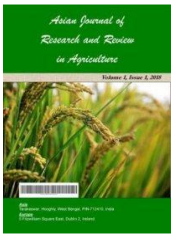

Asian Journal of Research and Review in Agriculture

3(4): 93-112, 2021; Article no.AJRRA.754

Magnetic Field and Application of Silicon Dioxide Nano-Particles Alter the Chlorophyll Content and Chlorophyll a Fluorescence Parameters in Sesame (*Sesamum indicum* L.) under Water Stress Conditions

Maryam Janalizadeh [a#], Ahmad Nezami [b*], Hamid-Reza Khazaie [b], Morteza Goldani [b] and Hassan Feizi [c]

[a] Crop Physiology, Faculty of Agriculture, Ferdowsi University of Mashhad, Iran.
[b] Department of Agro-Technology, Faculty of Agriculture, Ferdowsi University of Mashhad, Iran.
[c] Department of Plant Productions, Torbat-e-Heydarieh University, Iran.

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Original Research Article

Received 25 October 2021
Accepted 27 December 2021
Published 29 December 2021

ABSTRACT

Seed priming by magnetic fields has been introduced as a new, efficient and suitable method, particularly for organic and biodynamic systems to invigorate of seeds and also to improve seedling establishment and crops yield. Magnetic treatments also are used to enhance tolerance of crop plants to many biotic and abiotic stresses. On the other hand, in modern agro-ecological systems, silica-based fertilizers, especially in Nano-forms, are utilized to boost the growth and production of plants and to improve plants tolerance to various environmental stresses. In order to investigate the single and combined effects of magneto-priming and silicon dioxide (SiO_2) nanoparticles (NPs) on some physiological responses of water-stressed sesame, a factorial experiment based on completely randomized design with three replicates was carried out under greenhouse conditions. For this aim, at first, seeds of sesame exposed to a static magnetic field with a magnitude of 75 mT for 1h, then seedlings were treated with four doses of SiO_2 NPs (un-application of SiO_2 (control) and 10, 50 and 100 mg/l) at the stage of full establishment (viz. formation of 6 non-cotyledon leaves in plants) and immediately exposed to water stress at two levels (control (FC 90%) and water stress (FC 50%). Then in two stages of flowering and fruit set (capsule formation), Chlorophyll content was measured by a handy SPAD device and afterward chlorophyll fluorescence parameters including minimum fluorescence (F'o), maximum fluorescence (F'm), variable fluorescence (F'v) and Maximum quantum efficiency of photosystem II (F'v/F'm)

[#] Ph.D. Graduate Student;
**Corresponding author: Email: nezami@um.ac.ir;*

were measured by a portable fluorimeter. Results showed that at the flowering stage of sesame, the chlorophyll content in magneto-priming treatment was higher than un-magneto-priming under non-stress and water stress conditions almost in all concentrations of SiO_2 NPs. The most chlorophyll content was in water stress, magneto-priming and 10 mg/l of SiO_2 NPs. Also under water stress conditions, the F'v/F'm ratio in magneto-priming treatment and in all doses of SiO_2 nanoparticles was higher than un-magneto-priming. In the fruit set stage, magneto-priming almost at all doses of SiO_2 nanoparticles reduced the minimum fluorescence of sesame leaves compared to un-magneto-priming under non-water stress and water stress conditions. F'v/F'm ratio in two treatments of un-magneto-priming, non-water stress and 50 mg/l SiO_2 NPs and the magneto-priming, non-stress and un-application of SiO_2 NPs was similar and maximum. These cases indicate the positive effects of magneto-priming and silicon dioxide nanoparticles on some physiological traits affecting water tolerance, particularly at the flowering stage of sesame, which is more vulnerable to water scarcity.

Keywords: Maximum quantum efficiency of photosystem II; minimum fluorescence; maximum fluorescence; variable fluorescence; magneto-priming.

1. INTRODUCTION

The world population is estimated to reach nine billion by 2050. In order to response the dietary needs of the world growing population by 2050, agricultural productions must be increased by 70% [1-2]. The ascending trend of Iran's population in recent years, followed by increasing the need and consumption of agricultural products, especially vegetable oils, has augmented imports of these products to our country. Therefore, in order to achieve to self-sufficiency in oil and oilseeds, increasing the oily crops cultivation and improving their yield, particularly with environmentally friendly methods, is necessary. However, water is a major constraint for producing of crops in this dry plateau. Therefore, selecting of oily crops resilient to water scarcity, such as sesame and improving water stress tolerance in them by new methods is very essential.

Sesame has the greatest oil content in comparison to other oilseeds [3]. Sesame oil contains a great deal of antioxidants and their derivatives, such as sesamol, sesamin, sesamolin, sesaminol and sesamolinol, hence sesame is called the “queen of oilseeds” because of its high quantity and quality of oil [4]. Despite the many benefits of this plant, sesame has ranked lower at the point of production view compared to other oilseeds and even has moved towards an orphan crop in recent years, due to a low seed yield, because of inadequate agronomic knowledge, using of non-hybrid and native cultivars with seed shedding trait and competition with other oily crops such as soybean, cottonseed, canola, palm oil, sunflower, peanut, olive, coconut, etc. and even maize as a non-oil seed crop [4,5]. At the other hand, although sesame has suitable tolerance to water stress, but it is more susceptible to water stress in germination and seedling stages due to low root growth. In addition it is vulnerable to water stress at flowering and early seed production stages due to the increment of leaf area index and formation of delicate meristemic organs [6, 7]. All these factors cause its yield does not reach to its maximum level in dry areas or in dry land conditions. Therefore, finding methods to improve sesame water stress tolerance, especially in susceptible growth stages, is essential to achieve potential yield.

Today, seed priming is known as an effective technique to increase seed germination, seedling emergence and crop establishment [8], plant protection against biological and non-biological stresses [9] and yield enhancer [10] Priming is a method by which the seeds of plants by exposing to natural and artificial compounds are prepared for germination physiologically and biochemically before being placed in culture medium and being exposed to adverse environmental conditions. It seems that due to stress memory phenomenon, tolerance to various environmental stresses increases in primed seeds [11, 12, 13] Improving the growth and tolerance of magneto-primed wheat seeds to salinity stress conditions was described by Rathod [13] based on the theory of stress memory, (a possible mechanism that may be derived from priming-related epigenetic mechanisms; Because of gene expression caused by DNA methylation and histone modification are responsible for creating stress memory [13]).

The seed magneto-priming technique is based on the placing of seeds between two magnets or a magnetic field before imbibition. After magneto-priming, germination and seedling growth parameters are evaluated. It has been cited that physiological and growth responses of magneto-primed plants occur even in last stages of plants growth such as crop harvesting [14]. In a study, applying a magnetic field with strength of 5 mT for two hours caused increase in the chlorophyll content of sugar beet leaves [15]. Atak et al. [16,17] also reported the positive effect of magneto-priming on soybean with an increase in chlorophyll a, b and total chlorophyll content. In the study of Baghel et al. [18] on soybean, the content of chlorophyll a, b and total chlorophyll under water stress decreased at all stages of growth; However, they found that the total chlorophyll content in the leaves of magneto-primed plants increased under non stress and water stress conditions during vegetative and flowering stages. In their study, chlorophyll b increased significantly, while chlorophyll a increased to a lesser extent after magneto-priming. Also in another study on soybean, the OJIP curve (poly phasic chlorophyll fluorescence curve) of magneto-primed leaves showed higher fluorescence yield in the J-I-P phases. An increase in the fluorescence curve after magneto-priming was described as a result of faster reduction of electron acceptors downstream of the photosynthetic pathway of photosystem II, especially plastoquinone (PQ) and Quinone A (Q_A) [19].

Currently, the use of nanoparticles in agriculture as Nano fertilizers, due to their faster and easier penetration into plant cell membranes, has attracted many researchers' attention [20]. In one study, it was found that silicon dioxide nanoparticles increased the activity of nitrate reductase enzyme and increased water use efficiency of soybean [21]. Although silicon is never considered as an essential element for plant growth, but its application in Nano and bulk forms has increased plants tolerance to various environmental stresses and crops yield [22,23]. Growth and yield parameters in water-stressed rice plants treated with SiO_2NPs were higher than water-stressed plants without SiO2NPs addition [24]. SiO_2-NPs increased the weight of potato tuber, stimulated the roots and sprout length and enhanced the chlorophyll and carotenoid content as well [25]. Nanostructured SiO_2 has been shown to be useful when applied to the roots of 1-year old *Larix olgensis* seedlings, which promoted main root length and chlorophyll content [26]. In addition, SiO_2 nanoparticles accelerated plant growth by increasing gas exchange and chlorophyll fluorescence attributes such as net photosynthesis rate, transpiration rate, stomatal conductance, electron transport rate, effective photochemical efficiency and real photochemical efficiency [27,28].

Due to the importance of this subject and the lack of information about the effects of magneto-priming and SiO_2 NPs on physiological traits affecting sesame water tolerance (such as chlorophyll content and chlorophyll fluorescence parameters) at different growth stages, the present study was carried out with the mentioned objectives.

2. MATERIALS AND METHODS

2.1 Treatment of Seeds with Magnetic Field

Local sesame seed lot was prepared from Kalat city (in Khorasan-Razavi Province, Northeast of Iran). Initially, sesame seeds were magnetically primed using a device designed to magnetize of the seeds (Fig. 1). The relationship between the magnitude of the magnetic field generated by this device and the space of two magnets from each other is shown in Fig. 2. To apply a strong and constant magnetic treatment of 75 mT, the seeds were placed in a thin polyethylene bag between the magnets for 1 hour.

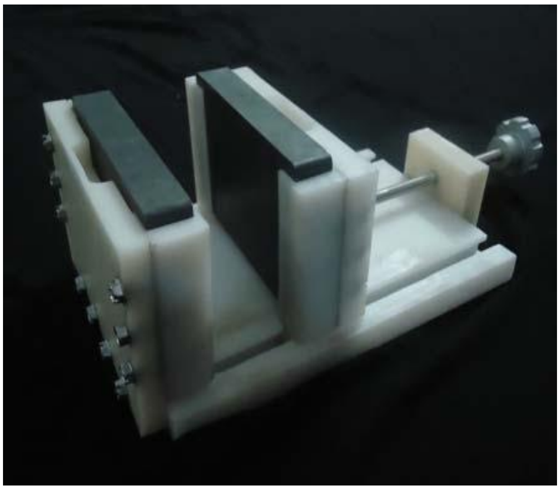

Fig. 1. A calibrated device for magnetizing of seeds [29]

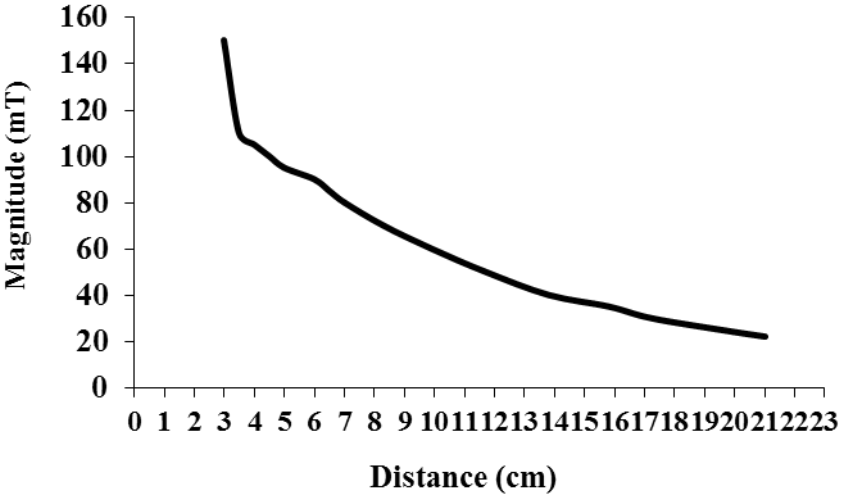

Fig. 2. Relationship between magnetic field strength and the distance between two magnets

2.1 Experimental Procedure

To study the effects of magneto-priming and silicon dioxide nanoparticles on some of physiological responses of sesame under water stress conditions, magneto-primed and unprimed sesame seeds were densely planted in 6 kg pots with equal volume of field soil and sand. Then plants were gradually thinned. The soil of the pots was disinfected by mancozeb fungicide before sowing the seeds. The greenhouse pests control operations were carried out by installing insects glue. Irrigation of plants was done every other day before the application of water stress. Water stress treatment was applied after complete establishment of plants (six leaves formation). Also, in order to investigate the effect of foliar application of SiO_2 nanoparticles on water tolerance of sesame, these treatments were applied immediately after water stress treatment. Experiment was conducted as a factorial trial in a completely randomized design with three replicates, in which the experimental treatments were two levels of irrigation (soil moisture status at 90% field capacity (FC) as control and 50% FC as water stress), There were two levels of magneto-priming (control and 75 mT treatment for one hour) and four levels of nanoparticles (control (un-application) and three concentrations of 10, 50 and 100 mg/l of SiO_2 NPs) as well.

2.2 Water Stress Treatment under Greenhouse Conditions

To determine the amount of water required for each pot in each irrigation regime, at the onset of the experiment, the amount of moisture in the soil field capacity was determined. For this purpose, three pots with similar weight and size were selected and all of them were filled with equal amounts of soil prepared for the experiment. They were then saturated with enough water and then placed under poly ethylene plastic bags to drain the water only by gravity. Their weights were then recorded every eight hours by a digital scale. When the weight fixed, the amount of water in the field capacity was determined and based on this, the amount of water required to reach the control level (90% of FC) and stress treatment (50% of FC) were also calculated. In other words, first the difference between pots weight at 100% of field capacity and similar pots with completely dry soil (Oven dried) was calculated and then 50% of it, considered as water stress (50% FC).

Then the pots were weighed daily and if their weight reached to a certain level viz. 80 and 40% FC for control and stress treatment, respectively, watering to reach the required level in control (90% FC) and water stress (50% FC) treatment was carried out.

2.3 Foliar Application and Properties of SiO_2 Nanoparticles

In this experiment, white, powdery and amorphous nanoparticles of silicon dioxide with the size of 20-30 nm and a purity of 98% made in the United States of America were used. The X-ray diffraction pattern (XRD) and the image of silicon dioxide nanoparticles taken with a transient electron microscope (TEM) are shown in Figs. 3 and 4 respectively. Nanoparticles were sprayed at the mentioned concentrations immediately after water stress treatment by a handy sprayer. The real image of the nanoparticles used in this experiment is also shown in Fig. 5. SiO_2 nanoparticles were purchased from Zist-Azma Company located at Ferdowsi University of Mashhad, Islamic Republic of Iran.

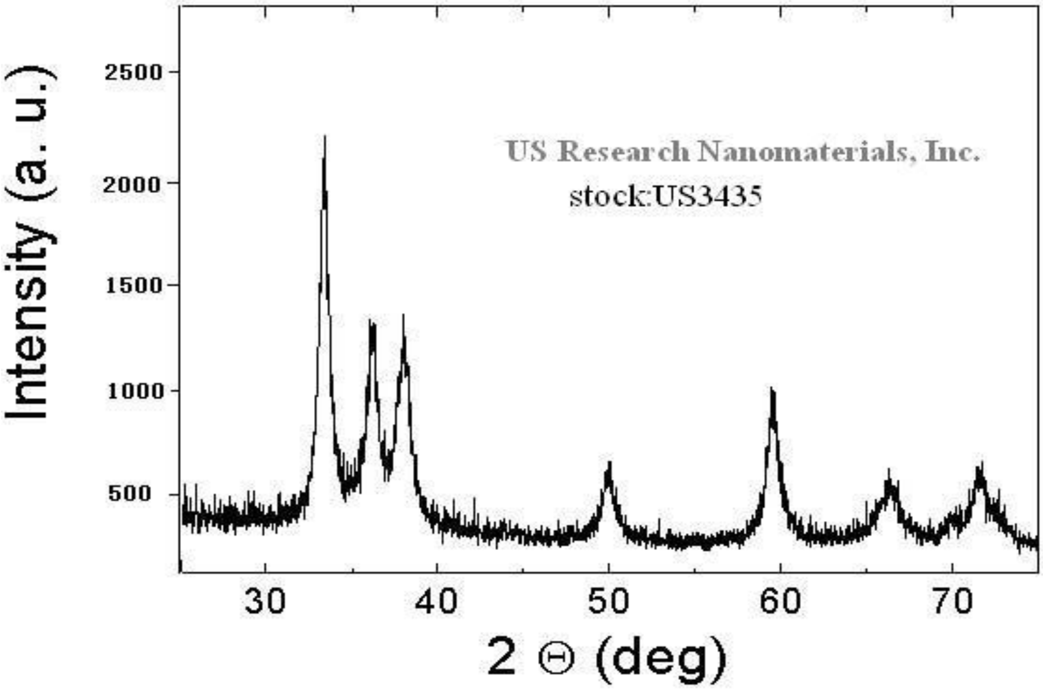

Fig. 3. X ray diffraction image of SiO_2 NPs

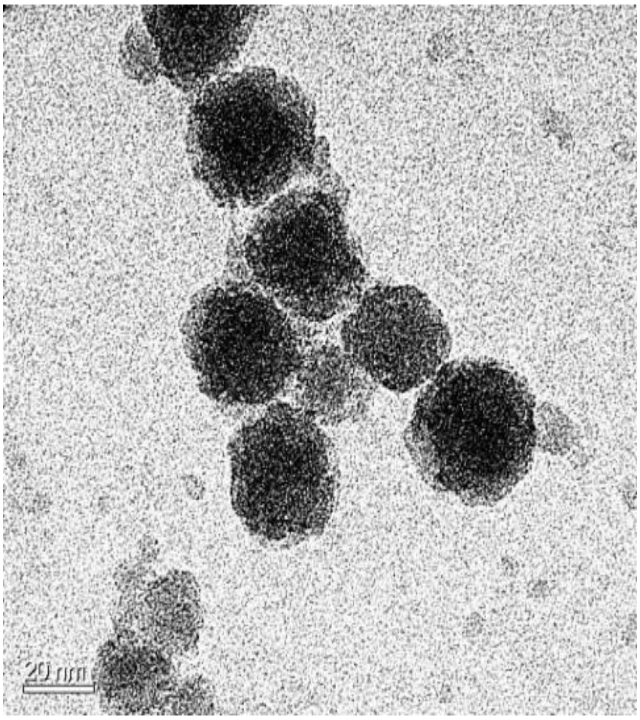

Fig. 4. Image of SiO_2 NPs prepared by TEM Microscope

Fig. 5. Close shot from SiO_2 NPs used in this experiment

2.4 Determination of Chlorophyll Content

This index was measured in two growth stages (flowering and fruit set) of sesame using the SPAD chlorophyll meter (Minolta-502 model) from upper, middle and lower parts of the fully developed sesame leaves. To increase the accuracy of each replicate, three plants were measured, and then the mean of nine data was considered as the chlorophyll content of that replication.

2.5 Determination of Chlorophyll Fluorescence Parameters

Fluorescence status of plants similar to SPAD number was measured in two stages of flowering and fruit set by a portable chlorophyll Fluorometer (model OS1-FL) from the middle part of the leaf and with a distance from the main vein of the youngest mature leaf of the plant. The measured parameters include the initial or minimum fluorescence reflectance from an adapted leaf to light when all reaction centers of PSII are open (F'o), the maximum fluorescence of an adapted leaf to light when all PSII reaction centers are closed (F'm), the variable fluorescence (F'v) and the maximum initial quantum photochemical efficiency potential of photosystem II: F'v/F'm. F'v calculated as F'm-F'o. All measurements were taken between 10 to 13 o'clock to minimize daily changes in light intensity.

2.6 Statistical Analysis

Statistical analysis of all data was done by MSTAT-C software. Finally, the shapes were drawn by MS Excel and the mean of data were compared with Duncan test at 1 and 5% probability level.

3. RESULTS AND DISCUSSION

3.1 Effects of Magneto-priming, SiO_2 Nanoparticles and Water Stress on Sesame Chlorophyll Content at Flowering Stage

In this study, the single effect of magneto-priming, silicon dioxide nanoparticles and water stress as well as the interaction effects of nanoparticles, water stress and also the interaction effects of magneto-priming, SiO_2 nanoparticles and water stress on chlorophyll content (SPAD) of sesame leaves were significant (Table 1). A comparison of the interactions of magneto-priming, SiO_2 nanoparticles and water stress on this trait at the flowering stage is shown in Fig. 6.

As can be observed, under non-stress conditions, and in un-magneto-primed plants (control), un-application of SiO_2 nanoparticles produced higher leaf chlorophyll content than application of nanoparticles at all concentrations of 10, 50 and 100 mg/L, although these differences were not significant., but in plants raised from magnetized seeds, 50 mg/l SiO_2 NPs was better than un-application of SiO_2 or other doses of nanoparticles under non-water stress conditions. Also under water stress conditions, in un-magneto-priming, 50 mg/l of SiO_2 nanoparticles and in magneto-priming treatment, 10 mg/l of SiO_2 nanoparticles, created the

Table 1. Sources of variations, degree of freedom and mean of squares of some physiological traits of magneto-primed sesame exposed to water stress and SiO_2 nanoparticles at the flowering stage.

Sources of variations		**Mean of squares**				
	Degree of freedom	**Chlorophyll content**	**Primary fluorescence**	**Maximum fluorescence**	**Variable fluorescence**	**Maximum quantum efficiency of PSII**
Magneto-priming	1	245.255^{***}	37576^{***}	45942^{***}	420^{***}	0.048133^{***}
SiO_2 Nano-particles	3	24.508^{*}	923^{***}	5776^{***}	2221^{***}	0.000194^{***}
Water stress	1	401.942^{***}	193167^{***}	859^{***}	219781^{***}	0.392408^{***}
Magneto-priming × Water stress	1	0.827^{ns}	6^{ns}	256230^{***}	258720^{***}	0.063075^{***}
Magneto-priming×SiO_2 Nano-particles	3	11.294^{ns}	301^{***}	24369^{***}	22354^{***}	0.005572^{***}
SiO_2 Nano-particles× Water stress	3	45.605^{**}	327^{***}	12334^{***}	14904^{***}	0.005025^{***}
Magneto-priming×SiO_2 NPs×Water stress	3	50.179^{**}	120^{***}	5312^{***}	6777^{***}	0.001303^{***}
Error	32	7.096	12	20	25	0.000025
Total	47					

, **, * and ns are significant at 5, 1, 0.1 probability level and non-significant respectively*

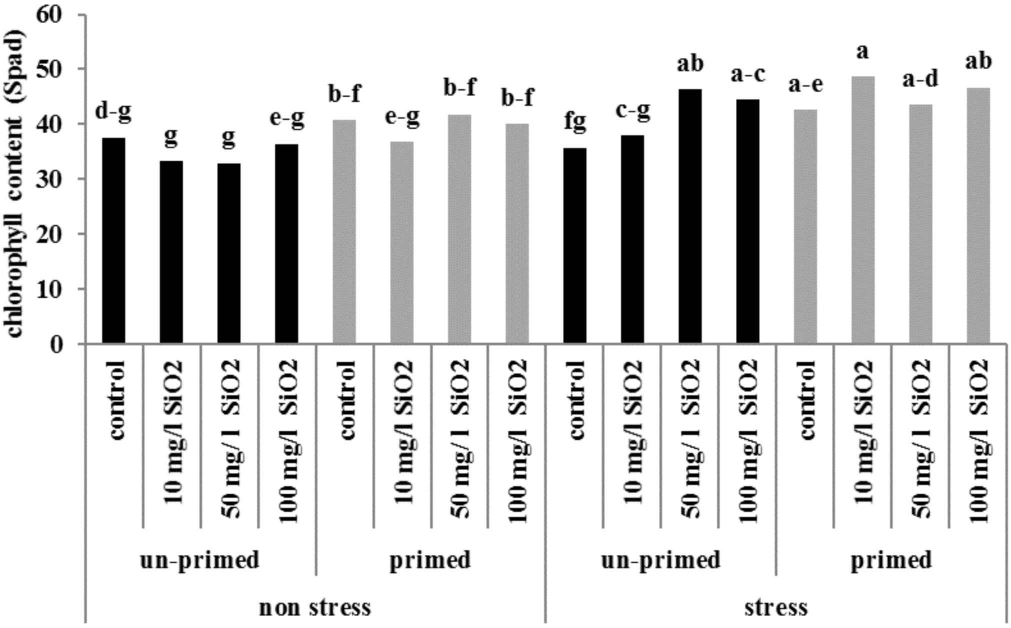

Fig. 6. Interaction effects of magneto-priming, silicon dioxide nanoparticles and water stress on the chlorophyll content of sesame at the flowering stage. Bars with the same letter have no significant difference based on Duncan's test at the 1% probability level

highest chlorophyll content in plant leaves compared to un-application of SiO_2 NPs or other doses of SiO_2 NPs. In summary, the highest chlorophyll content belonged to water stress, magneto-priming and 10 mg/l of SiO_2 NPs and the lowest rate belonged to non-stress treatment, un-magneto-priming and 50 mg/l of SiO_2 nanoparticles. In this study, in both water stress and non-stress conditions and in most of SiO_2 NPs doses, magneto-priming produced more chlorophyll content in sesame leaves than un-magneto-priming (Fig. 6).

Numerous studies have shown that magnetic fields, whether in the form of water or seeds treatment, increase the amount of chlorophyll pigments [30,31]. Magnetic fields also showed an increase in the chlorophyll content of sugar beet [32] onion [33] cotton [34] potato and wild *Solanum* species [35] soybeans and oil palms [35].

It is believed that the increase in the content of photosynthetic pigments in magnetized plants is due to the proliferation in cytokinin and auxin phytohormones synthesis, which is induced by magnetic fields. Cytokinin plays an important role in chloroplast development, shoot formation, lateral bud growth, and induction of several genes involved in nutrient metabolism for chloroplast growth [17]. Treating faba bean (*Vicia faba*) seeds with a magnetic field considerably increased the amount of indole-3-acetic acid (IAA) and Gibberellic acid (GA3) in germinating seeds as well as in the above-ground parts and roots of seedlings [36]. Furthermore the enhancement of chlorophyll and carotenoid synthesis in leaves under magnetic fields treatment, may be due to the increase in proline and GA3, which trigger the accumulation of Mg^{2+} for chlorophyll synthesis [37] and K^+ which leads to increase the number of chloroplasts [38]. This may eventually lead to increase in the thickness of mesophyll tissue [39].

It has also been reported that treatment of irrigation water with magnetic fields increased the uptake of nutrients such as nitrogen, potassium, calcium, magnesium, sulfur, zinc, iron and manganese in chickpea seedlings. In chlorophyll, magnesium is the central ion, and porphyrin is a large organic molecule consisting of four nitrogen atoms that forms bonds with magnesium in an annular arrangement, so magnetized water by enhancement of absorption in nitrogen and magnesium elements, stimulates the chlorophyll formation [40]. It seems that magneto-priming has similar effects on chlorophyll synthesis.

In this study, magneto-priming in both non-stress and water stress conditions and in most concentrations of SiO_2 nanoparticles increased the chlorophyll content of sesame leaves compared to un-priming (Fig. 6). An increase in chlorophyll content was also observed in soybean plants derived from magneto-primed seeds under water stress and non-water stress conditions [18]. In mentioned study, seed magneto-priming increased the chlorophyll content by 40% in the reproductive phase compared to untreated plants under non-water stress conditions, and the increase in total chlorophyll content in the reproductive phase was due to a further increase in chlorophyll b (about 82%) compared with chlorophyll a. Also, under water stress conditions, magneto-priming caused a 72% increase in total chlorophyll content in the vegetative phase (30 days after emergence) and 34% in the reproductive phase (40 days after emergence) compared to un-primed plants [18]. In similar studies, magneto-priming increased chlorophyll content in soybeans under salt stress conditions [41, 42].

As shown in Fig. 6, except in un-application of SiO_2 NPs and un-magneto-priming treatment, where water stress reduced the chlorophyll content, water stress caused a relatively significant increase in sesame leaf chlorophyll content at all doses of SiO_2 nanoparticles in the magneto-priming and un-priming treatments. In fact, the effect of water stress on chlorophyll is very diverse and depends on the severity of stress, environmental conditions and plant genotype and even its growth stage. In some plant species, water stress decreased chlorophyll content but in others increased it. Anjum et al. [43] reported that water stress increased the total amount of chlorophyll in barley.

In our experiment, the effect of SiO_2 nanoparticles on increment of chlorophyll content was higher than un-application of SiO_2 in both magneto-priming and un-priming treatments especially under water stress conditions. In other words, foliar application in all three concentrations of NPs (10, 50 and 100 mg/l) produced more leaf chlorophyll content than un-application in both magneto-priming and un-magneto-priming treatments under water stress conditions, which shows the positive role of SiO_2 nanoparticles in pigments production (Fig. 6).

The positive effect of silicon and SiO_2 NPs on leaf chlorophyll content has also been reported by some researchers [44,45]. Maghsoudi et al. [46] reported that water stress caused a significant decrease in chlorophyll a and b content in four wheat cultivars, but application of silicon significantly changed the chlorophyll content and increased chlorophyll a and b in all wheat cultivars. In another study, silica nanoparticles improved germination, stem and root growth rate, relative leaf water content and photosynthetic pigments of maize [47].

Also in a similar study on wheat exposed to salinity stress, the chlorophyll a, b and total chlorophyll content in leaves increased significantly with silicon treatment and the highest effect of silicon obtained in non-stress conditions and at a concentration of 0.25 mM. But under salinity stress, the level of 0.5 mM had the greatest effect on these traits [44].

3.2 Effects of Magneto-priming, SiO_2 Nanoparticles and Water Stress on Chlorophyll Fluorescence Parameters at Flowering Stage

ANOVA showed that at flowering stage of sesame, the single and almost all interaction effects of magneto-priming, water stress and silicon dioxide nanoparticles on minimum fluorescence (F'o), maximum fluorescence (F'm), variable fluorescence (F'v) and F'v/F'm ratio or the maximum quantum electron transfer performance of photosystems II were significant (Table 1). As shown in Figure 7, magneto-priming in both non-stress and water stress conditions and at all doses of silicon dioxide nanoparticles, caused a significant reduction in the amount of initial (minimum) fluorescence of sesame leaves, compared to un-priming. Also, in both water stress and non-stress conditions, and in magneto-priming treatment, the lowest amount of F'o obtained at 100 mg/l of SiO_2 nanoparticles. In the un-magneto-priming and in non-water stress conditions, no significant difference was observed between the Nanoparticles doses on F'o, while in water stress conditions, minimum fluorescence at 100 mg/l of SiO_2 nanoparticles was lower than un-application of SiO_2 and two other doses of SiO_2 NPs in un-priming (Fig. 7).

In this study, the lowest F'o was observed in magneto-priming, non-water stress and 100 mg/l SiO_2 NPs and the highest F'o was recorded at water stress, un-magneto-priming and 10 mg/l SiO_2 NPs (Fig. 7). In addition, as shown in Figure 7, water stress in both magneto-priming and un-priming treatments and at all SiO_2 NPs doses significantly increased the minimum fluorescence.

Chlorophyll fluorescence is a red and far-red light (650-800nm) that re-emitted in a few nanosecond after being absorbed by chlorophyll molecules of plant leaves [48,49],. By measuring the intensity and nature of this light, plant photochemistry and Eco-physiology can be investigated. Light energy (photon) that has been absorbed by a leaf will excite electrons in chlorophyll molecules and PSII. Energy in photosystem II can be converted to chemical energy to drive photosynthesis (photochemistry). If photosynthesis (photochemistry) is inefficient, excess energy can damage the leaf. Energy can be emitted in the form of heat (non-photochemical quenching) or emitted as chlorophyll fluorescence. These three processes are in competition, so fluorescence yield is high when less energy is emitted as heat or used in photochemistry. Therefore, by measuring the amount of chlorophyll fluorescence, the efficiency of photochemistry and non-photochemical quenching (NPQ) can be assessed too [50,51].

Fluorescence rises to a minimal level of fluorescence called Fo level immediately after exposure to light, which at this time all of the PSII reaction centers are in the ‘open’ state (since QA, the primary electron acceptor of PSII, is maximally oxidized). The fluorescence then rises rapidly to the transient level, Fj and Fi, before reaching to a peak level, Fp or Fm. The difference between Fm and Fo is called the variable fluorescence or Fv. Fv shows the complete reduced state of primary electron acceptor Q_A. Changes in the fluorescence level between Fi and Fp are almost entirely due to more reduction of the plastoquinone pool, which is largely determined by the relative rates of PSII photochemistry and oxidation of plastoquinol by electron transfer to PSI [52].

It should be noted that when the light intensity is moderate, most of it is spent on photochemical activity (photosynthesis) and a small part of the sun's energy is emitted in the form of minimum fluorescence [53]. So the increase in minimum fluorescence yield indicates damage to the electron transfer chain of photosystem II due to a decrease in the capacity of Q_A and its complete lack of oxidation due to slow flow along the path of photosystem II and total inactivation of photosystem II as well [54].

Significant increase in minimum fluorescence in water stressed plants in our experiment, may indicate that photosystem II has different performance in different irrigation regimes, and perhaps the severity of stress in this experiment was so high that it could destroy photosystem II reaction centers. Because the increase in minimum fluorescence indicates the destruction of the reaction centers of photosystem II, changes in its structure and even changes in the pigments of photosystem II, under water stress conditions [55]. Baker and Rosenqvist [52] also suggested that an escalation in minimum fluorescence could be a sign of damage to the photosystem II reaction center, which has reduced the absorption of light and consequently caused an increase in unused and emitted light. In general, the lower of Fo value displays the faster carbon fixation or beginning of electron transfer. Environmental stresses cause a sharp increase in primary fluorescence by creating structural changes and damage to the reaction centers of photosystem II [56] which is similar to the results of our experiment.

However, it should be noted that water stress does not create significant changes in Fo alone and usually heat stress alone or with water stress can cause destruction in the reaction center of photosystem II [57]. Because our experiment was performed in greenhouse conditions and in summer season, the ambient temperature was probably high at the time of chlorophyll fluorescence measurement and has intensified the effect of water stress on increasing this parameter by creating heat stress. Increased primary fluorescence due to water stress has been reported by other researchers as well [58,59].

Investigation of the interaction effects of magneto-priming, water stress and silicon dioxide nanoparticles on maximum fluorescence showed that in the non-water stress conditions, magneto-priming at all doses of SiO_2 nanoparticles reduced the maximum fluorescence compared to un-magneto-priming, while in the water stress conditions, superiority of magneto-primed plants to un-primed ones was obvious (Fig. 7). In other words magneto-priming increased the maximum fluorescence of sesame in all doses of SiO_2 NPs in comparison to un-magneto-priming under water stress conditions.

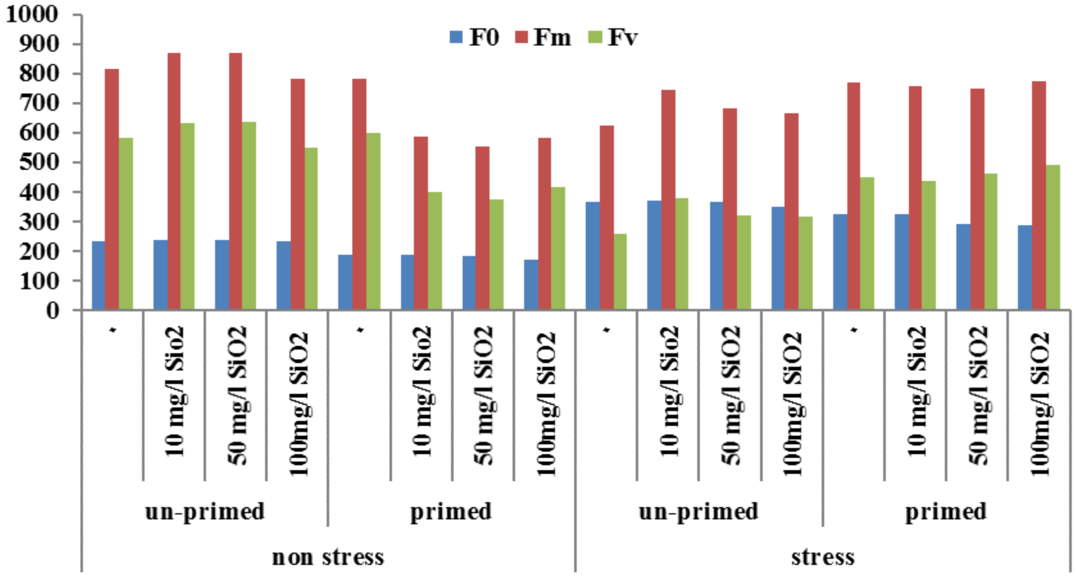

Fig. 7. Interaction effects of magneto-priming, water stress and SiO_2 nanoparticles on the chlorophyll fluorescence parameters of sesame at the flowering stage

The most amount of F'm was in the non-stress conditions, un-magneto-priming and 50 mg/l SiO_2 NPs and the lowest F'm was in the non-stress conditions, magneto-priming and foliar application of SiO_2 NPs with similar dose (Fig. 7). Also, maximum fluorescence decreased under water stress in un-priming and at all SiO_2 NPs doses; but, in magneto-priming, F'm, in most doses of SiO_2 nanoparticles, was even higher in the water stress conditions in comparison to non-water stress (Fig. 7). In other words water stress reduced the maximum fluorescence at all doses of nanoparticles in the un-priming, but except in un-application of SiO_2, spraying with three concentrations of 10, 50 and 100 mg/l of SiO_2 NPs increased F'm in magneto-priming treated plants in water stress conditions compared to non-water stress conditions (Fig. 7).

The ability of the maximum fluorescence in the leaves indicates the high capacity of photosystem II to release electrons after a light saturation pulse, so that the reducing capacity of the electron acceptors such as Q_A was lower than that of the released electrons [50]. It seems that, magneto-priming alone or magneto-priming with SiO_2NPs increased the ability of plants to ameliorate the harmful effects of water stress on photosynthesis by increasing the Fm.

Analysis of the interaction effects of magneto-priming, water stress and SiO_2 nanoparticles on variable fluorescence showed that in the non-water stress conditions, magneto-priming is better than un-priming only in control (un-application of SiO_2 NPs), but in the water stress conditions, at all doses of SiO_2 NPs, magneto-priming is better than un-priming in variable fluorescence (Fig. 7). Water stress also caused a significant decrease in variable fluorescence, especially in the un-magneto-priming and at all doses of SiO_2 nanoparticles, while in magneto-priming treatment, variable fluorescence at concentrations of 10, 50 and 100 mg/l of SiO_2 nanoparticles under water stress even more than non-stress conditions (Fig. 7).

At the flowering stage, the highest and the lowest variable fluorescence belonged to the treatments of un-priming, non-stress and 50 mg/l of SiO_2 NPs and un-priming, water stress and un-application of SiO_2 NPs respectively. In general, water stress reduced variable fluorescence, especially in the un-magneto-priming and in most doses of SiO_2 nanoparticles (Fig. 7).

Basically, Fm is high when the electron acceptor (Q_A) is in the reduced state, and therefore the value of Fv also increases; but when quinone A is in the oxide state, the amount of chlorophyll fluorescence and Fv decreases. Environmental stresses reduce the amount of Fv due to inhibition of photosystem II photooxidation. Since Fv represents the complete reduction of quinone, it can be inferred that water stress has disrupted electron transfer to photosystem I, especially in un-magneto-primed plants.

Interaction effects of magneto-priming, water stress and SiO_2 Nano-particles on F'v/F'm ratio was significant too (Table 1). Fig. 8 displays that in non-water stress conditions, seed magneto-priming, especially in the un-application of SiO_2 NPs performed better than un-magneto-priming on the maximum quantum efficiency of photosystem II. While under water stress conditions, we observed a significant increase in the F'v/F'm ratio at all SiO_2 nanoparticles doses in magneto-priming treatment compared to un-priming. Also, at the flowering stage, the highest and the lowest maximum quantum efficiency of photosystem II were observed in magneto-priming, non-stress and un-application of SiO_2 NPs and un-priming, water stress and un-application of SiO_2 NPs, respectively (Fig. 8). In the latter treatment, the F'o was higher, which reduced F'v as a component of fraction and therefore reduced this ratio (Fig. 8).

In general, high quantum yield of photosystem II indicates the high capacity of electron release to produce energy in the light cycle [50] so it seems that in the magneto-priming and in non-water stress conditions and un-application of SiO_2 NPs and un-Priming, non-water stress and two concentrations of 10 and 50 mg/l of SiO_2 NPs, this event has occurred. Notable point in this experiment is a significant decrease in the F'v/F'm in both magneto-priming and un-magneto-priming treatments and in all doses of SiO_2 NPs under water stress conditions (Fig. 8). Meng et al. [60] also reported that water stress significantly reduced the fluorescence properties of chlorophyll in the leaves of *Plectranthus scutellarioides* by stopping electron transfer and reducing the photochemical activity of photosystem II. The parameters most affected by water and salinity stress were the time required to reach maximum chlorophyll fluorescence (Fm), Fv/Fm ratio, and PIabs [60, 61].

Under water stress conditions, the accumulation of non-reduced Q_B increases, indicating that electrons were not transferred from Q_A to Q_B. Under such conditions, the accumulation of Q_A also increases. The reason is not yet clear; however, reducing of carbon dioxide assimilation due to closed stomata under water stress may lead to un-consumption of electron transfer chain products (ATP and NADPH), thereby cause increase in the amount of reduced ferredoxin, followed by Increase in the production of active radicals and thereby alter or degrade thylakoid membrane proteins. Definitely, degradation of thylakoid membrane proteins inhibit electron transfer from the photosystem II acceptor site, reduce electron transfer rate, increase chlorophyll fluorescence (Fo), and decrease the maximum quantum yield of photosystem II [62,63]. In general, changing the activity of photosystem II and also destroying the structure of D1 protein in PSII, increase chlorophyll fluorescence under water stress conditions [64]. The decrease in electron transfer rate and quantum yield of PSII under water stress conditions may be due to the disruption of the Calvin cycle, delay in the reduction of quinones, and destruction of the electron transfer chain of the thylakoid membrane [63]. In one experiment, the Fv/Fm ratio of chickpea genotypes was significantly reduced due to water stress, and more sensitive genotypes had lower Fv/Fm ratios [65]. Similar results were reported by Xu et al. [59] on rice plant. In another experiment on soybeans conducted by Baghel et al. [18] magneto-primed plants showed more active reaction centers with higher electron transfer efficiency under non-water stress and water stress conditions during vegetative and reproductive growth stages. In their study, magneto-primed plants recovered after water stress showed a higher Fv/Fm ratio compared to un-primed plants under stress conditions, especially in the reproductive phase. Also in their study and under stress conditions, electron transfer in cross section of leaves (ETo/CSm) of un-primed plants was further reduced in the reproductive phase, while magneto-priming treatment significantly improved this index by 43% in the reproductive phase. In maize, treatment of seeds by electromagnetic field with densities of 100 and 150 mT for 10 minutes reduced the harmful effects of water stress on growth by improving the efficiency of photosystem II [47].

In our experiment, in water stress conditions and in both un-priming and magneto-priming treatments, application of SiO_2 nanoparticles increased the F'v/F'm ratio compared to un-application of SiO_2 NPs. Therefore, it seems that the use of SiO_2 nanoparticles had a positive effect on this trait especially under water stress conditions (Fig. 8).

Other studies also showed that Photosystem I and II can be revitalized by foliar application of Silicon [66]. Some researchers stated that Si application improves pigment quality and photosystem II efficiency of some of plants such as *Spartina densiflora* (a C4 plant) under salt stress conditions [66, 67,68].

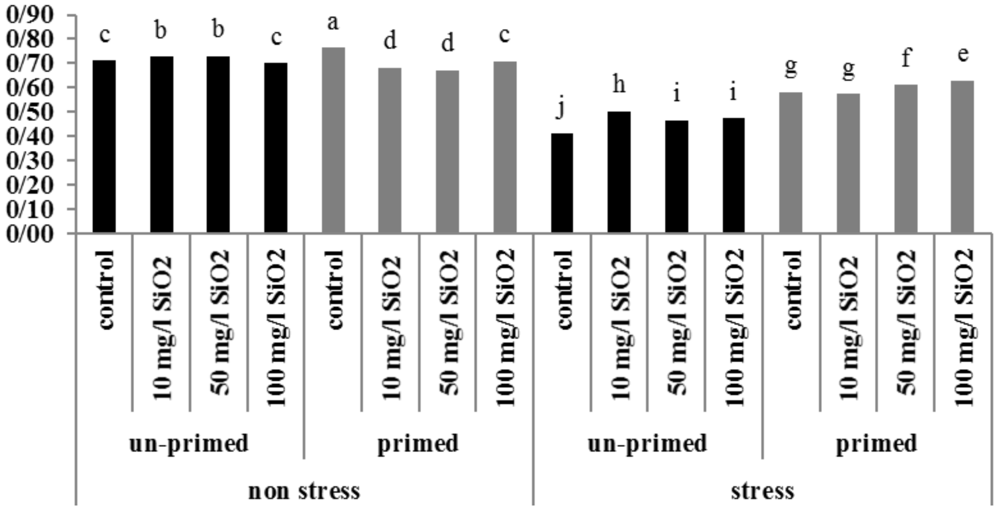

Fig. 8. Interaction effects of magneto-priming, SiO_2 nanoparticles and water stress on the maximum quantum efficiency of photosystem II at flowering stage of sesame. Bars with the same letter have no significant difference based on Duncan's test at the 1% probability level

3.3 Effects of Magneto-priming, SiO_2 Nanoparticles and Water Stress on Sesame Chlorophyll Content at Fruit Set Stage

None of experimental factors had a significant effect on the chlorophyll content of sesame leaves at the fruit set stage (data are not shown); nevertheless, an important point was the increase in chlorophyll content at all levels of the trial factors in the fruit set stage compared to the flowering stage. Therefore, it seems that the chlorophyll content has increased with the aging of sesame plants. Similar results were reported by Xu et al. on rice plant [59].

3.4 Effects of Magneto-priming, SiO_2 Nanoparticles and Water Stress on Sesame Chlorophyll Fluorescence Parameters at Fruit Set Stage

Similar to the flowering stage, the interaction effects of magneto-priming, water stress and silicon dioxide nanoparticles on all parameters of chlorophyll fluorescence in fruit set stage of sesame were significant (Table 2). Comparison of means at this stage showed that under control (non-water stress) conditions, magneto-priming at all doses of SiO_2 nanoparticles significantly reduced the minimum fluorescence of sesame leaves compared to un-magneto-priming and almost the same trend was observed under water stress conditions (Fig. 9).

In addition water stress caused a significant increase in primary fluorescence, in both magneto-priming and un-priming treatments and in all doses of silicon dioxide NPs (Fig. 9). Furthermore, in non-stress conditions, in both magneto-priming and un-priming treatments, foliar application of SiO_2 nanoparticles significantly reduced the primary fluorescence, compared to un-application of SiO_2 NPs, while in water stress conditions, foliar application of SiO_2 NPs at doses of 10, 50 and 100 mg/l caused further increase of F'o in un-priming treatment compared to un-application; but, in magneto-priming treatment, application of SiO_2 NPs with the mentioned doses compared to un-application, caused reduction in the amount of minimum fluorescence (Fig. 9), which showed the positive role of magneto-priming and SiO_2 nanoparticles in mitigating the adverse effect of water stress on primary fluorescence.

In this study, the lowest and the highest primary fluorescence belonged to magneto-priming, non-stress and 50 mg/l of SiO_2 nanoparticles and un-priming, water stress and 100 mg/l of SiO_2 nanoparticles respectively (Fig. 9).

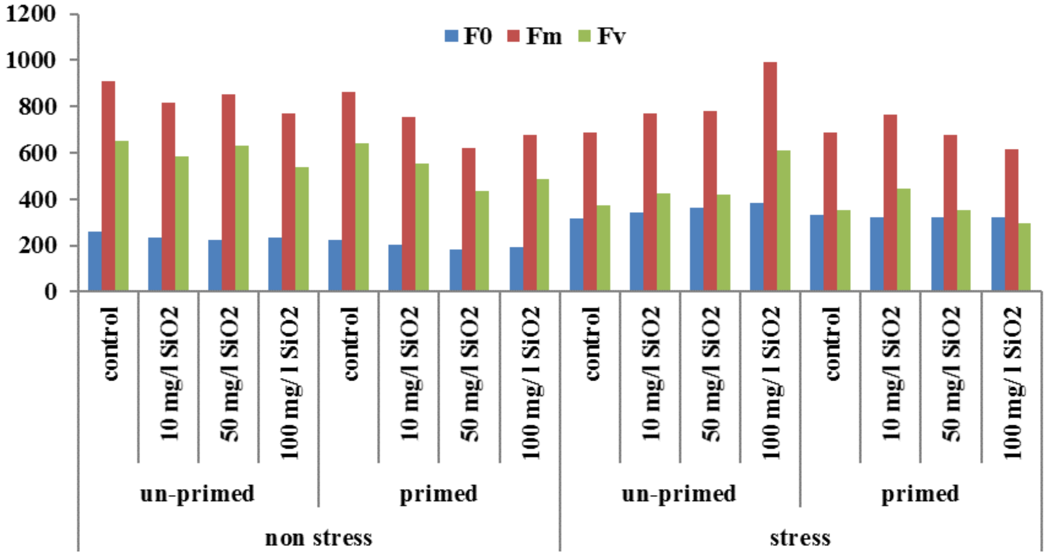

Fig. 9. Interaction effects of magneto-priming, SiO_2 nanoparticles and water stress on fluorescence parameters at fruit set stage in sesame

The interaction effects of magneto-priming, water stress and SiO_2 NPs on maximum fluorescence is shown in Figure 9. As can be seen, in the non-water stress conditions, seed magneto-priming at all doses of SiO_2 NPs significantly reduced the maximum fluorescence compared to the un-priming, and the same trend was observed almost in the water stress conditions. In other words, magneto-priming in both non-stress and water stress conditions and in almost all concentrations of SiO_2 nanoparticles, caused a significant reduction in the maximum fluorescence. Furthermore in water stress conditions, especially in un-priming, we observed a decrease in F'm in all levels of SiO_2 NPs except 100 mg/l compared to non-stress conditions, while in magneto-priming treatment only in un-application of SiO_2 NPs and 100 mg/l of nanoparticles, the water stress caused a significant decrease in maximum fluorescence compared to non-stress conditions (Fig. 9). In our experiment, the highest F'm belonged to the un-magneto-priming, water stress and 100 mg/l of SiO_2 NPs and the lowest belonged to the magneto-priming, water stress and 100 mg/l of SiO_2 NPs treatment (Fig. 9).

In Joshi [69] study on soybeans, fluorescence yield was higher in phase I and P, in magneto-primed plants. Also, fluorescence yield in phase I increased by 7.4% and 10.4% in 150 and 200 mT treatments, respectively, and in P (Fm) phase, this yield increased by 9.7% and 15.9%, respectively, compared to the control. The increase in chlorophyll fluorescence curve after magnetic treatment in his study was attributed to the faster reduction of electron acceptors downstream of photosynthetic pathway of photosystem II, especially plastoquinone (PQ) and Q_A, and the decrease in Fm in the control (un-priming) in his study attributed to a decrease in the number of photosystem II reaction centers present for the reduction of Q_A. Also, the decrease in fluorescence in the control treatment was due to the slow flow of electrons and the decrease in the cross section of absorption.

But, in our study, the F'm was reduced in magneto-priming treatment, compared to un-magneto-priming in both water stress and non-stress conditions and also in all doses of SiO_2 nanoparticles, so our study results are in conflict with the Joshi [69] results. Water stress reduced F'm in both magneto-primed and un-primed plants almost in all doses of Sio2 NPs.

Under non-water stress conditions, Sio2 NPs decreased the F'm compared to un-application of Sio2 NPs in magneto-primed plants and un-primed ones. But under water stress conditions Sio2 NPs at all doses increased F'm particularly in un-primed plants in comparison to un-application of Sio2 NPs. In Maghsoudi et al [46] study, water stress reduced the maximum and variable fluorescence of photosystem II in all wheat cultivars. They also found that silicon application increased all of these parameters in water-stressed plants compared to untreated ones.

Table 2. Sources of variance, degree of freedom and mean of squares of some physiological traits of magneto-primed sesame exposed to water stress and SiO_2 nanoparticles at fruit set stage

Sources of variations	Degree of freedom	Mean of squares			
		Primary fluorescence	Maximum fluorescence	Variable fluorescence	Maximum quantum efficiency of PSII
Magneto-priming	1	12384***	159737***	83167***	0.002852***
SiO_2 Nano-particles	3	250***	6643***	5284***	0.000958***
Water stress	1	171244***	15373***	289231***	0.376302***
Magneto-priming×Water stress	1	305***	438***	1474 ***	0.005419***
Magneto-priming×SiO_2 Nano-particles	3	999***	32449***	23128***	0.003347***
SiO_2 Nano-particles × Water stress	3	2124***	41168***	25897***	0.001497***
Magneto-priming×SiO_2 NPs× Water stress	3	720***	25336***	22264***	0.005158***
Error	32	6	14	16	0.000025
Total	47				

, **, * and ns are significant at 5, 1, 0.1 of probability level and non-significant respectively*

The interaction effects of magneto-priming, SiO_2 nanoparticles and water stress on variable fluorescence is shown in Fig. 9. As can be seen, in the non-water stress conditions, magneto-priming caused less F'v than un-magneto-priming in all doses of SiO_2 NPs. Also, under water stress, at all concentration of SiO_2 nanoparticles except 10 mg/l, magneto-priming caused a significant decrease in the amount of variable fluorescence compared to the un-magneto-priming (Fig. 9). Water stress also significantly reduced the variable fluorescence in both magneto-priming and un-priming treatments and almost in most concentrations of SiO_2 nanoparticles (Fig. 9). In summary, the maximum and minimum of F'v were recorded in two treatments of un-magneto-priming, non-stress and un-application of SiO_2 nanoparticles and magneto-priming, water stress and 100 mg/l of SiO_2 nanoparticles, respectively (Fig. 9).

The interaction effects of magneto-priming, water stress and silicon dioxide nanoparticles on F'v/F'm ratio is revealed in Fig. 10. As can be seen, the maximum photochemical efficiency of photosystem II in two treatments of un-magneto-priming, non-water stress and 50 mg/l SiO_2 nanoparticles and the treatment of magneto-priming, non-stress and un-application of SiO_2 NPs are similar and maximum. The lowest F'v/F'm ratio was observed in the treatment of magneto-priming, water stress and 100 mg/l of SiO_2 nanoparticles (Fig. 10).

Also, a look at Fig. 10 shows that in the non-water stress conditions, magneto-priming except at dose of 50 mg/l of nanoparticles caused a significant increase in the F'v/F'm ratio in comparison to un-priming. But under water stress conditions, magneto-priming was superior to un-magneto-priming in this index only at 10 mg/l of nanoparticles. In other words, the F'v/F'm ratio in magneto-priming treatment under water stress conditions and in all doses of nanoparticles except 10 and 50 mg/l was lower compared to un-priming (Fig. 10).

In Rathod study on two wheat cultivars, the Fv/Fm ratio in magneto-primed plants was lower than un-primed cultivars under salt stress conditions [13]. In Joshi [69] study on soybeans, the Fv/Fm ratio did not show a significant difference between control and magneto-priming treatment. Also Javed et al. [47] reported that magneto-priming did not have effect on Fv/Fm ratio of maize under water stress conditions.

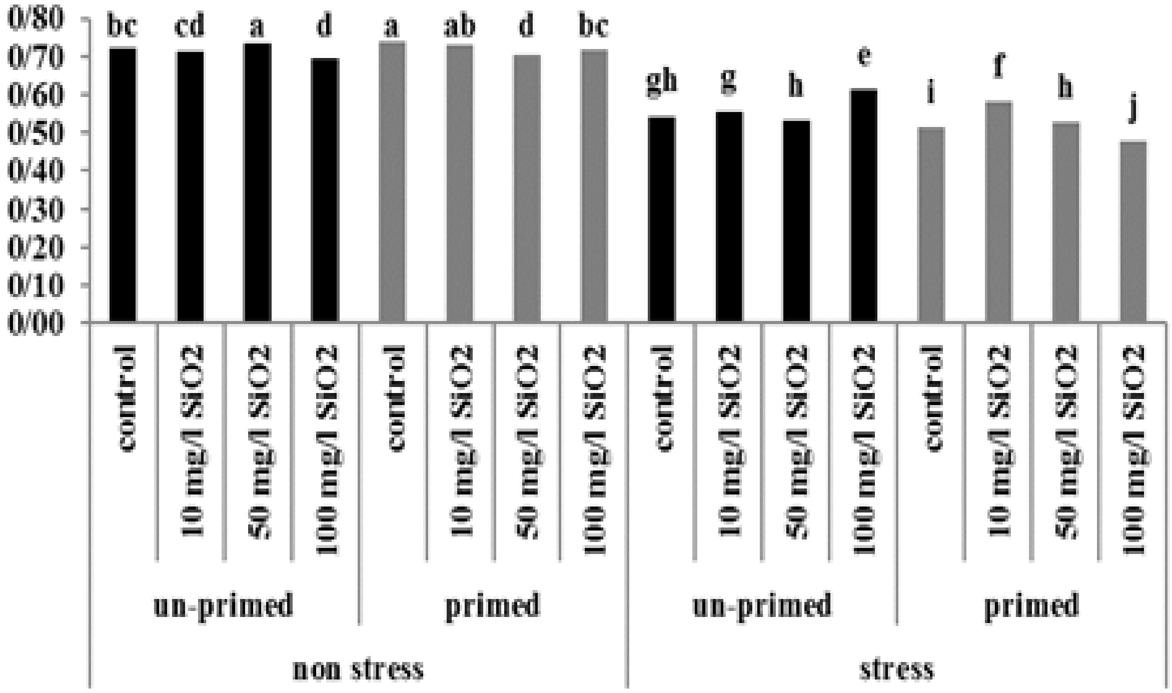

Fig. 10. Interaction effects of magneto-priming, SiO_2 NPs and water stress on F'v/F'm ratio at fruit set stage in sesame. Bars with the same letter have no significant difference based on Duncan's test at the 1% probability level

In our experiment, water stress reduced the F'v/F'm ratio in all treatments (Fig. 10). Similar results were reported by Xu et al. on rice plant [59]. Maximum quantum yield of photosystem II (F'v/F'm ratio) is highly dependent on the amount of leaf water, and since water stress reduced leaf water content, this ratio also decreased (data are not shown).

4. CONCLUSION

Results of this experiment showed that at the flowering stage, the chlorophyll content of sesame, under non-water stress and water stress conditions, in magneto-priming treatment and almost in all concentrations of SiO_2 nanoparticles, were higher than un-magneto-priming. In addition, at this stage, we observed a significant increase in F'm and F'v/F'm ratio at all doses of SiO_2 nanoparticles in magneto-primed plants compared to un-primed ones, under water stress conditions. Also at the fruit set stage, magneto-priming almost at all doses of SiO_2 nanoparticles significantly reduced the minimum, maximum and variable fluorescence of sesame leaves compared to un-magneto-priming under non-water stress and water stress conditions. Under water stress conditions, SiO_2 nanoparticles increased the F'm and F'v especially in un-magneto-primed plants compared to un-application of SiO_2 NPs. The maximum of F'v/F'm ratio was in two treatments of un-magneto-priming, non-stress and 50 mg/l SiO_2 NPs and also the magneto priming, non-stress and un-application of SiO_2 NPs treatment. These cases probably indicate the positive effect of single and combined application of magneto-priming and SiO_2 NPs on some physiological characteristics associated with sesame water tolerance, under controlled conditions particularly at flowering stage of sesame which is more susceptible to water stress. Despite this for better understanding of magneto-primed sesame response to water stress after applying SiO_2 NPs, further studies and more research under controlled and field conditions are required.

ACKNOWLEDGEMENT

Authors greatly acknowledge Dr. Ebrahim Izadi Darbandi for his help in providing some of the experimental materials. In addition, we would like to express our appreciation to the admired staff of the research greenhouse and also to the head of the Crop Physiology Laboratory of the Faculty of Agriculture, Ferdowsi University of Mashhad, because of their cooperation in carrying out of this research project.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Shelden MC, Roessner U. Advances in functional genomics for investigating salinity stress tolerance mechanisms in cereals. Frontiers in Plant Science. 2013;4:123.
2. Godfray HCJ, Beddington JR, Crute IR, Haddad L, Lawerence D, Muir JF, Toulmin C. Food security : the challenge of feeding 9 billion people. Science. 2010;327(5967):812-818.
3. Uzun B, Ulger S, Cagirgan MI. Comparison of determinate and indeterminate types of sesame for oil content and fatty acid composition. Turkish Journal of Agriculture and Forestry. 2002;26(5):269- 274.
4. ASGA. Sesame Markets; 2011. Available: http://www.sesamegrowers.org/usesofsesame.htm.
5. FAOSTAT. Food and Agriculture of the United Nations; 2002. Available: http://faostat.fao.org
6. Orruno E, Morgan MRA. Purification and characterization of the 7S globulin storage protein from sesame (*Sesamum indicum* L.). Food Chemistry. 2007;100:926-934.
7. Khajeh-Poor MR. Industrial crops production. Isfahan Industrial University Press. [In Persian]; 2006.
8. Ashraf M, Foolad RM. Pre-sowing seed treatment-a shot gun approach to improve germination, plant growth and crop yield under saline and non-saline conditions. Advances in Agronomy. 2005;88: 223-271.
9. Uchida A, Jagendorf AT, Hibino T, Takabe T. Effects of hydrogen peroxide and nitric oxide on both salt and heat stress tolerance in rice. Plant Science. 2002;163:515–523.
10. Harris D, Rashid A, Miraj G, Arif M, Shah H. Priming seeds with Zinc sulfate solution increases yields of maize (*Zea mays*) on Zinc deficient soils. Field crop Research. 2007;102:119-127.
11. Pill WG, and Necker AD. The effects of seed treatments on germination and

establishment of Kentucky bluegrass (*Poa pratense*). Seed Science and Technology, 2001; 29: 65-72.

12. Chen K, Fessehaie A, Arora R. Dehydrin metabolism is altered during seed osmopriming and subsequent germination under chilling and desiccation in *Spinacia oleracea* L. cv. Bloomsdale: Possible role in stress tolerance. Plant Science. 2012;183**:**27–36.
13. Rathod GR. Effect of magneto-priming on carbohydrate metabolism under salinity in wheat (*Triticum aestivum* L.). Master of Science Thesis. Post-Graduate School, Indian Agricultural Research Institute, New Delhi, India; 2013.
14. Zúñiga O. Benavides JA. Ospina-Salazar DI. Jiménez CO. Gutiérrez MA. Magnetic treatment of irrigation water and seeds in agriculture. Ingeniería y Competitividad. 2016;18(2):217 – 232.
15. Rochalska M. Influence of frequent magnetic field on chlorophyll content in leaves of sugar beet plants. Nukleonika. 2005;50 (2):25-28.
16. Atak Ç. Çelik O. Olgum A. Alikamanoğlu S. Rzakoulieva A. Effect of magnetic field on peroxidase activities of soybean tissue culture. Biotechnology and Biotechnological Equipment, 2007;21:166–171.
17. Atak Ç. Emiroğlu O. Alikamanoğlu S. Rzakoulieva A. Stimulation of regeneration by magnetic field in soybean (*Glycine max* L. Merrill) tissue cultures. Journal of Cell and Molecular Biology. 2003;2:113–119.
18. Baghel L, Kataria S, and Guruprasad K.N. Effect of static magnetic field pretreatment on growth, photosynthetic performance and yield of soybean under water stress. *Photosynthetica,* 2018; *56:718–730.*
19. Shine MB, Guruprasad KN, Anand A. Superoxide radical production and performance index of Photosystem II in leaves from magneto-primed soybean seeds. Plant Signaling and Behavior. 2011;6(11):1635-1637.
20. Derosa MR, Monreal C, Schmitzer M, Walsh R, Sultan Y. Nanotechnology in fertilizers. Nat Nanotechnology. 2010;1:193-225.
21. Lu CM, Zhang CY, Wu JQ, Tao MX. Research of the effect of nanometer on germination and growth enhancement of *Glycine max* and its mechanism. Soybean Science. 2002;21:168-172.
22. Yavaş İ, Ünay A. The role of silicon under biotic and abiotic stress conditions. Türkiye Tarımsal Araştırmalar Dergisi. 2017;4(2):204-209.
23. Yassen A, Abdallah E, Gaballah M, Zaghloul S. Role of silicon dioxide nano fertilizer in mitigating salt stress on growth, yield and chemical composition of cucumber (*Cucumis sativus* L.). International Journal of Agricultural Research. 2017;12 (3):130-135.
24. Elshayb OM, Abdelwahed MNM, Ibrahim H, Amin HE, Atta AM. Application of silica nanoparticles for improving growth, yield, and enzymatic antioxidant for the hybrid rice ehr1 growing under water regime conditions. Materials. 2021;14:1150.
25. Mushinskiy AA, Aminova EV, Korotkova AM. Evaluation of tolerance of tubers *Solanum tuberosum* to silica nanoparticles. Environ Sci Pollut Res Int. 2018;25:34559-34569.
26. Bao-shan L, Shao-qi D, Chun-hui L, Li-jun, F, Shu-chun Q, Min Y. Effect of TMS (nanostructured silicon dioxide) on growth of changbai larch seedling. Journal of Forestry Research. 2004;15(2):138-140.
27. Siddiqui MH, Al-Whaibi MH, Faisal M, Al Sahli AA. Nanosilicon dioxide mitigates the adverse effects of salt stress on *Cucurbita pepo* L. Environmental Toxicology Chemistry. 2014;33:2429–2437.
28. Xie Y. Li B., Zhang Q. and Zhang C. Effects of nano-silicon dioxide on photosynthetic fluorescence characteristics of *Indocalamus barbatus* Mc Clure. Journal of Nanjing Forestry University (Natural Science Edition). 2012;2:59–63.
29. Feizi H, Sahabi H, Rezvani Moghaddam P, Shahtahmassebi N, Gallehgir O, and Amirmoradi Sh. Impact of intensity and exposure duration of magnetic field on seed germination of tomato (*Lycopersicon esculentum* L.). Notulae Scientia Biologicae, 2012; 4(1):116-120.
30. Dhawi F, Al-Khayri JM. Magnetic fields induce changes in photosynthetic pigments content in date palm (*Phoenix dactylifera* L.) seedlings. The Open Agriculture Journal. 2009; 2:121-125.
31. Rãcuciu M, Creangă D, Horga I. Plant growth under static magnetic field influence. Romanian Journal of Physics. 2008;53:353–359.
32. Rochalska M. Influence of frequent magnetic field on chlorophyll content in

leaves of sugar beet plants. *Nukleonika,* 2005; *50 (2): 25-28.*

33. Novitsky YI, Novitskaya GV, Kocheshkoiva TK, Nechiporenko GA, Dobrovolskii M.V. Growth of green onions in a weak permanent magnetic field. Russian Journal of Plant Physiology. 2001;48:709–715.
34. Leelapriya T, Dilip KS, Sanker-Narayan PV. Effect of weak sinusoidal magnetic field on germination and yield of cotton (*Gossypium* sp.). Electromagn Biol Med. 2003;22:117–125.
35. Tican LR, Auror CM, Morariu VV. Influence of near null magnetic field on in vitro growth of potato and wild *solanum* species. Bioelectromagnetics. 2005; 26:548–557.
36. Podleśna A, Bojarszczuk J, Podleśny, J. Effect of pre-sowing magnetic field treatment on some biochemical and physiological processes in faba bean (*Vicia faba* L. spp. Minor). Journal of Plant Growth Regulation. 2019;38:1153–1160.
37. Shaddad MA. The effect of proline application on physiology of *Raphanus sativus* plants grown under salinity stress. Biol Plant. 1990;32(2):104–112.
38. Garcia RF, Arza, PL. Influence of a stationary magnetic field on water relations in lettuce seeds. Part I: Theoretical Considerations, Bioelectromagnetics. 2001;22:589–595.
39. Selim AH, El-Nady MF. Physio-anatomical responses of drought stressed tomato plants to magnetic fields. Acta Astronaut. 2011;69:387– 396.
40. Grewal, HS, Maheshwari, B.L. Magnetic treatment of irrigation water and snow pea and chickpea seeds enhances early growth and nutrient contents of seedlings. Bioelectromagnetics. 2011;32:58-65.
41. Baghel L, Kataria S. Jain M. Mitigation of adverse effects of salt stress on germination, growth, photosynthetic efficiency and yield in maize (*Zea mays* L.) through magnetopriming. Acta Agrobotanica. 2019; 72, 1757.
42. Baghel L, Kataria S, and Guruprasad KN. Static magnetic field treatment of seeds improves carbon and nitrogen metabolism under salinity stress in soybean. Bioelectromagnetics, 2016; 37: 455-470.
43. Anjum F, Yaseen M. Rasul E. Wahid A. and Anjum S. Water stress in barley. I. Effect on chemical composition and chlorophyll content. Pakistanian Journal of Agricultural Science. 2003;40:45-9.
44. Tuna AL., Kaya, C., Higgs, D., Murillo-Amador, B., Aydemir, S., and Girgin, A.R. Silicon improves salinity tolerance in wheat plants. Environmental and Experimental Botany. 2008;62:10-16.
45. Ashkavand P, Tabari M, Zarafshar M, Tomášková I, Struve D. Effect of SiO_2 nanoparticles on drought resistance in hawthorn seedlings. For Res Pap 2015; 76: 350-359.
46. Maghsoudi K, Emam Y, and Ashraf M. Influence of foliar application of silicon on chlorophyll fluorescence, photosynthetic pigments, and growth in water-stressed wheat cultivars differing in drought tolerance. Turkish Journal of Botany. 2015; 39: 625-634.
47. Javed N, Ashraf M, Akram NA., aAl-Qurainy, F. Alleviation of adverse effects of drought stress on growth and some potential physiological attributes in maize (*Zea mays* L.) by seed electromagnetic treatment. Photochemistry and Photobiology. 2011; 87(6): 1354-1362.
48. Damn A, Guanter L, Paul-Limoges E., Vander Tol C, Hueni A. Buchmann N, Eugster W, Amman C Schaepman ME. Far red sun-induced chlorophyll fluorescence shows ecosystem–specific relationships to gross primary production: an assessment based on observational and modeling approaches. Remote sensing of Environment. 2015;166: 91-105.
49. Verrelst J, Van der Tol C, Magnani F, Sabater N, Rivera JP. Mohammad G and Moreno J. Evaluating the predictive power of sun-induced chlorophyll fluorescence to estimate net photosynthesis of vegetation canopies. A scope modeling study. Remote Sensing of Environment. 2016;176: 139-151.
50. Maxwell K, Johnson GN. Chlorophyll fluorescence a practical guide. Experimental Botany. 2000;51: 659–668.
51. Fracheboud, Y. Using chlorophyll fluorescence to study photosynthesis. Institute of Plant Sciences ETH, Universitatstrass, CH-8092 Zurich; 2006.
52. Baker NR, Rosenqvist E. Applications of chlorophyll fluorescence can improve crop production strategies: an examination of future possibilities. Journal of Experimental Botany. 2004;55(403):1607–1621.
53. Rohacek K, Soukupova J, Bartak M. Chlorophyll fluorescence: A wonderful tool to study plant physiology and plant stress. In Schoefs B, (eds). Plant Cell

Compartments- Selected Topics. Research Signpost, Kerala, India. 2008;41-104.

54. Zlatev ZS. Yordanov IT. Effects of soil drought on photosynthesis and chlorophyll fluorescence in bean plants. Bulgarian Journal of Plant Physiology. 2004;30:3-18.
55. Havaux M, Niyogi K.K. The violoxanthin cycle protects plants from photooxidative damage by more than one mechanism. Proceeding of National Academical Science. 1999;96: 8762- 8767.
56. Andrews JR, Fryer, M.J, Baker, N.R. Characterization of chilling effects on photosynthetic performance of maize crops during early season growth using chlorophyll fluorescence. Journal of Experimental Botany. 1995;46:1195–1203.
57. Havaux M., Emez M, and Lannoye R. Selection de varieties de ble dur (Triticum *durum* Desf.) et de ble tender (*Triticum aestivum* L.) adapted a la secberesse par I mesure de I extinction de la et de ble tender (*Triticum aestivum* L.) adapted a la secberesse par I mesure de I extinction de la fluorescence de la chlorophylle in viva. Agronomie. 1998;8(3):193-199.
58. Mamnoei E, and Seyed Sharifi R. Study the effects of water deficit on chlorophyll fluorescence indices and the amount of proline in six barley genotypes and its relation with canopy temperature and yield. Journal of Plant Biology. 2010; 2 (5):51-62. [In Persian with English abstract]
59. Xu Q, Ma X, Lv T, Bai M, Wang Z. and Niu J. Effects of water stress on Fluorescence parameters and photosynthetic characteristics of drip irrigation in rice. Water. 2020;12:289.
60. Meng LL. Song JF. Wen J. Effects of drought stress on fluorescence characteristics of photosystem II in leaves of *Plectranthus scutellarioides*. Photosynthetica. 2016;54:414-421.
61. Kalaji HM, Govindjee and Bosa K.. Effects of salt stress on photosystem II efficiency and CO_2 assimilation of two Syrian barley landraces. Environmental and Experimental Botany. 2011;73:64-72.
62. Piper FI, Corcuera LJ, Alberdi, M, Lusk, C. Differential photosynthetic and survival responses to soil drought in two evergreen Nothofagus species. Annals of Forest Science. 2007;64:447-452.
63. Tilahun A, Sven, S. Mechanisms of drought resistance in grain: PSII stomatal regulation and root growth. Ethiopian Journal of Science and Technology. 2003; 26:137-144.
64. Ahmed S. Nawata E. Hosokawa M. Domae Y. Sakuratani T. Alterations in photosynthesis and some antioxidant enzymatic activities of mung bean subjected to water logging. Plant Science. 2002;163:117-123.
65. Rahbarian R. Khavari-nejad R.A., Ganjeali, A., Bagheri A.R. Najafi F. Drought stress effects on photosynthesis, chlorophyll fluorescence and water relations in tolerant and susceptible chickpea (C*icer arietinum* L.) genotypes. Acta. Bio. Craco. Ser. Botany. 2011;53:47-56.
66. Mateos-Naranjo E, Galle A, Florez-Sarasa I, Perdomo JA, Galmes J, Ribas-Carbo M, Flexas J. Assessment of the role of silicon in the Cu-tolerance of the C4 grass *Spartina densiflora*. Journal of Plant Physiology. 2015;178:74–83
67. Gorbe E, Calatayud A. Applications of chlorophyll fluorescence imaging technique in horticultural research: A review. Sci Hortic. 2012;138:24–35.
68. Oukarroum A, Bussotti F, Goltsev V, Kalkaji HM. Correlation between reactive oxygen species production and photochemistry of photosystems I and II in *Lemna gibba* L. plants under salt stress. Environ Exp Bot. 2015;109:80–88.
69. Joshi J. Physiological and Biochemical changes in soybean after treatment with magnetic field and strobilurin F500. Ph.D dissertation. School of life sciences. India; 2014.
