Оригинальная статья / Original article

https://doi.org/10.18619/2072-9146-2023-6-108-116
УДК 633.11:631.811.98:631.67(213.5)

Nilofar Maheri [1]*, Tayyeb Sakinejad [1], Adel Modhej [2], Mohammad Dadnia [1], Seyed Marashi [2]

[1] Islamic Azad University, Ahvaz Branch
Golestan Boulevard, Farhang Shahr Street, Postal code 61349-37333, PO Box 1915, Ahvaz, Iran

[2] Islamic Azad University, Shoushtar Branch
University Boulevard, postal code 6451761117, Shushtar, Iran

***Correspondence Author:** eshomeli@gmail.com

Acknowledgments:This study is a part of a doctoral thesis that was completed with the help of technical and support staff in the Department of Agriculture, Islamic Azad University of Ahvaz, Iran, and therefore they all deserve to be thanked. Also, it is grateful to all agricultural, laboratory and library divisions who helped during the implementation of the thesis.

Conflict of interest: The authors declare that they have no conflict of interest.

Authors' Contribution: All authors participated in the analysis of materials, writing the text of the article and forming conclusions.

For citations: Maheri N., Sakinejad T., Modhej A., Dadnia M., Marashi S. The effect of growth regulators and irrigation on remobilization and grain filling of bread wheat in tropical climatic conditions. *Vegetable crops of Russia.* 2023;(6):108-116. https://doi.org/10.18619/2072-9146-2023-6-108-116

Received: 06.09.2023
Accepted for publication: 24.09.2023
Published: 04.12.2023

The effect of growth regulators and irrigation on remobilization and grain filling of bread wheat in tropical climatic conditions

Abstract

To study the remobilization rate affected by growth regulators in wheat a field experiment was carried out in the south of Iran over 2017-2019 with a split-split plot design and three iterations in completely randomized blocks. The main plots were two irrigation regimes (full irrigation and irrigation interruption at the grain-filling stage), two wheat cultivars (Chamran 2 and Durum Karkheh cv.s) were as sub plots, and four growth regulators (control (no growth regulator), salicylic acid, jasmonic acid, and cytokinin) placed in sub-sub plots. Results revealed the significant impact of the triple interaction on grain yield. The highest grain yield (4803 kg/Ha) was observed for Chamran 2 cv. treated with complete irrigation and salicylic acid. Although grain yield declined by 15.5% in the Karkheh cv. with irrigation interruption at the grain-filling stage and non-administration of growth regulators, treatment with salicylic acid managed to attenuate the adverse impact of drought stress in grain yield. The highest current photosynthesis and its contribution were observed in cultivars treated with complete irrigation. Moreover, irrigation regimen and growth regulators each had significant impacts on proline, catalase enzyme, and stomatal conductance. Overall, results suggested that using salicylic acid in Chamran 2 cv. would be advisable to increase growth and grain yield and reduce decline under stress.

Keywords: **Wheat; catalase; cytokinin; proline; salicylic acid**

Н. Махери [1]*, Т. Сакинежад [1], А. Модхей [2], М. Даднія [1], С. Мараши [2]

[1] Исламский университет Азад, филиал в Ахвазе
Golestan Boulevard, Farhang Shahr Street, Postal code 61349-37333, PO Box 1915, Ahvaz, Iran

[2] Исламский университет Азад, филиал Шуштара
University Boulevard, postal code 6451761117, Shushtar, Iran

***Автор для переписки:** eshomeli@gmail.com

Благодарности. Это исследование является частью докторской диссертации, которая была завершена с помощью технического и вспомогательного персонала Департамента сельского хозяйства Исламского университета Азад в Ахвазе, Иран, и поэтому все они заслуживают благодарности. Также выражается благодарность всем сельскохозяйственным, лабораторным и библиотечным подразделениям, оказавшим помощь при выполнении диссертационной работы.

Конфликт интересов. Авторы заявляют об отсутствии конфликта интересов.

Вклад авторов: Все авторы участвовали в анализе материалов, написании текста статьи и формировании выводов.

Для цитирования: Maheri N., Sakinejad T., Modhej A., Dadnia M., Marashi S. The effect of growth regulators and irrigation on remobilization and grain filling of bread wheat in tropical climatic conditions. *Vegetable crops of Russia.* 2023;(6):108-116. https://doi.org/10.18619/2072-9146-2023-6-108-116

Поступила в редакцию: 06.09.2023
Принята к печати: 24.09.2023
Опубликована: 04.12.2023

Изучение влияния регуляторов роста и орошения на ремобилизацию и налив зерна мягкой пшеницы в условиях тропического климата

Резюме

Чтобы изучить скорость ремобилизации пшеницы, под влиянием регуляторов роста, в Южном Иране в 2017-2019 годах был проведён полевой эксперимент с разделением и тройным циклом в полностью рандомизированных кварталах. Основные участки – два режима орошения (регулярное орошение и перерыв в орошении на стадии созревания зерна), два сорта пшеницы (Chamran 2 и Durum Karkheh) находившиеся на дополнительных участках, и четыре варианта с регуляторами роста (контроль (отсутствие регулятора роста), салициловая кислота, жасмоновая кислота и цитокинин), помещённые в подподразделенные участки. Результаты показали значительное влияние трёх факторов на урожайность зерна. Самая высокая урожайность зерна (4803 кг/га) отмечена у сорта Chamran 2 при полном орошении и с обработкой салициловой кислотой. При том, что урожайность зерна сорта Durum Karkheh снизилась на 15,5%. при прекращении орошения на стадии пополнения зерна и отсутствия применения регуляторов роста обработка салициловой кислотой позволила ослабить негативное влияние давления засухи на урожайность зерна. Наибольший фотосинтез и его влияние наблюдались при полном орошении. Более того, режим регулярного орошения и регуляторы роста оказали значительное влияние на пролин, фермент каталазу и устьичную проводимость. В итоге результаты показали, что использование салициловой кислоты на сорте Chamran 2 позволяет увеличить рост и урожайность зерна и снизить потери под влиянием стрессовых условий.

Ключевые слова: **пшеница; каталаза; цитокинин; пролин; салициловая кислота**

Introduction

Wheat (*Triticum aestivum* L.) is among the most essential crops worldwide with the largest under-cultivation area at 221 million hectares (and total production of 766 million tons) in 2021. The area under wheat cultivation and its production were 6.70 million hectares and 16.75 million tons, respectively, in the same year in Iran [36]. A total of 20% of the calories consumed by the world population is estimated to be supplied by wheat, which is cultivated in 14.6% of all agricultural land worldwide annually [36]. Wheat is cultivated in winter and early spring in Iran. Water availability to plants declines as the temperature rises from mid-spring, which aligns with wheat's growth period (pollination and grain filling) [23]. Drought and water shortage are thus among the most crucial factors limiting wheat production in arid and semi-arid areas [41]. While cereal breeding research in Iran has chiefly been focused on introducing high-yield crops in optimal irrigation conditions over the past decades, the confined wheat farm irrigation –specifically at the end of the season- has placed a greater accentuation on the identification and introduction of cultivars yielding a favorable yield with a maximum of two irrigation turns in spring following spring precipitations [34]. The fact that the largest part of Iran's area is considered among arid and semi-arid regions indicates that drought is among the most crucial abiotic stresses in the country [37]. Plants need mechanisms to identify and respond to stresses since they cannot escape them. Osmotic regulation is one of such mechanism. Playing a prominent role in the osmotic regulation inside the cell, proline is among the amino acids involved in osmotic regulation [33]. Cereal grain yield depends on the three factors of current photosynthesis, stored assimilate transfer to grains before flowering, assimilates stored temporarily in the stem following flowering [21]. Researchers argue that plants increase dry matter transfer to grains as they suffer stresses due to moisture and nutrient scarcity to compensate the resulting reduced photosynthesis [7]. Limited water content in soil increases the dependence of crop yield on dry matter redistribution processes at the grain-filling stage due to reduced leave area and, consequently, reduced current photosynthesis [16]. Growth regulators such as salicylic acid, jasmonic acid, and cytokinin can help prevent the adverse impacts of drought stress on plants under drought conditions [19]. Salicylic acid (orthohydroxybenzoic acid) is a water-soluble phenolic compound, an antioxidant, and one of the plant hormones closely involved in the plant's response to abiotic stresses including drought [13, 26]. Jasmonates are among the newest growth regulators reducing environmental stresses in plants. Jasmonic acid has been reported to have protective effects against drought stress through antioxidant activity, altering proteins, and malondialdehyde [22]. Cytokinin is another growth-regulating hormone with favorable impacts on plant survival under abiotic stresses [39]. Cytokinin plays a significant part in growth regulation and photosynthesis system stability during drought and moderates many of the physiological activities that drought stress induces [40]. Sedaqat and Emam [27] reported that interrupting irrigation reduced grain yield significantly compared to conventional irrigation. They also suggested that although irrigation interruption reduced yield and its components, spraying growth regulators made up for some of the reduced yields due to drought stress.

Given the prominent role of growth regulators in attenuating the impacts of drought stress in plants, the present study seeks to examine the influence of growth regulators on the transmission rate, physiological traits, and grain yield in wheat cultivars in response to growth regulators and irrigation regimens.

Material and methods

Experimental design, treatments, and crop management

The present study was performed on a field in Ahwaz situated in the southwest of Iran (31°20'52" N. 48°40'31" E.; 22.5m above sea level) during 2017-2019. Tables 1 and 2 demonstrate the average meteorological indices and soil characteristics of the research site. The study was carried out on wheat cultivated in split-split fields in the form of completely randomized blocks with three irrigations. The primary irrigation regimen factor was investigated in the two levels of irrigation until the end of the season and irrigation interruption at the grain-filling stage (69th Zadoks stage at March 19th to April 17th in the first year and March 17th to April 19th in the second year). Wheat cultivars included Chamran 2 and Durum Karkheh, and growth regulators were examined in the four groups of no growth regulator (control), salicylic acid, jasmonic acid, and cytokinin placed in sub-sub plots. A total of 96 plots were tested. Wheat grains used in the present study included Chamran 2 and Durum Karkheh cultivars obtained from Khuzstan Agriculture Research Center. Chamran 2 is a high-yield cultivar resistant to late-season heat tolerance up to 38°C that matures quickly and is suitable for cultivation in rain irrigation systems thanks to its thicker stems. Chamran 2 wheat line is resistant to brown and strip rust, sees shattering, and dormancy. Durum Karkheh cv is also suitable for cultivation in the hot and arid areas of the south of the country with a mean shrub height of approximately 9 cm and resistance to strip rust, powdery mildew, and Karnal bunt. Each plot contained eight five-meter lines placed 20 cm from one another. The main plots and sub-plots had distances of 1.5 and one meter, respectively. Sub-sub plots had a distance of half a meter, and iterations were placed two meters away from one another. Following land preparation through pre-planting, potassium and phosphorus fertilizers from a triple superphosphate source containing 100 kg pure phosphorus, potassium fertilizer at the 100 kg/Ha potassium sulfate rate, and nitrogen fertilizer from a urea source (46%) at a rate of 150 kg/Ha were distributed in the farm to provide the necessary nutrient, half of which was spread with a disc and the other half of nitrogen was distributed at the end of the tillering stage and beginning of stem growth. Seeds were planted in November 6th, 2017, and 2018. The seeds were manually prepared and planted regularly at a density of 400 seeds/m^2. Planting strips were then covered with 4 cm of soil. The first irrigation was performed after planting. Drought stress was applied at the seed-filling stage per research design. Treatment with 0.5mmol jasmonic acid, 1mmol salicylic acid, and 50μM cytokinin was performed at the two stages of stem growth and flag leaf growth (30th and 41st Zadoks stages, respectively) using a 20l spray pump in the early morning in the absence of wind. . To increase leaves adhesion cytokinin Tween 20 was administered to plants at the 0.5% volume ratio [15]. Weeds from the Gramine family that started to grow during crop growth were manually removed, and the farm remained intact in terms of pest attacks and diseases.

Table 1. Average biennial meteorological parameters of the tested site
Таблица 1. Средние двухлетние метеорологические параметры полигона

Month	Rainfall (mm)	Average minimum temperature (°C)	Average maximum temperature (°C)	Average minimum relative humidity (%)	Average maximum relative humidity (%)
August	0.0	32.9	48.1	14.3	49.1
September	0.0	26.4	42.5	13.8	43.8
October	0.0	21.9	38.4	11.42	35.12
November	12.5	17.6	32.1	10.3	28.8
December	25.0	8.5	24.3	8.1	26.1
January	29.0	8.1	21.2	7.9	25.4
February	28.5	12.1	22.5	8.3	26.0
March	14.5	14.4	30.7	13.3	31.0
April	10.0	19.3	37.6	14.5	28.0

Table 2. Soil characteristics of the tested field
Таблица 2. Характеристики почвы опытного поля

Crop year	Soil depth	Soil Texture	pH	EC	Organic Matter	K	P	N
	(cm)			(ds.m-1)	(%)	(mg.kg)		(%)
2016-17	0-30	Sandy Loam	7.51	3.92	0.88	174	10.35	0.42
2017-18	0-30	Sandy Loam	7.3	3.71	0.91	180.1	11	0.38

Measuring traits

Crops were harvested from the four middle strips with an area of around two meters square after excluding half a meter from either end of each plot and the first and last rows of the plot to examine grain yield. Grain was separated from straw after threshing, and kg/Ha grain yield was calculated [21].

Catalase activity

Fresh leaf samples were obtained from the plants, which were frozen in liquid nitrogen and stored at -80°C until biochemical analysis to examine the catalase antioxidant enzyme's activity in the full flowering stage (59thZadoks stage). For this purpose, 900µl of the reaction solution (containing 10 mM hydrogen peroxide solution in PVP-free phosphate-buffered saline and 100µ lenzyme extract) was added to hydrogen peroxide (H_2O_2) resulting in immediate H2O2 decomposition due to catalase, which was measured using a spectrophotometer (Uvi Light XS 5 SECOMAM model) to calculate enzyme activity [10].

Proline

The proline content accumulated in the plant at the flowering stage was calculated in mg/g f.w. at the 520 nm wavelength using a spectrophotometer based on the proline content standard curve at the flowering stage [9].

Stomatal conductance

A Leaf Prometer (Decagon Devices INV. Version 1.06) was used to calculate stomatal conductance (by putting the conductance of a leaf in series with two known conductance elements, and comparing the humidity measurements between them). It displayed information in mmol/m²s (millimoles per meter squared seconds) unit.

The amount and contribution of remobilization and the amount and contribution of current photosynthesis were also calculated from the following formulas [42]:

Dry weight of vegetative organs in stage – maximum dry matter yield of vegetative organs (g/m²) = amount of dry matter in physioligical remobilization (g/m²).

Contribution of remobilization process in grain yield (%) = Dry matter weight in remobilization process (g/m²)/grain yield (g/m²) x 100.

Weight of dry matter in remobilization process (g/m²) - grain yield (g/m²) = Weight of dry matter resulting from current photosynthesis (g/m²).

Contribution of remobilization in grain yield-100=contribution of current photosynthesis in grain yield.

Statistical analysis

To perform complex variance analysis, a split-split statistical design was used as completely randomized blocks after performing the Bartlett test. Variance analysis was performed in SAS (V.8), and Duncan's test was conducted to compare means at the 5% significance level. The resulting tables were ultimately drawn in Word 2007.

Results and Discussion

Grain yield

We observed grain yield to be under a significant influence of year, irrigation regimen treatments, wheat cultivars, and growth regulators, the mutual impact of irrigation regimen and growth regulators, and the interaction between irrigation regimen, wheat cultivars, and growth regulators (Table 3).

Table 3. Composite variance analysis of studied traits in wheat in two years of experiment (first series)
Таблица 3. Комплексный дисперсионный анализ изучаемых признаков пшеницы за два года опыта (первая вариация)

S.O.V	Df	Seed yield	Catalase	Proline	Stomatal conductance
Year (Y)	1	131.2*	1.04 ns	4.07*	0.19 ns
(Year)*Replication	4	9.17	3.61	0.27	2.2
Irrigation regime (I)	1	409251 *	7501.2 **	603*	2248.1 *
Y*I	1	1563.2 ns	0.28 ns	0.58 ns	4.78 ns
Main plots error	4	18044	139.5	2.04	30.62
Varieties (V)	1	316450 *	3.1 ns	425.2 **	0.17 ns
Y*V	1	269.9 ns	10.66 ns	0.09 ns	1.44 ns
I*V	1	93 ns	15.4 ns	*198.2	0.05 ns
Y*V*I	1	101.5 ns	28.75 ns	0.08 ns	1.02 ns
Sub-plots error	8	18039.42	102.18	1.22	18
Growth regulators (G)	3	267531 **	5129.76 **	267.01 **	0.03 ns
Y*G	3	714.2 ns	16.44 ns	0.17 ns	0.17 ns
I*G	3	825709 **	6008.2 **	0.031 ns	0.12 ns
Y*I*G	3	810.6 ns	30.12 ns	0.04 ns	0.67 ns
V*G	3	282.2 ns	2.65 ns	0.02 ns	1.75 ns
Y*V*G	3	500.4 ns	45.01 ns	0.07 ns	2.32 ns
I*V*G	3	109631.5 **	20.36 ns	0.003 ns	3.14 ns
Y*I*V*G	3	628.4 ns	52.05 ns	0.01 ns	5.32 ns
Sub sub plots error	48	6500	85.09	0.12	16.08
Coefficient of variation (%)	-	18.13	8.53	17.40	6

*ns, * and **: no significant, significant at the 5% and 1% probability levels, respectively.*

Results revealed that the highest yield was observed in 2017 (at an average of 4,676 kg/Ha) due to yield components in this year, which increased yield by 10% compared to 2018 (Table 4). The reason for this yield difference appears to be the higher precipitation rate in the first year of the study.

The highest grain yield (4,803 kg/Ha) was observed under complete irrigation until the end of the season and treatment with salicylic acid in the Chamran 2 cv (not significantly different from complete irrigation until the end of season and treatment withjasmonic acid in Chamran 2), which was significantly higher (by 15.5%) than plants treated with interrupted irrigation at the grain-filling stage and no growth regulator (Table 5).

The reduced grain yield due to drought stress could stem from pollen grain sterility due to the stress, abnormal

Table 4. Mean comparison of traits under year, irrigation regime, cultivars, and growth regulators
Таблица 4. Сравнение средних показателей по годам, режиму орошения, сортам и регуляторам роста

Treatment	Seed yield (kg.ha^{-1})	Catalase (Unit.mg^{1} Protein)	Proline	Stomatal conductance	Remobilization rate (g.m^{-2})	Remobilization contribution (%)	Current photosynthesis (g.m^{-2})	Current photosynthesis contribution (%)
Year								
2017	4676 a	114.1°	431.02 a	36.01°	109.2 a	23.35 a	363.42 a	76.65 b
2018	4215 b	103.04°	424.29 a	32.11 b	91.1 b	21.63 b	325.4 b	78.37 a
Irrigation regime								
Full irrigation	4903 a	90.63 b	430.01 a	37.11 a	85.24 b	17.37 b	405.09 a	82.63 a
Stop irrigation in the stage of seed filling	3987 b	126.52 a	425.3 a	31.02 b	115.07 a	28.85 a	283.67 b	71.15 b
Varieties								
Chamran 2	4728 a	109.26 a	442.12 a	35.1 a	108.8 a	23.01 a	366.3 a	77 ab
Karkheh	4163.2 b	107.74 a	413.18 b	33.03 b	91.51 b	21.98 b	324.61 b	78.02 a
growth regulators								
Control	3800 c	89.08 c	402.58 c	30 c	112.01 a	29.47 a	268.01 c	70.53°
Jasmonic acid	4761 ab	115.03 ab	430.03 b	36.21 a	100.15 b	21.03 b	375.97 ab	78.97°
Salicylic acid	4880 a	117.16 a	460.2 a	38.03 a	93.4 c	19.13 c	394.61 a	80.87 a
Cytokinin	4342 b	113.1 b	417.8 bc	32.01 b	95.2 c	21.92 b	339.03 b	78.08 a

Different letters in each column indicate a significant difference by Duncan's multiple range test at the 5% probability level.

Table 5. Mean comparison of traits under the interaction of irrigation regime×varieties×growth regulators
Таблица 5. Среднее сравнение признаков при взаимодействии режима орошения, сорта, регуляторов роста

Irrigation regime	Varieties	Growth regulators	Seed yield (kg.ha-1)
Full irrigation	Chamran 2	Control	4552 bc
		Jasmonic acid	4765 a
		Salicylic acid	4803 a
		Cytokinin	4724 ab
	Karkheh	Control	4512 c
		Jasmonic acid	4603.1 b
		Salicylic acid	4689.7 ab
		Cytokinin	4584 b
Stop irrigation in the stage of seed filling	Chamran 2	Control	4101 ef
		Jasmonic acid	4360.5 d
		Salicylic acid	4402 d
		Cytokinin	4301 de
	Karkheh	Control	4065 f
		Jasmonic acid	4237 de
		Salicylic acid	4252 de
		Cytokinin	4194.1 e

Different letters in each column indicate a significant difference by Duncan's multiple range test at the 5% probability level.

photosynthesis, and reduced material transfer to grain, leading to grain weight and yield decline [11]. The present study found that growth regulators enhanced grain yield under complete irrigation and interrupted irrigation at the grain-filling stage by 15.5 and 7.5%, respectively. Treatment with salicylic acid under interrupted irrigation enhanced yield under both normal irrigation and drought stress conditions by increasing growth and leaf area [25]. In this regard, Sadaqat and Emam [27] suggested that although interrupting irrigation reduced yield and its components, spraying growth regulators made up for a portion of the reduced yield due to the drought stress, which is consistent with our results. On the other hand, the results of the present study revealed that the highest grain yield was observed in the Chamran 2 cv. This finding indicated that Chamran 2 cv had a higher capability in terms of grain production and consequently, yield components compared to Kharkheh, resulting in better yield and potential to utilize available resources and conditions. As Shakirova and Bezrukova [31] reported, salicylic acid enhanced plant growth and photosynthesis under stress conditions through anti-stress reactions including increased proline accumulation, resulting in improved growth after stress relief. Results of other studies also pointed out the positive impact of growth regulators on grain yield under interrupted irrigation [32]. Results of stepwise linear multivariate regression (Table 6) indicated that grain yield (Y) was a function of number of seeds per spike (X1), weight per thousand spikes (X2), and number of spikes per meter square (X3). These traits were entered into the stepwise regression model and justified about 98.8% of variations. The number of seeds per spike, weight per thousand spikes, and number of spikes per meter square were revealed to be remarkably significant in this model. The number of seeds per spike and the number of spikes per meter square had the greatest and smallest impact on grain yield, respectively. The mathematical regression model is as follows:

$$(X3)0.51+(X2)0.67+(X1)0.88+715.12=Y$$

Catalase enzyme activity

As the table indicating the results of complex variance analysis (Table 3) demonstrates, irrigation regimen and growth regulators and the interaction between them left a significant impact on catalase activity. Among the studied cultivars, Chamran 2 had the highest catalase activity at 109.26 mmol decomposed peroxide per minute per mil-

Table 6. Step-by-step regression steps for grain yield as a function variable and other traits as an independent variable
Таблица 6. Пошаговая регрессии для урожайности зерна как функциональной переменной и других признаков как независимой переменной

Variable added to the model	Step-by-step regression step		
	3	2	1
Constant number	482.05	591.22	715.12
Grains/Spikes	0.42 **	0.73 **	0.88 **
1000-grain weight		0.54 **	0.67 **
Spikes/m²			0.51 **
Explanatory coefficient	67.38	70.23	98.8

The step-by-step regression coefficients in the last step are significant at the probability levels of 1% (step 1) and 5% (step 2).

ligram protein, while Karkheh had the lowest values figures; however, the differences were not statistically significant (Figure 1).

Moreover, examination of the mutual impact of irrigation regimen and growth regulators revealed that the highest catalase activity was observed at the grain-filling stage under treatment with jasmonic and salicylic acid, indicating a growth improvement of 25 and 23%, respectively, compared to complete irrigation and no growth regulator administration (Table 5). Catalase which catalyze decomposition of hydrogen peroxide to water and molecular oxygen, is important members of the antioxidant defense system in plant cells and is activated due to high hydrogen peroxide contents in the internal environment [24]. In the stress conditions such as drought, hydrogen peroxide accumulates (oxidative stress) and reduces the activity of peroxidase enzyme (one of the important enzymes involved in physiological processes), so antioxidants such as catalase are activated to protect peroxidase. [5]. Salicylic acid appears to regulate antioxidant compounds' synthesis under environmental stress, which enhances plant resistance against drought stress [14, 17]. In this regard, Agarwal et al. [1] reported that spraying 1mM of salicylic acid on wheat under drought stress increased catalase and superoxide dismutase enzymes' activity. Moreover, Ananieva et al. [2] reported that treatment with salicylic acid alone increased catalase activity by 17% compared to the control treatment, which resonates with our results.

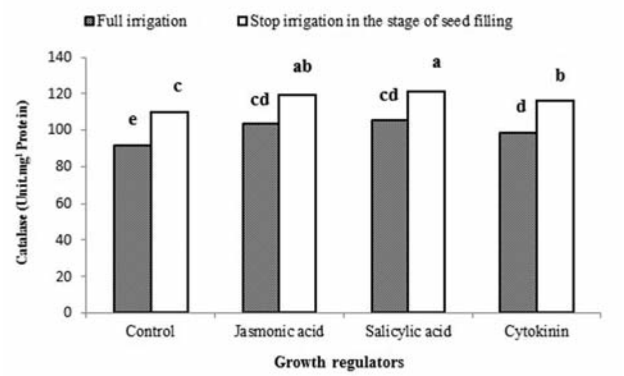

Fig. 1. Relationship between irrigation regime and growth regulators and catalase activity
Рис. 1. Связь режима орошения с регуляторами роста и активностью каталазы

Proline

Results of complex variance analysis indicated that proline was significantly affected by year, irrigation regimen, cultivar, and growth regulators and the interaction between irrigation regimen and cultivars (Table 3). The results revealed that proline accumulation was higher in 2017 compared to 2018 by 38.21% (Table 4). Examining the mutual impact of irrigation regime on cultivars revealed that drought stress increased proline significantly in both studied cultivated in both years, so Chamran 2 cv had the highest proline at the grain-filling stage under interrupted irrigation while the Karkheh cv had the lowest proline content under complete irrigation (Figure 2). These results suggest that increasing resistance to drought enhances cultivars' capability to accumulate amino acids especially proline [3]. Previous studies suggest that proline accumulation increases in response to treatment with salicylic acid [35] so that it declines at lower salicylic acid concentrations but increases immediately after treatment with higher concentrations [28]. In this regard, Ashraf and Foolad [6] observed that proline accumulation was increased compared to other amino acids (particularly glycine) in root growth sites under drought conditions. This reveals that proline probably stimulates root growth under drought stress, which is in agreement with the present results.

Stomatal conductance

Results of complex variance analysis revealed that the irrigation regime treatment left significant impacts on stomatal conductance at the 5% significance level (Table 3). The highest stomatal conductance was observed under complete irrigation, which was approximately 8% higher at the grain-filling stage compared to interrupted irrigation (Table 4). The trend of stomatal conductance indicates its decline with the onset of drought stress. Closure of stomata is among plants' first responses to drought stress. Stomatal closure may limit the plant's access to carbon dioxide. The plant maintains its stomatal conductance and transpiration at maximum for a while after the drought stress is applied, and narrows and eventually closes its stomata as the stress persists [12]. Studies suggest that plants under no moisture stress (control treatments) had the lowest stomatal resistance compared to other treatments, suggesting that stomatal conductance would be lower under stress conditions [20].

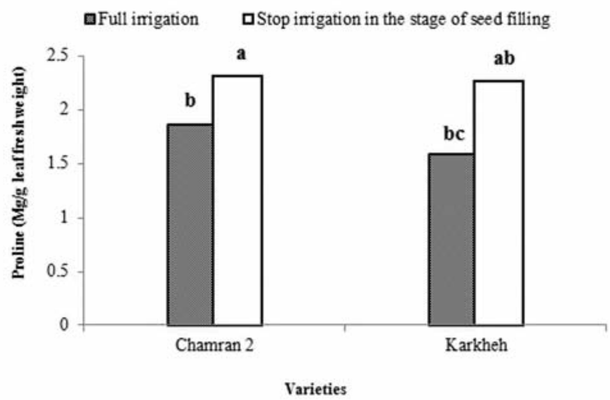

Fig. 2. Effect of irrigation regeme on proline accumulation by Chamran 2 and Karkheh cvs
Рис. 2. Влияние режима орошения на накопление пролина у сортов Chamran 2 и Karkheh

Remobilization rate

Results of complex variance analysis revealed that the irrigation regime treatment, year, cultivar, and growth regulators left significant impacts on the dry matter remobilization rate (Table 7). Results indicated that the remobilization rate was higher in 2017 than in 2018 by 16.5% (Table 4). The present study found that interrupted irrigation increased remobilization in various parts of the plant at the grain-filling stage. The highest retransmission rate was thus observed under the interrupted irrigation treatment until the end of the period, which indicated an increase of approximately 26% (Table 4). In terms of growth regulator, the control treatment indicated the highest remobilization, whereas the lowest rates were observed in plants treated with salicylic acid (Table 4). Among

Table 7. Composite variance analysis of studied traits in wheat in two years of experiment (second series)
Таблица 7. Комплексный дисперсионный анализ изучаемых признаков пшеницы за два года опыта (вторая вариация)

S.O.V	df	Remobilization rate	Remobilization contribution	Current photosynthesis	Current photosynthesis contribution
Year (Y)	1	56.31 *	3.44 *	110.3 *	30.6 **
(Year)*Replication	4	6.2	0.38	24.66	1.08
Irrigation regime (I)	1	9841.2 *	355.1 *	605811**	704.15 *
Y*I	1	35.02 ns	1.66 ns	75.2 ns	3.16 ns
Main plots error	4	160.3	30.5	9621.44	50.01
IVarieties (V)	1	11348.2 **	691.02 **	470552*	589.26 *
Y*V	1	2.34 ns	0.13 ns	205.3 ns	0.39 ns
I*V	1	13.67 ns	0.24 ns	198.4 ns	10.89 ns
Y*V*I	1	10.19 ns	1.51 ns	266.02 ns	25.11 ns
Sub-plots error	8	157.2	23.6	7583.1	43.04
Growth regulators (G)	3	8071.9 **	438.01 **	514331.2 **	9.75 ns
Y*G	3	3.27 ns	6.23 ns	180.4 ns	15.61 ns
¬I*G	3	50.14 ns	14.51 ns	770.3 ns	0.26 ns
Y*I*G	3	69.24 ns	20.94 ns	1050.2 ns	7.05 ns
V*G	3	12.43 ns	5.11 ns	92.23 ns	5.01 ns
Y*V*G	3	15.01 ns	10.33 ns	165.01 ns	12.38 ns
I*V*G	3	20.51 ns	0.67 ns	853.1 ns	0.59 ns
Y*I*V*G	3	39.07 ns	4.23 ns	996.04 ns	7.01 ns
Sub sub plots error	48	128.4	19.52	4023.7	39.22
Coefficient of variation (%)	-	11.33	19.6	18.43	8.08

*ns, * and **: no significant, significant at the 5% and 1% probability levels, respectively*

studied cultivars, Chamran 2 indicated the highest remobilization rate, which was about 16% higher than Karkheh (Table 4). The present study found that water limitations appear to reduce grain yield under drought stress through reduced photosynthesis. As a result, the stored photosynthetic materials are retransmitted. The retransfer of photosynthesis materials thus becomes more crucial in grain filling [4]. Treatment with salicylic acid appears to provide plants with better conditions to perform more current photosynthesis under drought stress, resulting in a larger amount of dry matter accumulation. On the contrary, current photosynthesis drops under drought stress in the absence of salicylic acid as a result of which the plant supplies a portion of the dry matter through photosynthesis material retransfer [30].

Remobilization contribution

Results of complex variance analysis revealed that the irrigation regimen treatment, year, cultivar, and growth regulators left significant impacts on dry matter remobilization contribution (Table 7). Results indicated that the remobilization contribution was higher in 2017 than in 2018 by 7.36%. Increasing the drought stress increased the remobilization contribution significantly, so the highest remobilization contribution was observed at the grain-filling stage under interrupted irrigation, which was about 40% higher than in no-stress conditions (Table 4).

In terms of growth regulator, the control treatment indicated the highest remobilization contribution, whereas the lowest contributions were observed in plants treated with salicylic acid (Table 4). Among the cultivars, Chamran 2 had the highest remobilization contribution at a rate of approximately 5% higher than Karkheh (Table 4). It would appear that the high remobilization contribution and remobilization rate in Chamran 2 wheat cv may be due to its fast maturation and its greater reliance on previous storages in leaves and stems. Accumulated reserves are also highly correlated with the plant's life cycle, which contributed to remobilization in this cultivar. In this regard, Voltas et al. [38] reported that environmental conditions during the stages of plant growth determine the photosynthesis materials available for grain growth and reserve (grain) potential. Further, they found that genotypes with higher dry matter remobilization from aerial organs outperformed others in terms of dry matter efficiency, which was consistent with our results. The present study recorded that ceasing irrigation at the grain-filling stage increased dry matter transmission rate and contribution so that drought stress increased the contribution of vegetative parts in grain yield as a result of the decline in current photosynthesis [8].

Current photosynthesis

Results of complex variance analysis revealed that the irrigation regimen treatment, year, cultivar, and growth regulators left significant impacts on current photosynthesis (Table 7). Results indicated that the current photosynthesis was higher in 2017 than in 2018 by 10.5% (Table 4). The highest current photosynthesis was observed under complete irrigation throughout all growing stages (control), which surpassed irrigation interruption at the grain-filling stage by approximately 30% (Table 4). In terms of growth regulator, the control treatment indicated the lowest current photosynthesis, whereas the highest current photosynthesis was observed in plants treated with salicylic acid (Table 4). Among the cultivars, Chamran 2 had the highest current photosynthesis at a rate of approximately 12% higher than Karkheh (Table 4). Researchers examined the retransfer of photosynthesis materials from stems to grains and the speed of grain filling under drought stress and found that genotypes with faster accumulation and material transmission were less affected by late-season stresses [18]. Salicylic acid appears to increase current photosynthesis in plants through better nutrient absorption and increased growth and leaf area index [13, 14, 29]. It could also be suggested that current photosynthesis declines due to nutrient and moisture stresses, in response to which the plant increases dry matter retransmission to grains [7].

Current photosynthesis contribution

Results of complex variance analysis revealed that the irrigation regimen treatment, year, and cultivar left significant impacts on current photosynthesis contribution (Table 7). Results indicated that the current photosynthesis contribution was higher in 2017 than in 2018 by 3% (Table 4). The highest current photosynthesis contribution was observed under complete irrigation throughout all growing stages (control), which surpassed irrigation interruption at the grain-filling stage by approximately 14% (Table 4). Among the cultivars, Chamran 2 had a higher current photosynthesis contribution-compared to Karkheh (Table 4). It would appear that Chamran 2 cv had the highest current photosynthesis contribution due to its higher capability in utilizing environmental conditions. The contribution of materials stored in vegetative parts increases in responding to the needs of growing grains when current photosynthesis is inadequate due to environmental conditions. The present study observed that the current photosynthesis contribution in rain yield increased under optimal conditions, but decline under drought stress at the grain-filling stage as photosynthesis materials were retransferred to the grains to maintain grain yield. Retransmission thus acted as a moderator compensating the damages due to current photosynthesis deficiency [42].

Conclusion

The highest grain yield (4,803 kg/Ha) was observed in the Chamran 2 cv treated with complete irrigation and salicylic acid as grain yield declined by 15.5% in the Karkheh cv with irrigation interruption at the grain-filling stage and non-administration of growth regulators. Moreover, we found that interrupting irrigation at the grain-filling stage increased catalase activity and proline and reduced stomatal conductance significantly. Although the best results in terms of grain yield and current photosynthesis were observed under complete irrigation conditions and treatment with growth regulators, the moderating effect of regulators on wheat grain yield under drought stress was significant in the case of almost all regulators. Growth regulators thus increased grain yield under complete irrigation and interrupted irrigation by 15 and 7%, respectively. Besides, both Chamran 2 and Karkheh cvs were sensitive to drought stress at the grain-filling stage, resulting in damage to crops. The present study found that growth regulators such as jasmonic and salicylic acid compensated for the impacts of drought stress on the traits of grain yield and catalase. Overall, results suggested that using salicylic acid in Chamran 2 cv would be advisable in the Ahwaz region and similar areas in terms of climate to increase growth and grain yield and reduce decline under stress.

• Литература / References

1. Agarwal S.K.R., Sairam G.C., Srivastava T., Aruna C.R., Meena R. Role of ABA, salicylic acid, calcium and hydrogen peroxide on antioxidant enzyme induction in wheat seedlings. *Plant Science.* 2005;169:559-570. http://dx.doi.org/10.1016/j.plantsci.2005.05.004
2. Ananieva A.E., Christov L.P., Popova D. Exogenous treatment with salicylic acid leads to increased antioxidant capacity in leaves of barley plants exposed to paraquat. *Journal of Plant Physiology.* 2004;161:319-328. https://doi.org/10.1078/0176-1617-01022
3. Anjum S.A., Wang L.C., Farooq M., Hussain M., Xue L.L., Zou C.M. Brassinolide application improves the drought tolerance in maize through modulation of enzymatic antioxidants and leaf gas exchange. *Journal of Agronomy of Crop Science.* 2011;197:177-185. https://doi.org/10.1111/j.1439-037X.2010.00459.x
4. Ardalani S., Saeidi M., Abdoli M. Agronomic traits, photosynthesis and gas exchange variables of wheat genotypes in response to water deficit during vegetative growth period. *Environmental and Experimental Biology.* 2016;14(4):157-162. http://doi.org/10.22364/eeb.14.22
5. Ashraf M. Inducing drought tolerance in plants: some recent advances. *Biotechnology Advances.* 2010;28:169-183. https://doi.org/10.1016/j.biotechadv.2009.11.005
6. Ashraf M., Foolad M.R. Roles of glycine betaine and proline in improving plant abiotic stress resistance. *Environmental and Experimental Botany.* 2007;59:206-216. https://doi.org/10.1016/j.envexpbot.2005.12.006
7. Bahrani A., Heidari Sharif Abad H., Tahmasebi Sarvestani Z., Moafpourian G.H., Ayneh Band A. Remobilization of dry matter in wheat: effects of nitrogen application and post-anthesis water deficit during grain filling. *New Zealand Journal of Crop and Horticultural Science.* 2011;39(4):279-293. https://doi.org/10.1080/01140671.2011.599397
8. Bani Saidi A.K., Motamedi M. The effect of nitrogen consumption on grain yield and dry matter transfer of corn under drought stress conditions. *Journal of Plant Ecophysiology.* 2019;41:77-68. (In Persian) https://www.magiran.com/volume/153052
9. Bates L.S., Waldren R.P., Teare L.D. Rapid determination of free proline for water-stress studies. *Plant and Soil.* 1973;39:205-207. https://doi.org/10.1007/BF00018060
10. Boominathan R., Doran P.M. Ni induced oxidative stress in roots of the Ni hyperaccumulator, Alyssum bertolonii. *New Phytologist.* 2002;156:205-215. https://doi.org/10.1046/j.1469-8137.2002.00506.x
11. Dong B., Zheng X., Liu H., Able J.A., Yang H., Zhao H. Effects of drought stress on pollen sterility, grain yield, abscisic acid and protective enzymes in two Winter wheat cultivars. *Frontiers in Plant Science.* 2017;8:1008. https://doi.org/10.3389%2Ffpls.2017.01008
12. Ertek A., Kara B. Yield and quality of sweet corn under deficit irrigation. *Agricultural Water Management.* 2013;129:138-144. https://doi.org/10.1016/j.agwat.2013.07.012
13. Fairoj S.A., Islam M.M., Islam M.A., Zaman E., Momtaz M.B., Hossain, M.S., Jahan N.A., Shams S.N.U., Urmi T.A., Rasel M.A., … Murata Y. Salicylic acid improves agro-morphology, yield and ion accumulation of two Wheat (*Triticum aestivum* L.) genotypes by ameliorating the impact of salt stress. *Agronomy.* 2023;13:25. https:// doi.org/10.3390/agronomy13010025
14. Fan Y., Lv Z., Li Y., Qin B., Song Q., Ma L., … Huang Z. Salicylic acid reduces wheat yield loss caused by high temperature stress by enhancing the photosynthetic performance of the flag leaves. *Agronomy.* 2022;12(6):1386. https://doi.org/10.3390/agronomy12061386
15. Ghatei A., Bakhshandeh A., Abdali Mashhadi A., Siadat S.A., Alami saeid K., Gharineh M. Effect of Different Nitrogen Levels and Cytokinin Foliar Application on Yield and Yield Components of Wheat at Terminal Heat Stress Conditions in Ahwaz. *Journal of Crop Production and Processing.* 2015;5(16):107-97. http://dx.doi.org/10.18869/acadpub.jcpp.5.16.97
16. Haghjoo M., Bahrani A. Grain yield, dry matter remobilization and chlorophyll content in maize (*Zea mays* L.) as influenced by nitrogen and water deficit. *Bangladesh Journal of Botany.* 2015;44(3):359-365.

http://dx.doi.org/10.3329/bjb.v44i3.38540
17. Hayat Q., Hayat S., Irfan M., Ahmad A. Effect of exogenous salicylic acid under changing environment: A review. *Environmental and Experimental Botany.* 2010;68:14-25. https://doi.org/10.1016/j.envexpbot.2009.08.005
18. Hossain A., Sarker M., Hakim M., Lozovskaya M., Zvolinsky V. Effect of temperature on yield and some agronomic characters of spring Wheat (*Triticum aestivum* L.) genotypes. *International Journal of Agricultural Research Innovation and Technology.* 2013;1(29):44-54. http://dx.doi.org/10.3329/ijarit.v1i1-2.13932
19. Madadi A., Fallah S.A. The effect of proline and salicylic acid on physiological parameters and yield of silage maize under different moisture regimes. *Journal of Crop Production and Processing.* 2018;8(1):15-29. http://dx.doi.org/10.29252/jcpp.8.1.15
20. Maes W.H., Achten W.M.J., Reubens B., Raes D., Samson R., Muys B. Plant water relationships and growth strategies of Jatropha curcas L. seedlings under different levels of drought stress. *Journal of Arid Environment.* 2009;73:877-884. https://doi.org/10.1016/j.jaridenv.2009.04.013
21. Modhej A., Naderi A., Emam Y., Aynehband A., Normohamadi Gh. Effects of post-anthesis heat stress and nitrogen levels on grain yield in wheat (*T. durum* and *T. aestivum*) genotypes. *International Journal of Plant Production.* 2020;2(3):257-268. https://doi.org/10.22069/ijpp.2012.617
22. Mousavoey M., Jahanbakhshgade-Kahriz S., Modaresi M., Parmoon Q., Ebadi A., Kohan mo M.A. Effect of salicylic acid and jasmonic acid on yield and yield components of Milk thistle under heat stress conditions. *Journal of Plant Research (Iranian Journal of Biology).* 2021;34(4):1-14. https://dorl.net/dor/20.1001.1.23832592.1400.34.4.5.8
23. Oweis T., Hachum A. Water harvesting and supplemental irrigation for improved water productivity of dry farming systems in West Asia and North Africa. *Agricultural Water Management.* 2006;80:57–73. http://dx.doi.org/10.1016/j.agwat.2005.07.004
24. Pakdaman N., Javanshah A., Nadi M. The effect of humic and fulvic acids as bio-fertilizers on the growth of Pistacia vera seedlings under alkaline conditions. *Pistachio and Health Journal.* 2018;1(4):13-20. https://doi: 10.22123/phj.2019.154962.1020.
25. Popova L.P., Maslenkova L.T., Yordanova R.Y., Ivanova A.P., Krantev A.P., Szalai G., Janda T. Exogenous treatment with salicylic acid attenuates cadmium toxicity in pea seedlings. *Plant Physiology Biochemical.* 2009;47:224-231. https://dorl.net/dor/20.1001.1.23222727.1391.1.1.5.2
26. Rivas-San Vicente M., Plasencia J. Salicylic acid beyond defence: its role in plant growth and development. *Journal of Experimental Botany.* 2011;62(10):3321-38. http://dx.doi.org/10.1093/jxb/err031
27. Sadaqat M.A., Emam Y. Effect of application of plant growth regulators on growth and grain yield of bread wheat (*Triticum aestivum* L.) cultivars under terminal drought stress conditions. *Iranian Journal of Crop Sciences.* 2016;19(2):147-132. http://dorl.net/dor/20.1001.1.15625540.1396.19.2.4.2
28. Safari M., Arghavani M., Kheiri A. Effect of salicylic acid on morphological and physiological characteristics of vetiver grass under water deficit stress conditions. *Journal of Crops Improvement.* 2018;19(3):591-603. https://doi.org/10.22059/jci.2017.60464
29. Sajdi N.A., Madani H., Habibi D., Pazoki A.R. Investigating the effect of selenium and salicylic acid on retransplantation, photosynthesis and grain yield of wheat cultivars under rainfed conditions. *Crop Production in Environmental Stress.* 2012;4(1):1-16. https://sid.ir/paper/232046/en
30. Shakirova F.M., Sakhabutdinova A.R., Bezrukova M.V., Fatkhutdinova R.A., Fatkhutdinova D.R. Changes in the hormonal status of wheat seedlings induced by salicylic acid and salinity. *Plant Science.* 2003;164:317-322. https://doi.org/10.1016/S0168-9452(02)00415-6
31. Shakirova F.M., Bezrukova M.V. Induction of wheat resistance against environmental salinization by salicylic acid. *Biology Bulletin.* 1997;24:109–112. https://www.elibrary.ru/item.asp?id=13254782
32. Shemi R., Wang R., Gheith E.S., Hussain H.A., Hussain S., Irfan M., Cholidah L., Zhang K., Zhang S., Wang L. Effects of salicylic acid, zinc and glycine betaine on morpho physiological growth and yield of maize under drought stress. *Scientific Reports.* 2021;11:3195-3204. https://doi.org/10.1038/s41598-021-82264-7
33. Silveira J.A.G., Araujo S.A.M., Lima J.P.M.S., Viegas, R.A. Roots and leaves display contrasting osmotic adjustment mechanisms in response to NaCl-salinity in *Atriplex nummularia* L. *Environmental and Experimental Botany.* 2009;66:1-8. http://dx.doi.org/10.1016%2Fj.envexpbot.2008.12.015
34. Tadesse W., Sanchez Gracia M., Gizaw S., Amiri A. Genetic grains in wheat breeding and its role in feeding in the world. *Crop Breeding Genetics and Genomics.* 2019;11:42-56. https://doi.org/10.20900/cbgg20190005
35. Tasgin E., Atici O., Nalbantoglu B. Effects of salicylic acid and cold on freezing tolerance in winter wheat leaves. *Journal of Plant Growth Regulation.* 2003;41: 231–236. https://doi.org/10.1023/B:GROW.0000007504.41476.c2
36. United States Department of Agriculture (USDA). World agricultural production. Department of Agriculture Foreign Agricultural Service Office of Global Analysis. 2021;30 pp. https://apps.fas.usda.gov/psdonline/circulars/production.pdf
37. Vega-Galvez A., Miranda M., Vergara J., Uribe E., Puente L., Martinez E.A. Nutrition Facts and functional potential of quinoa (Chenopodium quinoa Willd) an ancient Andean grain: A review. *Journal of the Science of Food and Agriculture.* 2010;90:2541-2547. h ttps://doi.org/10.1002/jsfa.4158
38. Voltas J., Romagosa I., Araus J.L. Grain size and nitrogen accumulation in skin reduction barly under Mediterranean conditions. *Field Crops Research* 2007;52:117-126. https://www.academia.edu/15313671
39. Wani S.H., Kumar V., Shriram V., Sah S.K. Phytohormones and their metabolic engineering for abiotic stress tolerance in crop plants. *The Crop Journal.* 2016;4(3):162-176. https://doi.org/10.1016/j.cj.2016.01.010
40. Werner T., Nehnevajova E., Köllmer I., Novák O., Strnad M., Kramer U., Schmülling T. Root-specific reduction of cytokinin causes enhanced root growth, drought tolerance, and leaf mineral enrichment in Arabidopsis and tobacco. *The Plant Cell.* 2010;22(12):3905-3920. https://doi.org/10.1105/tpc.109.072694
41. Zaheer M.S., Raza M.A.S., Saleem M.F., Erinle K.O., Iqbal R., Ahmad S. Effect of rhizobacteria and cytokinins application on wheat growth and yield under normal vs drought conditions. *Communications in Soil Science and Plant Analysis.* 2012;50:2521-2533. https://doi.org/10.1080/00103624.2019.1667376
42. Zhang Y., Sun N., Hong J., Zhang Q., Chao W., Xue Q., Zhou S., Huang Q., Wang Z. Effect of Source-Sink Manipulation on Photosynthetic Characteristics of Flag Leaf and the Remobilization of Dry Mass and Nitrogen in Vegetative Organs of Wheat. *Journal of Integrative Agriculture.* 2014;13(8):1680–1690. http://dx.doi.org/10.1016/S2095-3119(13)60665-6

About the Authors:
Nilofar Maheri – Ph.D. student in the Department of Agronomy, Ahvaz Branch, Islamic Azad University
Tayyeb Sakinejad – Ph.D. of Crop Physiology and Assistant Professor in the Department of Agronomy, Ahvaz Branch, Islamic Azad University
Adel Modhej – Ph.D. of Agronomy and Associate Professor in the Department of Agronomy, Shoushtar Branch, Islamic Azad University
Mohammad Reza Dadnia – Ph.D. of Crop Physiology and Assistant Professor in the Department of Agronomy, Ahvaz Branch, Islamic Azad University
Seyed Keivan Marashi – Ph.D. of Agronomy and Plant Breeding and Assistant Professor in the Department of Agronomy, Ahvaz Branch, Islamic Azad University

Об авторах:
Нилофар Махери – Ph.D. студент кафедры агрономии Ахвазского филиала Исламского университета Азад
Тайеб Сакинежад – Ph.D., (физиология сельскохозяйственных культур), доцент кафедры агрономии Ахвазского филиала Исламского университета Азад
Адель Модхей – Ph.D., (агрономия), доцент кафедры агрономии, Шуштарский филиал Исламского университета Азад
Мохаммад Реза Дадния – Ph.D., (физиология сельскохозяйственных культур), доцент кафедры агрономии Ахвазского филиала Исламского университета Азад
Сейед Кейван Мараши – Ph.D., (агрономия и селекция растений), доцент кафедры агрономии Ахвазского филиала Исламского университета Азад