science Forum (Journal of Pure and Applied Sciences)

Journal Homepage: <https://atbuscienceforum.com.ng/index.php/jpas>



Eco-Physiological Response of Rice (*Oryza sativa* L.) Cultivars to Water Stress and Zeolite Amendment: Implications for Sustainable Production

Oras Muhsen Kadim

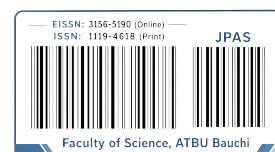
Mussaib Technical Institute, Al-Furat Al-Awsat Technical University Babylon, Iraq.

Abstract

A field experiment was conducted during the 2023 growing season, at Al-Jailawiyah, Babylon, Iraq, to evaluate the effects of natural zeolite soil amendment and three irrigation schedules on crop growth, grain yield and health-promoting secondary metabolites of the three rice (*Oryza sativa* L.) cultivars, including Nemat, Chakhenoe and the local Huweizawi. The experiment was designed as factorial randomized complete block with three levels for each of zeolite amendment (0, 10 and 20 t ha⁻¹) and three irrigation intervals (daily, every 3 and 6 days) and was laid out in a randomized complete block design with three replications. Morphological, yield and biochemical parameters -including leaf area, productive tiller number and grain yield, total phenolics, total flavonoids and anthocyanins - were determined at key developmental stages. Significant cultivar × amendment × irrigation interactions were observed for all measured traits. The cultivar Nemat appeared to be the best performer as it recorded the largest leaf area, the maximum number of productive tillers and the highest grain yield while Chakhenoe accumulated the highest contents of phenolic compounds and anthocyanins. Application of zeolite at 20 t ha⁻¹ dramatically boosted yield components, and it increased the contents of the secondary metabolites compared to the unmodified control. In the same way, the most intensive irrigation (daily) improved growth, yield and biochemical indices than less regular irrigation. The combination Nemat × 20 t ha⁻¹ zeolite under daily irrigation produced the highest grain yield, and Chakhenoe under daily irrigation (especially with 20 t ha⁻¹ zeolite) was the richest in phytochemicals profile. These results suggest that it would be possible to increase both the productivity and the nutritionally relevant phytochemicals contents in rice by using natural zeolite with an appropriate irrigation schedule, especially when the water supply is limited. From the perspective of ecology and agriculture, using zeolite as a soil amendment is a cost-effective way to improve water retention and keep the soil's nutrients. Further experiments need to explore the ability of zeolite to make the best use of water and improve the quality of the soil in the long term.

Keywords

Rice Cultivars,
Zeolite Amendment,
Irrigation Regime,
Water Stress,
Secondary Metabolites,
Sustainable Agriculture.



Introduction

Rice (*Oryza sativa* L.) is a primary crop with an essential role for the food security of over half of the world's population (FAO, 2024). With the growing population and changing climate, rice production has become threatened in many areas around the world. Water shortage and soil salinity stand out as critical factors that hinder efforts to increase rice yields and maintain plant functions. Particularly for Iraq, which lies in an arid and semi-arid region (Central Statistical Organization, 2024), the deficit of water availability due to inconsistent rainfall and high evapotranspiration rates impacts rice's physiological processes and, consequently, its yield (Hassan et al., 2023).

Water stress limits photosynthesis, stomatal conductance, and causes oxidative stress in rice plants (Al-Amiri, 2014; Mondal, 2021). These factors reduce plant biomass and yield. Therefore, adaptation strategies for water management and improvement of soil quality are essential to ensure sustainability. Eco-physiological strategies with a focus on sustainable soil use and water management are implemented to guarantee productivity while conserving the environment (Jarosz et al., 2022; Hassan et al., 2023).

Natural Zeolite: Environmental Benefits for Sustainable Agriculture Essay

Natural zeolite crystalline aluminosilicate mineral has drawn increasing attention as an environmentally friendly soil conditioner that improves water retention properties, nutrients availability, and microbiological activity (Roinesh et al., 2015; Boros-Lajszner et al., 2017). The mineral has a remarkably high cation-exchange capacity, which ensures slow release of nutrient to avoid leaching and create a more sustainable and efficient nutrient cycle (Mondal, 2021). According to Susiyant et al. (2020), zeolite as a soil amendment is more likely to improve rice growth in the rain-fed condition by maintaining soil moisture and osmotic potential. Additionally, the mineral has the ability to promote the biosynthesis of

antioxidant compounds such as polyphenols, flavonoids, and anthocyanins, which play a significant role in enhancing the nutritional value and crop resistance to environmental stress (Al-Fatlawi, 2023; Song et al., 2021).

In recent years, scientists have begun to study the interaction between water stress and the use of zeolites in the rice genotype (Al-Wardi, 2023). The importance of studying the impact of various environmental conditions on different rice genotypes cannot be denied since plants differ significantly in their ability to maintain photosynthesis, osmotic potential, and secondary metabolism under water-deficient conditions (Ayka, 2021; Hassan et al., 2023). Understanding the response of individual genotypes to the impact of environmental conditions is a factor in the sustainable development of agriculture in the context of impending climatic changes.

The purpose of this study is to evaluate the interactive effects of water stress and a zeolite amendment on the growth, yield, and secondary metabolites of rice cultivars diverse in genetic background and eco-physiological behavior. By highlighting the relationships among water use efficiency, soil properties, and biochemical responses, this research provides insights into the adaptive mechanisms by which the targeted crop management affects the plant's physiology and environmental sustainability.

Materials and Methods

Plant Materials

Three rice (*Oryza sativa* L.) cultivars were used in this study, which were different in many ways. The first cultivar, Huweizawi, is a local traditional cultivar type that has red grain and is well-adapted to the semi-arid region of central Iraq. The second cultivar, Chakhenoe, is an Indian black grain cultivar, which was introduced to Iraq in 2019 and has a high antioxidant content. The third cultivar, Nemat, is a black grain cultivar that was originally introduced to Iraq from Iran (AM013/Sangetrarom line) and has a strong

vegetative vigor and stability in yield.

Zeolite Mineral

Natural zeolite was applied as a soil amendment at rates of 0, 10, and 20 t ha⁻¹. The zeolite used was of the clinoptilolite type, with 85% purity; it was ground to a fine powder and thoroughly mixed into the top 20 cm of soil before transplanting. Zeolite was selected as a soil amendment due to its high cation exchange capacity and water retention capability, which are expected to improve the nutrient status of the plants and reduce the negative effects of water stress.

Site and Soil Preparation

The field experiment was conducted in 2023 at Al-Jailawiyah, Al-Musayyib District, north of Babylon, Iraq (32°39'N 44°18'E). A semi-arid climate with hot summers and moderately cold winters. The experimental site was prepared by plowing, harrowing, and leveling the land before planting to ensure uniformity of water distribution during growth period. The chemical analysis of the soil indicated that it was clay loam with a pH of 7.8, organic matter of 1.2%, total nitrogen of 0.08%, available phosphorus of 12 mg kg⁻¹, and exchangeable potassium of 180 mg kg⁻¹.

Seed Preparation and Nursery Management

The seeds of the three cultivars were soaked in clean water for 48 hours. Every 12 hours, they were aerated. After that, the soaked seeds were covered with moist jute sacks for 24 hours to allow for germination. The pre-germinated seeds were then evenly placed on shallow nursery beds with moistened soil and covered again with jute for five days. The nursery beds were watered twice daily and were protected from direct sunlight and pests. The nursery seedlings were uprooted after 25 days and thinned out to form uniform seedlings. The uniform seedlings were then planted in the field with a spacing of 25 cm between rows and hills. One seedling was placed in each hill.

Field Management and Fertilization

The experiment was carried out in a well-maintained field to avoid environmental fluctuations. Weeds were uprooted three times at an interval of 15 days after transplanting. Compound fertilizer NPK (18:18:18) was applied at a rate of 400 kg ha⁻¹ as a basal dose during field preparation. Urea (46% N) was used as a top dressing, and it was applied in two equal splits (140 kg ha⁻¹ each) at 10 and 30 days after transplanting to enhance vegetative growth and panicle initiation. Insect pests and diseases were controlled by applying appropriate integrated pest management measures.

Irrigation Treatments

Three irrigation treatments were performed to impose different levels of water stress:

irrigated daily (control, no stress),

irrigated every 3 days (moderate stress), and

irrigated every 6 days (severe stress).

The irrigation treatments were initiated two weeks after transplanting and continued until physiological maturity. Irrigation was done manually, using surface irrigation, and depths were adjusted to ensure uniformity of water application. The amount of water applied was measured at the end of each treatment to compute water use efficiency.

Experimental Design

The experiment was laid out in a factorial experiment based on a Randomized Complete Block Design (RCBD) with three replications. The treatments consisted of three wheat cultivars namely; Nemat, Chakhenoe, and Huweizawi, three irrigation intervals including daily, every 3 and 6 days, and three levels of zeolite application rates (0, 10, and 20 t ha⁻¹). Each plot was 6 square meters (4 m × 1.5 m), and the total number of treatments was 81. Data were recorded from the middle part of each plot for avoiding the marginal effects.

Measured Traits

A complete set of morphological, yield, and biochemical characters were recorded as:

Flag leaf area (cm²): It was calculated from 10 randomly selected plants from each plot at physiological maturity by using the formula:

$$\text{Leaf area} = \text{Leaf length} \times \text{Maximum width} \times 0.74$$

Number of effective tillers (tillers m⁻²): It was counted from one square meter in each plot at harvest.

Grain Yield (t ha⁻¹): The total number of panicles was counted in a 1 m² quadrat and hand-threshed; grains were oven-dried to constant weight, and the yield was extrapolated to tons/hectare. Total Phenolic Contents: Total phenolics were determined by mixing 1 ml of extract with 1 ml of diluted Folin-Ciocalteu reagent and 1 ml of 1 mol/L Na₂CO₃ solution. After standing for 3 min at room temperature, the mixture was read at 765 nm against a blank. The contents were expressed as milligrams of

gallic acid equivalent per kilogram of dry weight.

Total Flavonoid Contents: Total flavonoid contents were determined by reacting 1 ml of extract with 1 ml of 1 mol/L AlCl₃ in methanol and measuring the absorbance at 400 nm. The concentrations were expressed as milligrams of quercetin equivalent per kilogram of dry weight.

Total Anthocyanin Content (mg kg⁻¹ dry weight): Total anthocyanin content was estimated using a pH differential method in two buffer systems (pH 1.0 and 4.5) and by measuring the absorbance at 510 and 700 nm to obtain the anthocyanin concentration.

Statistical Analysis

All the collected data were analyzed using Microsoft Excel 2019 and SPSS version 26 for Windows. Analysis of variance (ANOVA) was used to evaluate the treatment main effects and interactions on the basis of a 5% probability level ($p < 0.05$). The Least Significant Difference (LSD) test was performed to compare the means of the treatments. The coefficient of variation (CV%) was also calculated to express the degree of precision of the experiment.

unamended control accounted for 30.80 cm² (Table 1). In addition, irrigation frequency also affected this parameter, as plots that were watered every day registered 37.75 cm², those watered every three days obtained 35.44 cm², and those watered every six days reached 32.47 cm² (Table 1).

Finally, the largest single treatment combination found was Nemat × Z20 × daily irrigation (45.27 cm²), whereas the smallest combination recorded was Chakhenoe × Z0 × irrigation every six days (25.17 cm²) (Table 1).

Results and Discussion

Flag Leaf Area (cm²)

The flag leaf area varied significantly due to cultivar, zeolite rate and irrigation regime (Table 1). Overall, the cultivar Nemat had the largest mean flag leaf area among the treatments evaluated (37.41 cm²), followed by Huweizawi (35.79 cm²) and Chakhenoe (32.46 cm²) (Table 1). The increment in zeolite rate resulted in a positive change: the 20 t ha⁻¹ treatment had the highest average leaf area (38.98 cm²), while the 10 t ha⁻¹ treatment obtained 35.89 cm² and the

Table (1): Effect of zeolite levels and irrigation intervals on flag leaf area (cm²) in three rice cultivars.

Cultivar	Irrigation Interval	Zeolite			Cultivar x Irrigation Interval
		Z0	Z10	Z20	
Nemat (Iranian)	Daily	35.55	40.72	45.27	40.52
	Every 3 days	33.66	37.51	41.20	37.45
	Every 6 days	30.56	34.60	37.57	34.24
Chakhenoe (Indian black)	Daily	29.54	35.92	38.60	34.58
	Every 3 days	28.10	34.84	36.06	33.01
	Every 6 days	25.17	30.86	33.10	29.71
Huweizawi (Local)	Daily	33.69	38.22	42.31	38.07
	Every 3 days	31.28	36.45	39.82	35.85
	Every 6 days	29.61	33.89	36.84	33.44
LSD0.05		4.27			2.10
		Cultivar x Zeolite			Average
Nemat (Iranian)		33.27	37.61	41.35	37.41
Chakhenoe (Indian black)		27.60	33.87	35.92	32.46
Huweizawi (Local)		31.52	36.19	39.66	35.79
LSD0.05		1.20			1.09
		Irrigation Interval x Zeolite			Average
Daily		32.93	38.28	42.06	37.75
Every 3 days		31.01	36.27	39.03	35.44
Every 6 days		28.45	33.12	35.84	32.47
LSD0.05		1.20			1.18
Average of Zeolite		30.80	35.89	38.98	
LSD0.05		1.22			

Table (2). Effect of zeolite levels and irrigation intervals on the number of tillers per plant in three rice cultivars.

Cultivar	Irrigation Interval	Zeolite			Cultivar x Irrigation Interval
		Z0	Z10	Z20	
Nemat (Iranian)	Daily	260.96	281.77	320.10	287.61
	Every 3 days	241.79	266.82	290.75	266.45
	Every 6 days	233.27	249.85	270.81	251.31
Chakhenoe (Indian black)	Daily	210.72	255.69	269.64	245.37
	Every 3 days	220.91	241.47	258.61	240.33
	Every 6 days	201.80	229.81	241.91	224.50
Huweizawi (Local)	Daily	241.66	272.82	287.93	267.47
	Every 3 days	233.40	259.59	271.79	254.92
	Every 6 days	230.70	243.20	260.20	244.70
LSD0.05		12.27			9.11
		Cultivar x Zeolite			Average
Nemat (Iranian)		245.34	266.14	293.88	268.45
Chakhenoe (Indian black)		211.16	242.41	256.72	236.78
Huweizawi (Local)		235.25	258.53	273.20	255.69
LSD0.05		6.30			8.25
		Irrigation Interval x Zeolite			Average
Daily		237.80	270.09	262.56	266.81
Every 3 days		232.03	255.96	273.72	253.90
Every 6 days		221.92	240.95	277.64	240.17
LSD0.05		6.36			8.25
Average of Zeolite		230.58	255.66	274.63	
LSD0.05		9.21			

Number of Tillers per Plant (Tillers plant⁻¹)

The number of tillers per plant responded to all experimental factors and their interactions (Table 2). Cultivar means indicate that Nemat produced the highest tiller density (268.45 tillers plant⁻¹), Huweizawi was intermediate (255.69 tillers plant⁻¹), and Chakhenoe produced the fewest tillers (236.78 tillers plant⁻¹) (Table 2). Zeolite increased tiller production in a dose-dependent manner: means were 230.58, 255.66 and 274.63 tillers plant⁻¹ for Z0, Z10 and Z20, respectively (Table 2). By irrigation regime, the highest mean tiller number occurred under daily irrigation (266.81 tillers plant⁻¹), followed by every three days (253.90) and every six days (240.17) (Table 2). The maximum three-way combination—Nemat × Z20 × daily irrigation—reached 320.10 tillers plant⁻¹, whereas the minimum combination—Chakhenoe × Z0 × every six days—was 201.80 tillers plant⁻¹ (Table 2).

Total Grain Yield (ton ha⁻¹)

Grain yield was strongly influenced by cultivar, zeolite application and irrigation frequency (Table 3). Averaged across treatments, Nemat obtained the highest mean yield (6.17 t ha⁻¹), followed by Huweizawi (5.84 t ha⁻¹) and Chakhenoe (5.47 t ha⁻¹) (Table 3). Zeolite amendment increased the yield significantly: mean yields were 4.83 t ha⁻¹ (Z0), 6.06 t ha⁻¹ (Z10) and 6.59 t ha⁻¹ (Z20) (Table 3). Similarly, the impact of irrigation intensity was considerable: the maximum average yield per

treatment was obtained for the daily-irrigated plots (6.44 t ha⁻¹), while less frequent irrigation, namely every-3-days and every-6-days, decreased the average yield to 5.69 t ha⁻¹ and 5.35 t ha⁻¹, respectively (Table 3). The treatment of Chakhenoe × Z0 × every-6-days had the lowest yield (4.00 t ha⁻¹), while the highest yield was achieved in the treatment Nemat × Z20 × daily (7.63 t ha⁻¹) (Table 3).

Total Phenolic Content (mg L⁻¹)

The total phenolic concentration varied with genotype and management (Table 4). The highest total phenolic content was recorded in Chakhenoe genotype (109.64 mg kg⁻¹), Huweizawi genotype remained in intermediate position (105.63 mg kg⁻¹) whereas; the lowest value was recorded in Nemat genotype (101.07 mg kg⁻¹) (Table 4). Zeolite application increased phenolic levels from 97.26 mg kg⁻¹ at Z0 to 107.38 mg kg⁻¹ at Z10 and 111.72 mg kg⁻¹ at Z20 (Table 4). Irrigation frequency influenced phenolic accumulation as well: daily irrigation produced the highest mean phenolic content (113.13 mg kg⁻¹), whereas every-6-day irrigation resulted in the lowest (96.12 mg kg⁻¹) (Table 4). The greatest three-way value was recorded for Chakhenoe × Z20 × daily irrigation (120.38 mg kg⁻¹); the lowest combination was Nemat × Z0 × every-6-days (80.10 mg kg⁻¹) (Table 4).

Table (3). Effect of zeolite levels and irrigation intervals on total grain yield (ton ha⁻¹) in three rice cultivars.

Cultivar	Irrigation Interval	Zeolite			Cultivar × Irrigation Interval
		Z0	Z10	Z20	
Nemat (Iranian)	Daily	5.89	6.85	7.63	6.79
	Every 3 days	4.95	6.35	6.82	6.04
	Every 6 days	4.89	5.88	6.29	5.69
	Daily	5.10	6.31	6.89	6.1

Chakhenoe (Indian black)	Every 3 days	4.12	5.73	6.01	5.29
	Every 6 days	4.00	5.31	5.78	5.03
Huwezawi (Local)	Daily	4.45	6.60	7.22	6.42
	Every 3 days	4.74	5.87	6.67	5.76
	Every 6 days	4.36	5.70	6.00	5.35
LSD0.05		0.81			0.61
		Cultivar x Zeolite			Average
Nemat (Iranian)		5.24	6.36	6.91	6.17
Chakhenoe (Indian black)		4.40	5.78	6.23	5.47
Huwezawi (Local)		4.84	6.06	6.63	5.84
LSD0.05		0.35			0.30
		Irrigation Interval x Zeolite			Average
Daily		5.48	6.59	7.25	6.44
Every 3 days		4.60	5.98	6.50	5.69
Every 6 days		4.41	5.63	6.02	5.35
LSD0.05		0.35			0.28
Average of Zeolite		4.83	6.06	6.59	
LSD0.05		0.31			

Table (4). Effect of zeolite and irrigation intervals on total phenolic content (mg L^{-1}) in three rice cultivars.

Cultivar	Irrigation Interval	Zeolite			Cultivar x Irrigation Interval
		Z0	Z10	Z20	
Nemat (Iranian)	Daily	105.81	110.75	114.94	110.50
	Every 3 days	90.30	107.54	111.65	103.16
	Every 6 days	80.10	92.70	95.87	89.55

Chakhenoe (Indian black)	Daily	109.75	117.37	120.38	115.83
	Every 3 days	101.96	113.68	116.97	110.87
	Every 6 days	94.33	102.55	109.82	102.23
Huwezawi (Local)	Daily	107.62	113.93	117.66	113.07
	Every 3 days	95.66	110.57	115.57	107.27
	Every 6 days	89.82	97.30	102.60	96.52
LSD0.05		0.81			0.61
		Cultivar x Zeolite			Average
Nemat (Iranian)		92.07	103.66	107.49	101.07
Chakhenoe (Indian black)		102.01	111.20	115.72	109.64
Huwezawi (Local)		97.70	107.27	111.94	105.63
LSD0.05		6.44			2.06
		Irrigation Interval x Zeolite			Average
Daily		107.73	114.01	117.66	113.13
Every 3 days		95.97	110.59	114.73	107.09
Every 6 days		88.08	97.52	102.76	96.12
LSD0.05		2.02			1.92
Average of Zeolite		97.26	107.38	111.72	
LSD0.05		2.11			

Total Flavonoid Content (mg L⁻¹)

Flavonoid content followed patterns similar to total phenolics (Table 5). Chakhenoe accumulated the most flavonoids on average (13.80 mg kg⁻¹), Huwezawi had 12.47 mg kg⁻¹, and Nemat the least (11.05 mg kg⁻¹) (Table 5). Flavonoid means increased with zeolite: 10.47 mg kg⁻¹ (Z0), 12.53 mg kg⁻¹ (Z10) and 14.32 mg kg⁻¹

(Z20) (Table 5). Daily irrigation produced higher flavonoid levels (13.22 mg kg⁻¹) compared with every-3-day (12.45 mg kg⁻¹) and every-6-day (11.16 mg kg⁻¹) regimes (Table 5). The maximum observed value occurred under Chakhenoe × Z20 × daily irrigation (17.35 mg kg⁻¹); the minimum was Nemat × Z0 × every-6-days (8.20 mg kg⁻¹) (Table 5).

Table (5). Effect of zeolite and irrigation intervals on flavonoid content (mg L^{-1}) in three rice cultivars.

Cultivar	Irrigation Interval	Zeolite			Cultivar x Irrigation Interval
		Z0	Z10	Z20	
Nemat (Iranian)	Daily	10.34	12.16	14.65	12.54
	Every 3 days	9.45	10.89	12.57	10.97
	Every 6 days	8.20	9.51	11.77	7.83
Chakhenoe (Indian black)	Daily	12.87	15.46	17.35	15.22
	Every 3 days	11.92	13.97	15.86	13.92
	Every 6 days	9.34	12.71	14.72	12.25
Huweizawi (Local)	Daily	11.63	13.64	15.83	13.70
	Every 3 days	10.85	12.66	13.91	12.47
	Every 6 days	9.65	11.82	12.25	11.23
LSD0.05		1.42			0.63
		Cultivar x Zeolite			Average
Nemat (Iranian)		9.33	10.85	12.99	11.05
Chakhenoe (Indian black)		11.38	14.05	15.98	13.80
Huweizawi (Local)		10.71	12.70	14.00	12.47
LSD0.05		0.42			0.35
		Irrigation Interval x Zeolite			Average
Daily		11.61	13.75	15.94	13.22
Every 3 days		10.74	12.50	14.11	12.45
Every 6 days		9.06	11.35	12.91	11.16
LSD0.05		0.71			0.42
Average of Zeolite		10.47	12.53	14.32	
LSD0.05		0.91			

Anthocyanin content (mg L^{-1})

Anthocyanin concentration showed a pronounced genotype effect and a positive response to zeolite and irrigation (Table 6). Chakhenoe had the highest average anthocyanin concentration (66.74 mg kg^{-1}), Huweizawi averaged 57.79 mg kg^{-1} , and Nemat averaged 52.94 mg kg^{-1} (Table 6). Increasing zeolite from 0 to 20 t ha^{-1} raised anthocyanin means from 54.55 to 63.03 mg kg^{-1} .

Irrigation intensity likewise affected anthocyanin accumulation: daily irrigation averaged 63.42 mg kg^{-1} , every three days 59.76 mg kg^{-1} , and every six days 54.29 mg kg^{-1} (Table 6). The highest three-way combination was Chakhenoe $\times$ Z20 $\times$ daily irrigation (74.72 mg kg^{-1}); the lowest reported value was Nemat $\times$ Z0 $\times$ daily irrigation (40.60 mg kg^{-1}) (Table 6).

Table (6): Effect of zeolite and irrigation intervals on the growth and yield of three rice varieties in terms of anthocyanin content (mg L^{-1})

Cultivar	Irrigation Interval	Zeolite			Cultivar $\times$ Irrigation Interval
		Z0	Z10	Z20	
Nemat (Iranian)	Daily	52.33	57.71	62.44	57.49
	Every 3 days	50.63	55.90	57.91	54.81
	Every 6 days	40.60	47.54	51.42	46.52
Chakhenoe (Indian black)	Daily	64.82	71.23	74.72	70.26
	Every 3 days	60.53	68.66	70.63	66.60
	Every 6 days	58.29	64.45	67.39	63.37
Huweizawi (Local)	Daily	59.46	62.42	65.69	62.52
	Every 3 days	53.61	58.65	61.39	57.88
	Every 6 days	50.71	52.51	55.72	52.98
LSD0.05		3.82			2.45
		Cultivar $\times$ Zeolite			Average
Nemat (Iranian)		47.85	53.72	57.26	52.94
Chakhenoe (Indian black)		61.21	68.11	70.91	66.74
Huweizawi (Local)		54.59	57.86	60.93	57.79
LSD0.05		3.17			2.12
		Irrigation Interval $\times$ Zeolite			Average
Daily		58.87	63.78	67.62	63.42

Every 3 days	54.92	61.07	63.31	59.76
Every 6 days	49.87	54.83	58.18	54.29
LSD0.05	3.20			2.12
Average of Zeolite	54.55	59.90	63.03	
LSD0.05	1.32			

Discussion

The results of this study indicate that rice growth, yield, and biochemical composition are significantly influenced by cultivar, zeolite amendment, and irrigation interval. Specifically, of the three cultivars examined, Nemat consistently outperformed Chakhenoe and Huweizawi in terms of flag leaf area, number of tillers, grain yield, and secondary metabolite content. This superiority can be explained by inherent genetic differences that influence key physiological processes such as photosynthesis and respiration, ultimately promoting better vegetative growth and grain filling (Al-Wardi, 2023; Al-Adhari, 2023). Furthermore, these results are consistent with previous reports that have demonstrated varietal variation to be a decisive factor in determining rice productivity and adaptive capacity under varying environmental conditions (Abka, 2021; Fatlawi, 2020).

Application of zeolite at 20 t ha^{-1} (Z20) improved all the parameters studied significantly over the control (Z0) and the plots with a moderate amount of zeolite (Z10). This is explained by the fact that zeolite, due to its high porosity and cation exchange capacity, improves the physical and chemical properties of the soil, increases the availability of nutrients and water, and reduces their loss with the melt. Therefore, in the conditions of deficit irrigation, it acts as a sorbent and regulator of soil humidity, accumulating and slowly releasing bound water and nutrients, which allows the plants to resist drought and develop normally (Ranesh, 2015; Supapron et al., 2002). In addition, application of this mineral positively

affects the leaf surface area and the number of tillers per plant, which was also confirmed by Al-Hassani (2016, 2021). Thus, zeolite is a good soil conditioner that can increase the productivity of agricultural crops and alleviate the harmful effects of drought.

Irrigation frequency had a noticeable effect on the rice performance. Compared with daily irrigation, rice plants were subjected to daily irrigation every three or six days, which increased flag leaf area, tiller number, and grain yield (Al-Adi, 2014; Central Organization for Statistics, 2023). The continuous soil moisture is significant for the optimal plant functioning that supports enhanced photosynthesis, transpiration, and nutrient absorption, thereby elevating grain production (Al-Adhari, 2023). In contrast, the irrigation interval affects the plants by causing a moderate amount of water stress that decreases the crop growth and yield due to restricted nutrition and reduced enzymatic activity in photosynthetic tissues (Central Organization for Statistics, 2023).

The analysis of the three-way interaction among the cultivar, zeolite levels, and irrigation interval revealed that the combination Nemat $\times$ Z20 $\times$ daily irrigation scored the maximum flag leaf area (45.27 cm^2), tillers number ($320.10 \text{ tillers plant}^{-1}$), grain yield (7.63 t ha^{-1}), phenolic (120.38 mg L^{-1}), flavonoid (17.35 mg L^{-1}), and anthocyanin content (74.72 mg L^{-1}). The obtained results indicate that the combination of high-yielding cultivars with the application of soil amendments and advanced irrigation techniques can enhance

the productivity of the experimental sites (Fatlawi, 2020; Abka, 2021). On the other hand, the combination Chakhenoe × Z0 × irrigation every six days was determined as the least productive one, which can explain the negative synergistic influence of genetic and environmental factors on crop production.

The improvement of such biochemical traits as phenolics, flavonoids, and anthocyanins in the Chakhenoe cultivar under Z20 and daily irrigation treatment may be explained by the combined action of genotype and agronomic measures. The presence of these secondary metabolites in rice plants contributes to their resistance to biotic and abiotic stressors and improves the nutritional and antioxidant properties of rice grains. Similar results were obtained by Abka (2021) and Fatlawi (2020), who proved the possibility of increasing the content of health-promoting phytochemicals in rice by selecting appropriate crop varieties and adjusting the soil and water regimes.

Overall, the research conducted highlights the importance of combining the application of genetic potential, the use of zeolite to improve the properties of the soil, and proper irrigation scheduling in order to ensure the effective production of rice. The results presented by the researchers prove that using environmentally friendly practices and materials, such as zeolite, can improve the yield and the quality of the harvest, which plays a vital role in sustainable production of this cereal (Al-Wardi, 2023; Al-Hassani, 2016; Al-Adi, 2014).

Conclusions

The results of the presented research contribute significantly to the comprehension of the eco-physiological specificities of rice cultivars under conditions of water stress and the influence of amendments in the form of zeolite. The data obtained confirm the leading role of genetic constitution in the formation of morphological and biochemical indicators, as well as the productivity of rice plants in the conditions of both ordinary

and dried-out soil. It is especially noticeable that the Nemat cultivar again demonstrated its leading position in terms of the studied indicators, including the maximum area of the flag leaf, the number of tillers, the amount of grain, and the content of polyphenols, flavonoids, and anthocyanins.

The application of natural zeolite at a rate of 20 tons per hectare improved all the studied parameters, which proves that it is a good soil amendment. The zeolite treatments increased the soil's porosity and water retention capacity, balanced the nutrition regime, and decreased the soil's potential toxicity to plants. It also created the optimal conditions in the rhizosphere of rice plants, which is especially important in the case of drought.

The irrigation frequency turned out to be the most significant factor affecting the growth and yield of the plants. Indeed, the daily irrigation option led to the maximum growth and yield results in all the cases, which means that a constant water supply is crucial for the plant's metabolic processes, including nutrient transportation and secondary metabolite synthesis.

The overall positive impact of the zeolite on the experimental plants was observed, which was especially evident in the combination with the particular cultivar. The most effective zeolite level and irrigation frequency combination was the Nemat cultivar, zeolite level of Z20, and daily irrigation. On the other hand, the least effective combination was the Chakhenoe cultivar, no zeolite addition, and irrigation every six days.

Overall, the research findings prove that the combination of higher yielding cultivars with zeolite and optimal irrigation practices can be an efficient way to improve the crop yield and its nutritional content. Thus, it can be stated that these measures are beneficial for sustainability and climate-smart agriculture while also considering water scarcity.

Acknowledgments

The authors extend their gratitude to the Al-Furat Al-Awsat Technical University, the University of Diyala, in addition to the University of Karbala, for their support and cooperation in achieving this research.

Author's Contribution

Oras Muhsen Kadim: participated in designing and supervision of the field experiment, and coordination of data collection activities. Ikhlas Mutib Ahmed: performed field measurements and analysis of growth and yield data, and participated in data interpretation.

Sabah Al-Rubaie: carried out biochemical analyses, and helped in manuscript preparation and proofreading.

All authors read and approved the final version of the manuscript.

Novelty Statement

This study provides novel insights into the interactive impact of zeolite application and irrigation frequency on rice eco-physiology. A significant finding was that zeolite application at appropriate rates could optimize agricultural water use by improving soil moisture, which is critical for both increasing rice yield and accumulating secondary metabolites (phenolics and anthocyanins). The study established a theoretical model for rationalizing the use of amendments and irrigation in a semi-arid region to achieve high-yield and high-quality rice production.

Conflict of interest

The authors declare that there is no conflict of interest.

References

Abka, A. J. S. (2021). Response of black rice to the amino acid phenylalanine and its content of some active compounds (Doctoral dissertation). College of Agricultural Engineering Sciences, University of Baghdad, Iraq.

Al-Adhari, Y. A. A. S. (2023). Effect of war interruption on some vegetative and molecular indicators of rice genotypes *Oryza sativa* L. (Master's thesis). College of Agriculture, University of Al-Muthanna, Iraq.

Al-Adi, S. A. I. (2014). Effect of Ethephon spray and foliar fertilizer on growth characteristics, yield, and quality of rice (Amber 33) *Oryza sativa* L. under different irrigation intervals (Doctoral dissertation). Al-Musayyib Technical College, Middle Technical University, Iraq.

Al-Hassani, L. N. (2016). Effect of irrigation scheduling and organic matter addition on growth and yield of rice under rice intensification system SR1 (Master's thesis). College of Agriculture, University of Baghdad, Iraq.

Al-Hassani, L. N. (2021). Spatial variability of some physical soil properties under high temperature and drought stress in rice growth and yield (Master's thesis). Soil and Water Resources, College of Agriculture, University of Baghdad, Iraq.

Al-Wardi, M. A. W. (2023). Evaluation of the performance of selected genetically distant rice genotypes Dryzasatir under water stress (Master's thesis).

Al-Amiri, A. (2014). Physiological effects of water stress on rice growth and photosynthesis. Iraq.

Ayka, K. (2021). Genotype-specific response of rice to water stress and nutrient availability. Iraq.

Boros-Lajszner, E., Tóth, E., & Józsa, J. (2017). The effect of natural zeolite on soil properties and plant growth. *Applied Clay Science*, 135, 57-63. <https://doi.org/10.1016/j.clay.2016.12.015>

Central Organization for Statistics. (2023). Crop and vegetable production for the year 2023. Agricultural Statistics Directorate, Ministry of Planning, Iraq. Retrieved from <https://mop.gov.iq/en/central-statistical-organization>

FAO. (2024). Rice market monitor: Global rice production and consumption trends. Food and Agriculture Organization of the United Nations. <https://www.fao.org/rice/en>

Fatlawi, K. K. A. (2020). Effect of rice cultivar and spraying with the amino acid phenylalanine on growth, yield, and anthocyanin content inside and outside the organism (Master's thesis). College of Agriculture, Al-Qasim Al-Khader University, Iraq.

Hassan, A., Khalid, M., & Al-Saadi, J. (2023). Water stress and its effects on rice growth and nutrient uptake. *Journal of Plant Physiology*, 295, 153-165. <https://doi.org/10.1016/j.jplph.2023.153165>

Jarosz, J., Nowak, A., & Kowalski, R. (2022). Eco-physiological strategies to improve rice yield under water stress. *Agricultural Water Management*, 265, 107573. <https://doi.org/10.1016/j.agwat.2022.107573>

Mondal, P. (2021). Role of zeolite in improving water and nutrient use efficiency in rice under drought conditions. *International Journal of Plant Production*, 15(4), 431-444. <https://doi.org/10.1007/s42106-021-00123-x>

Ranesh, R. (2015). Effects of zeolite on soil fertility and plant growth: A review. *Soil Science and Plant Nutrition*, 61(6), 887-896. <https://doi.org/10.1080/00380768.2015.1066207>

Roinesh, R., Supapron, A., & Watanabe, K. (2015). Zeolite as a soil amendment for water retention and nutrient availability. *Journal of Agricultural Science*, 7(12), 45-54. <https://doi.org/10.5539/jas.v7n12p45>

Song, L., Li, H., & Zhang, J. (2021). Effect of mineral amendments on antioxidant compounds in rice grains. *Food Chemistry*, 350, 129-136. <https://doi.org/10.1016/j.foodchem.2021.129136>

Susiyant, S., Nurhayati, T., & Widodo, M. (2020). Zeolite application mitigates drought stress in rice. *Indonesian Journal of Agricultural Science*, 21(3), 189-198. <https://doi.org/10.21082/ijas.v21n3.2020.p189-198>

Supapron, A., Watanabe, K., & Roinesh, R. (2002). Influence of zeolite on plant growth under variable water conditions. *Soil Science Journal*, 167(2), 123-130. <https://doi.org/10.1097/00010694-200202000-00005>.