Quantitative Assessment of some oilseed response to salinity stress at the early growth stage

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ABSTRACT

In arid and semi-arid areas, salinity stress is one of the most serious global crop production problems. Furthermore, 90% of oil demand of IRAN are supplied through imports. In this regard, it is necessary to investigate the response of some oilseeds to salinity stress to identify salinity tolerant cultivars and achieve optimal yield. In this study, to quantify the response of Nima and Zafar rapeseed cultivars, as well as the Soheil camelina cultivar to salinity stress at the germination stage, an experiment including 17 water salinity levels of 85.0, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24, 26, 28, 30, 32 dS m^{-1}, each with three replicates was conducted at Tarbiat Modares University in 1398. Germination indicators were calculated using the SeedCalc package of the R software. MATLAB software was used to fit the salinity models of Maas and Hoffman (MH), van Genuchten and Hoffman (HVG), Dirksen and Augustijn (DA) and Homaee et al. (HF) to predict seed germination indices. The salinity tolerance threshold of the final germination percentage *index (FGP) for Soheil, Nima and Zafar cultivars is 32, 2, 4 dS m^{-1}, respectively, and the reduction slope for Nima and Zafar cultivars is 1.14 and 1.84 %, respectively. Also, the salinity tolerance threshold of germination rate index (GSI) for Soheil, Nima, and Zafar is equal to 2, 2, and 0.86 dS m^{-1}, respectively, and their reduction slope is equal to 2.4, 2.2 and 1.8 %. In addition to FGP and GSI indices, the salinity tolerance threshold of the seed vigor index for Soheil, Nima, and Zafar cultivars is 12, 4 and 8 dS m^{-1}, and their reduction slopes are equal to 7.7, 1.7, and 3.5, respectively. Based on all three indices of FGP, GSI and seed vigor, Soheil and Nima cultivars are tolerant to salinity, whereas the Zafar cultivar is moderately tolerant. Among the models fitted to FGP, GSI and seed vigor indices, nonlinear models performed better than linear models due to the Sigmoid nature of the curve. Linear MH model in FGP and GSI indices for Zafar cultivar because of trend linearity of the data provided good performance and in GSI and seed vigor indices, HVG and HF models had the best performance.*

Keywords: *electrical conductivity, germination percentage, germination rate, modeling*

1. *INTRODUCTION*

Salinity stress is the second most important environmental stress limiting plant growth in arid and semi-arid regions and causes extensive damage to crop production and yield. Given the continuous increase in the global human population, which is expected to reach 9.6 billion by 2050, salinity stress will pose a serious challenge to global food security [1]. Each year, approximately 1.5 million hectares of agricultural land become salinized [2], and currently more than one billion hectares of land in over 100 countries are affected by salinity [3].

As salinity in the root environment increases, the osmotic potential of the soil solution decreases, forcing plants to expend more energy on water uptake rather than on physiological processes such as photosynthesis. In addition, salinity stress causes specific ion toxicity and nutritional imbalances [4], and over time, the effects of ion toxicity become evident in plant tissues [5]. The impact of salinity on plants depends on several factors, including salinity level, crop type, stress intensity and duration, irrigation management, climatic conditions, and fertilization practices [6]. Due to limited water availability and poor water quality in arid and semi-arid regions, the use of alternative water sources such as saline water for crop production is inevitable. Since the germination stage is one of the earliest and most sensitive growth stages, quantifying plant responses to salinity and identifying salt-tolerant cultivars at this stage is of critical importance.

Seed germination is a complex process involving a series of physiological and biochemical changes resulting from embryo activation [7] and plays a vital role in successful plant establishment and crop

production [8]. Therefore, determining seed tolerance to various environmental stresses during germination is essential for understanding plant adaptation mechanisms [9]. One of the earliest effects of salinity stress on plants is delayed seed germination [10]. Barbour [11] reported that salinity stress reduces both germination rate and final germination percentage. Seed vigor, as an important physiological characteristic of seed quality, strongly influences seedling establishment [12]. Low seed vigor often results in poor crop establishment in the field [13], whereas seeds with high vigor exhibit greater tolerance to stresses such as salinity [14].

Oilseed crops constitute the second largest global food reserve after cereals [15]and serve as important raw materials for biofuels, industrial products such as plastics and resins, cosmetic applications, and human and animal consumption [16]. Rapeseed is the second most important oilseed crop worldwide after soybean. Its consumption has increased in recent years due to its demand as a primary feedstock for biodiesel production in Europe [17]. Rapeseed cultivars show high adaptability across most regions of Iran [18]and represent one of the most important oilseed crops in arid and semi-arid environments [19]. Rapeseed seeds contain approximately 40–45% oil, making them a valuable source of edible and industrial oil [20]. According to the Ministry of Agriculture, the cultivated area of rapeseed in Iran in 2017 was approximately 102.6 thousand hectares [21]. In addition, rapeseed is a rich source of essential nutrients due to its high nutrient uptake efficiency [22].

Camelina (Camelina sativa) has several advantages over other oilseed crops, including low water and nutrient requirements, adaptability to adverse environmental conditions such as semi-arid climates, and resistance to pests [23]. The European Free Trade Association (EFTA) reported that the global cultivation area of camelina in 2017 was approximately 17.2 million hectares [24]. However, reports from the Bioenergy Crop Assistance Program (BCAP) in early 2012 indicated that camelina cultivation was limited to only 20,234 hectares in the United States and several other Western countries [25]. In Iran, research on camelina cultivation has only recently begun. Camelina seed oil content ranges from 29% to 41% and is characterized by low levels of saturated fatty acids and high levels of omega-3 fatty acids, making it a high-quality edible oil source [26].

Given the increasing importance of oilseed crops under saline conditions, evaluating their early-stage responses to salinity stress is essential. Also, due to water scarcity in arid and semi-arid regions, the use of low-quality water resources such as saline and brackish water for crop production is unavoidable. Moreover, as approximately 90% of Iran's edible oil demand is met through imports, identifying salinity-resistant oilseed cultivars is essential for achieving optimal yield under saline conditions. Therefore, the objectives of this study were to calculate germination indices for Nima and Zafar *rapeseed cultivars and the Soheil camelina cultivar, evaluate the effects of salinity on these indices, determine salinity tolerance thresholds and reduction slopes, fit linear and nonlinear reduction functions based on electrical conductivity, assess the performance of the fitted models, select the most suitable model, and ultimately determine salinity tolerance levels of the studied cultivars.*

2. Theory of Models

The governing flow equations, the macroscopic root extraction term, reduction function and relative uptake assumptions are available in the paper of Homaee et al.[27]. Plant resistance to salinity is quantified as a continuous function of relative yield. This function has a sigmoidal form for many plants; however, the plant may die before the yield reaches zero.

Several models for $\alpha(h_0)$ *have been proposed by researchers such as Maas & Hoffman [28], Van Genuchten & Hoffman [29], Dirksen & Augustijn [30] and Homaee [4] as follows:*

Maas and Hoffman [28] (MH) proposed a two-piece linear model, on the basis of which, water uptake doesn't decrease until h_0^**. However, as osmotic potential increases, the water uptake decreases linearly:*

$$Y_r = \alpha(h_0) = \begin{cases} 1 & \text{if} \quad h \le h_0^* \\ 1 - \frac{a}{360}(h_0^* - h_0) & \text{if} \quad h \le h_0^* \end{cases} \qquad (1)$$

where h_0^* *and a are an osmotic threshold and the reduction slope, respectively. The factor 360 is used to convert the salinity-based slope (dS* m^{-1}*) to centimeter osmotic head [31].*
Since the linear assumption of Eq. (1) causes it does not fully fit to the real conditions in the field; Van Genuchten and Hoffman [29] proposed a non-linear macroscopic root water uptake model in saline soils:

$$\alpha(h_0) = \frac{1}{1+\left(\frac{h_0}{h_{050}}\right)^P} \quad (2)$$

where h_{050} is osmotic potential at which $\alpha(h_0)$ is reduced by 50%, and P is an empirical and dimensionless coefficient.

The plant's root water uptake remains constant until a certain level of salinity. This salinity is the osmotic threshold value or h0. Direksen and augustijin [30] proposed as modification for Eq. (2):*

$$\alpha(h_0) = \frac{1}{1+\left(\left(h_0^* - h_0\right)/\left(h_0^* - h_{050}\right)\right)^P} \quad (3)$$

This equation is more realistic than eq. (2). But difficulty in getting h_{050} is the most significant restriction for this Equation. Also, because p is not yet defined either physically or empirically, Homaee [4] described P as a crop, soil, and climate-specific variable, and proposed the following function to calculate it:

$$P = \frac{h_{050}}{h_{050} - h^*_0} \quad (4)$$

In fact, P is a function of h_0^* and h_{050}, and impact of h_{050} is on it greater than h_0^*.

with h_{50} having a larger impact than h.

Since the problem of getting h_{050} remained unsolved, Homaee et al. [27] (H) presented a non-linear two-threshold reduction function by replacing h_{0max} with h_{050}, where h_{0max} is the second threshold value of the reduction function.

$$\alpha(h_0) = \frac{1}{1+\left(1-\alpha_0\right)/\alpha_0\left[\left(h_0^* - h_0\right)/\left(h_0^* - h_{0\max}\right)\right]^P} \quad (5)$$

After h_0^*, the decrease in α due to salinity continues to be significant until a particular degree of salinity (h_{0max}) is reached; beyond h_{0max}, salinity rises do not result in a significant reduction in α. The factor α_0 is the value of α corresponding to h_{0max}. This reflects the facts at $h_0 \le h_{0max}$ the plant is still alive but the biological activities are at their minimum rate. The factor α_0 is the value of α corresponding to h_{0max}. Homaee et al. [27] defined the value of P as follows:

$$P = \frac{h_0^*}{\left(h_{0\max} - h_0^*\right)} \quad (6)$$

3. Materials and Methods

In order to quantify the response of Nima and Zafar rapeseed cultivars, as well as the Soheil camelina cultivar to salinity stress at the germination stage and selection of resistant cultivar, an experiment was conducted in a completely randomized design with three replicates at the at the Irrigation and Drainage Department's laboratory of Tarbiat Modares University in 1398. The applied saline water treatments were prepared by diluting natural saline water of Howz-e Soltan Lake, Qom, Iran (50,811N; 34,465E) with well water (EC = 0.85 dS m^{-1}). Salinity levels consisted of 0.85 (S1), 2 (S2), 4 (S3), 6 (S4), 8 (S5), 10 (S6), 12 (S7), 14 (S8), 16 (S9), 18 (S10), 20 (S11), 22 (S12), 24 (S13), 26 (S14), 28 (S15), 30 (S16), 32 (S17) dS m^{-1}. Electrical conductivity in each treatment was determined by a calibrated conductivity meter (Conductivity-meter SensoDirect CON200). Some properties of the original saline water are measured before dilution and are given in Table 1. First, seeds of the Nima and Zafar rapeseed cultivars were prepared from the Seed and plant improvement Institute (Karaj) and seeds of the Soheil camelina cultivar was prepared from the Cultivation and Development of Medicinal Plants Company of Behistun Shafa. Initially, 25 seeds were disinfected by 5% sodium hypochlorite solution for two minutes and then washed three times with distilled water. In Petri dish: 25 seeds placed on Whitman No. 1 paper and 10 ml of the solution with different salinity levels were added to each Petri dish. Petri dishes were closed. The Petri dishes were placed in a germinator at 25 °C for 7 days [32]. Seeds were counted every 24 hours for seven days. The criteria for seed germination was the root out with a size of 1 mm. Lengths of root and shoot measured in mm with a ruler.

Table 1*: Some chemical properties of the natural saline water before dilution*

EC (dS/m)	pH	HCO_3^- (g/l)	Cl^-	K^+	Na^+	Mg^{2+}	Ca^{2+}	SO_4^{2-} (mg/l)	B (mg/l)
144	8.15	2.06	38.64	0.66	27.6	5.37	0.288	81.96	13.15

Germination indicators

SeedCalc package [33] in R software was used to estimate germination indices. Computational germination parameters including final germination percentage (FGP) [32], germination rate (GSI) [34] and seed vigor [35] obtained using equations (7) to (9), respectively.

$$FGP=(n/N)\times 100 \quad (7)$$

$$GSI = \sum_{i=1}^{k}(n_i/t_i) \quad (8)$$

$$Vigor= FGP\times L_S \quad (9)$$

Where n is the number of germinated seeds, N is the total number of seeds, n_i is the number of germinated seeds per day, t is the number of days, L_S is the plant length and FGP is the final germination percentage. Root and stem lengths were measured with a millimeter ruler.

In this study, fitting and coding of models was performed using Matlab software. Appropriate optimization procedure of fitting models was performed on the measured data with frequent changes in the model parameters based on root-mean-square error reduction and minimizing square error between the predicted and measured data. The sum of squares error (SSR) and model performance evaluation statistics including RMSE, model efficiency (EF), maximum error (ME) and coefficient of residuals mass (CRM) are as follows:

$$SSR = \sum_{i=1}^{n}\left(O_i - P_i\right)^2 \quad (10)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2} \quad (11)$$

$$EF = \frac{\sum_{i=1}^{n}\left(O_i - \bar{O}\right)^2 - \sum_{i=1}^{n}\left(P_i - \bar{O}\right)^2}{\sum_{i=1}^{n}\left(O_i - \bar{O}\right)^2} \quad (12)$$

$$CRM = \frac{\sum_{i=1}^{n} O_i - \sum_{i=1}^{n} P_i}{\sum_{i=1}^{n} O_i} \quad (13)$$

$$ME = \max\left|P_i - O_i\right|_{i=1}^{n} \quad (14)$$

where O_i is measured value, P_i is simulated value; n is the number of samples and $\bar{O}$ is the average value [27].

4. Result and discussion

4.1 Modeling of FGP index

The measured values of electrical conductivity of FGP index under salinity stress based on different predictive models for Nima and Zafar rapeseed cultivars are given in Table 2. The salinity tolerance threshold of FGP index for Nima and Zafar cultivars is 2 and 4 dS/m, respectively. However, FGP was obtained 100% for Soheil camelina cultivar at all salinity levels and therefore its modeling was not possible.

Reduction slope is an important parameter in expressing plant salinity tolerance, and the slower the reduction slope, the better. According to Table 2, the reduction slope of FGP for Nima and Zafar cultivars decreased by increasing salinity levels by 1.1 and 1.8%, respectively. The slowness of the reduction slope results in 50% and 25% of the FGP index occurring in higher electrical conductivity. EC50 and ECmax values for Nima cultivar are 47.8 and 70.7 dS/m, respectively, and for Zafar cultivar are 31.2 and 44.8 dS/m, respectively. According to FGP index, which is the first important index in plant establishment, despite very good results from modeling FGP index and also more resistance of Nima to salinity stress, it should be noted that Soheil cultivar was more resistant to salinity than the two cultivars; and in no way, FGP does not decrease as salinity levels increase. Based on the electrical conductivity and the reduction slope of the FGP index, all three cultivars are highly resistant to salinity. Despite the fact that all three cultivars had low reduction slopes and high tolerances, the decreases germination percentage in Nima and Zafar can be due to the decrease in the germination rate and water uptake as well as the negative effects of low osmotic potentials and toxicity of Na^+ and Cl^- ions on catabolic and anabolic biochemical processes [36].

Table 2. Measured electrical conductivity of FGP under salinity stress based on different predictive models for the studied cultivars

Model	Index Parameter		Nima	Zafar
MH	h_0^*	(cm)	2	4

	Slope	(٪)	1.1	1.8
HVG	h_{050}	(cm)	47.78	31.2
	P		1.1	1.2
DA	h_0^*	(cm)	2	4
	h_{050}	(cm)	47.8	31.2
	P		1.09	1.15
HF	h_{0max}	(cm)	70.7	44.8
	α_0		0.25	0.25
	h_0^*	(cm)	2	4
	P		1.05	1.1

Table 3 presents the calculated parameters of performance evaluation criteria for different predictive models fitted to the FGP index under salinity stress for Nima and Zafar rapeseed cultivars. R^2 values for Nima and Zafar cultivars were 0.908-0.971 and 0.929-0.937, respectively. Also, the RMSE values of salinity models fitted to the FGP index for Nima cultivar also obtained in MH model equal to 0.032 and in other models equal to 0.0199. The RMSE value for Zafar cultivar in MH model was 0.035 and 0.038 for other models. The closer the ME and SSR values are to zero, the better the model performance. Also, the closer the EF value presented in Table 5 is to one, the smaller the difference between the simulated and measured values. The minimum ME and the maximum EF for Nima cultivar were obtained by DA and HF models. The lowest ME and the highest EF for Zafar cultivar were obtained by MH and HVG models. The lowest SSR values for both cultivars were obtained by the VG model. Given the positive CRM values of the HVG model, it tended to overestimate, while others tended to underestimate. All of the models provided satisfactory and acceptable results. In Nima cultivar, the nonlinear DA and HF models provided the best performance. In Zafar cultivar, due to the linear trend of the data, the MH linear model provided better performance. Between the two models of DA and HF in Nima cultivar, a model that has well- defined parameters and can also be easily measured will be more appropriate; For this reason, the HF model was recognized as the best model for estimating the FGP index for the Nima cultivar.

Table 3. Calculated statistical performance evaluation criteria for different predictive models fitted to FGP under salinity stresses for studied cultivars

Nima						
Model/Parameter	R^2	RMSE	SSR	EF	ME	CRM
MH	0.908	0.032	0.018	0.908	0.055	-0.016
HVG	0.970	0.019	0.006	0.970	0.017	7.72×10^{-4}
DA	0.971	0.019	0.006	0.971	0.013	-7.36×10^{-4}
HF	0.971	0.019	0.006	0.971	0.013	-7.31×10^{-4}
Zafar						
Model/Parameter	R^2	RMSE	SSR	EF	ME	CRM
MH	0.937	0.035	0.022	0.937	0.086	-0.006
HVG	0.929	0.038	0.024	0.929	0.086	0.003
DA	0.929	0.038	0.024	0.929	0.109	-0.008
HF	0.929	0.038	0.024	0.929	0.109	-0.008

In Fig.1, the results of fitting salinity models on the relative FGP index value in Nima and Zafar rapeseed cultivars are presented as a function of electrical conductivity, with observational data that shown in the graph with Ob. The salinity tolerance threshold, EC_{50} and EC_{max} can be distinguished from the figure, which these values for Nima cultivar are approximately equal to 2, 47.8 and 70.7 dS/m, respectively, and the EC^*, EC_{50}, and EC_{max} values for for Zafar cultivar are equal to 4, 31.2 and 44.8 dS/m. The figure depicts the proper performance of nonlinear and linear models. In comparison to other models, the MH model performed the worst in Nima cultivar and the best in Zafar cultivar. The reason for the linear model's poor performance in Nima cultivar is the Sigmoid-shaped curve and the high tolerance threshold. If the reduction threshold is removed or it is low, the curve will be deviates from sigmoid shape and the linear model will also have a good performance. Among the studied nonlinear models in Nima cultivar, HF model provided better performance than other models; However, it is impossible to detect it due to the proper performance of all nonlinear models, and for this purpose, the performance evaluation statistics of the proposed models presented in Table 5 should be used. In general, the figure depicts the proper performance of all models.

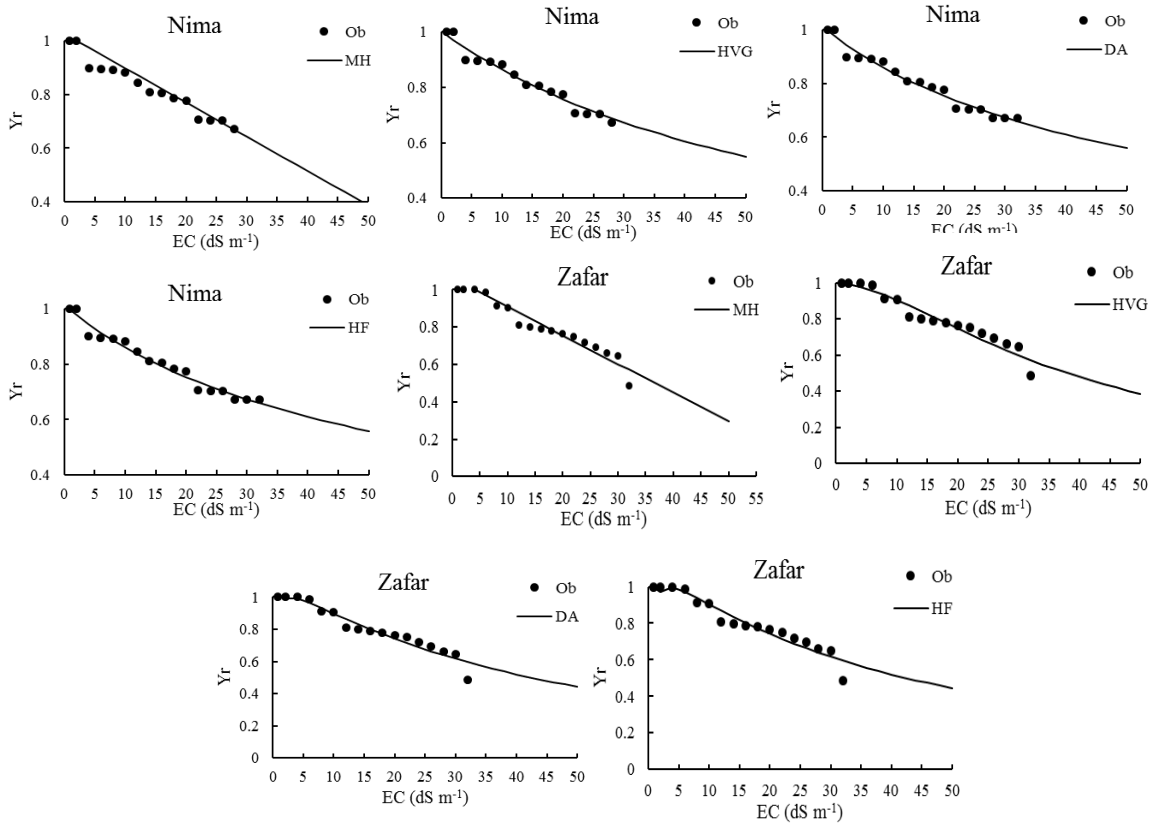


Fig. 1. Different predictive models fitted to FGP for Nima and Zafar cultivars

4.2 Modeling of GSI index

Table 4 presents the measured electrical conductivity of the GSI index under salinity stress based on different predictive models for the Nima and Zafar rapeseed cultivars, as well as the Soheil camlina cultivar. The salinity tolerance threshold of GSI indices in MH, DA, and HF models is equal to 2, 2 and 0.86 dS/m, respectively, based on the data presented in this table for Soheil, Nima, and Zafar, which are in accordance with the measured values. The measured reduction slopes of the GSI index for the Soheil, Nima and Zafar cultivars by the MH model were 2.4 %, 2.2 % and 1.8 %, respectively. The MH model, such as the nonlinear models, has a high accuracy in predicting the electrical conductivity values of the GSI index for all three cultivars. However, if the data has a high salinity tolerance threshold and a Sigmoidal shape, nonlinear models will perform better. The lowest slope of the GSI indicates that the EC_{50} and EC_{max} are both extremely high. The Soheil cultivar's EC_{50} and EC_{max} values are 22 and 35 dS/m, respectively, and these values in the Nima cultivar are 24 and 38 dS/m. In the Zafar cultivar, EC_{50} and EC_{max} values are 31 and 40 dS/m, respectively. In addition to the further tolerance threshold for Soheil and Nima, Zafar cultivar has a slower reduction slope and higher EC_{50} and EC_{max}. However, according to the FGP index, the high GSI index electrical conductivity values for Zafar cultivar, its FGP has decreased more than the others. Soheil has more salinity resistance than Nima, and Nima has more salinity resistance than Zafar. Of course, according to the GSI index, all three cultivars are resistant to salinity. In general, despite the decreasing trend of GSI, germination rate decreases with increasing salinity, which some attribute to decreased seed water uptake [37]) and according to some researchers, increased salinity stress was caused by low seed water content and caused cessation of metabolism or inhibition of certain steps in metabolic sequences of germination [38].

Table 4. Measured electrical conductivity of GSI under salinity stress based on different predictive models for the studied cultivars

Model	Index / Parameter	Soheil	Nima	Zafar

MH	h_0^*	(cm)	2	2	0.86
	Slope	(٪)	2.4	2.2	1.8
HVG	h_{050}	(cm)	22	24	31
		P	1.1	1.09	1.03
DA	h_0^*	(cm)	2	2	0.86
	h_{050}	(cm)	22	24	31
		P	1.1	1.09	1.03
HF	h_{0max}	(cm)	35	38	40
		α_0	0.25	0.25	0.25
	h_0^*	(cm)	2	2	0.86
		P	1.1	1.05	1.02

The calculated statistical performance evaluation criteria of various predictive models fitted to GSI index under salinity stress for Nima and Zafar rapeseed cultivars, as well as Soheil camlina cultivar are given in Table 5. For the Soheil cultivar, the R^2 values of the MH, HVG, DA and HF models are 0.973, 0.98, 0.977 and 0.977, respectively. For Nima cultivar, the R^2 obtained by MH, HVG, DA and HF models were 0.902, 0.951, 0.939 and 0.943, respectively, whereas the R^2 values for Zafar cultivar were equal to 0.935. 0.913, 0.908 and 0.912, respectively. Furthermore, the RMSE values of different predictive models for Soheil, Nima and Zafar cultivars ranged from 0.031 to 03.06, 0.041 to 0.057 and 0.044 to 0.052, respectively. In addition, the closer the ME and SSR are to zero, the better the model performance. The HVG model provides the lowest ME and SSR as well as the highest EF values for the Soheil and Nima cultivars. The minimum ME and SSR and the maximum EF for Zafar cultivar were obtained by MH model. However, the lowest SSR value for Soheil cultivar was observed in DA and HF models. Based on the negative CRM values, all models in the Soheil and Zafar cultivars tended to underestimate, while the MH and HF models in the Nima cultivar tended to underestimate. Furthermore, the results of all four salinity models that were fitted to the GSI index were satisfactory and acceptable. The HVG model outperformed other models in Soheil and Nima cultivars. The MH linear model in Zafar cultivar provided better performance than nonlinear models due to the linear trend of the data and the low threshold of the GSI index.

Table 5. Calculated statistical performance evaluation criteria for different predictive models fitted to GSI under salinity stresses for studied cultivars

Soheil						
Model/Parameter	R^2	RMSE	SSR	EF	ME	CRM
MH	0.973	0.036	0.024	0.007	0.022	-0.003
HVG	0.980	0.031	0.018	-0.009	0.014	-0.003
DA	0.977	0.033	0.020	-0.032	0.019	-0.007
HF	0.977	0.033	0.020	-0.032	0.019	-0.007
Nima						
Model/Parameter	R^2	RMSE	SSR	EF	ME	CRM
MH	0.902	0.057	0.056	0.902	0.043	-0.035
HVG	0.951	0.041	0.028	0.951	0.027	0.008
DA	0.939	0.045	0.035	0.939	0.034	0.002
HF	0.943	0.044	0.033	0.943	0.052	-0.010
Zafar						
Model/Parameter	R^2	RMSE	SSR	EF	ME	CRM
MH	0.935	0.044	0.033	0.935	0.118	-0.001
HVG	0.913	0.05	0.043	0.913	0.125	-0.015
DA	0.908	0.052	0.046	0.908	0.126	-0.017
HF	0.912	0.051	0.044	0.912	0.126	-0.015

Salinity models fitted to the GSI index in Soheil, Nima, and Zafar are shown in Figure 2. According to the figure, the reduction threshold, EC_{50}, and EC_{max} for the Soheil cultivar were approximately 2, 22 and 35 dS/m, respectively. The EC^*, EC_{50}, and EC_{max} values for Nima cultivar are 2, 24, and 38 dS/m, respectively, as shown in Fig. 2. These values are 0.86, 31, and 40 dS/m for the Zafar cultivar, respectively. As shown in the figure, the nonlinear models performed better than the linear models due to the Sigmoidal shape of the GSI curves in Soheil and Nima cultivars. Also, the linear model has given better results than the nonlinear DA, HVG and HF

models due to the low threshold and consequently the linearity of GSI data in Zafar cultivar. The HVG model provided the best performance for estimating the GSI index in Soheil and Nima cultivars and the MH model provided the best performance in Zafar cultivar. The performance evaluation statistics presented in Table 6 should be used to identify the best fitted model based on the appropriate results of all models. In general, from the figure, it can be seen that the proper performance of the models.

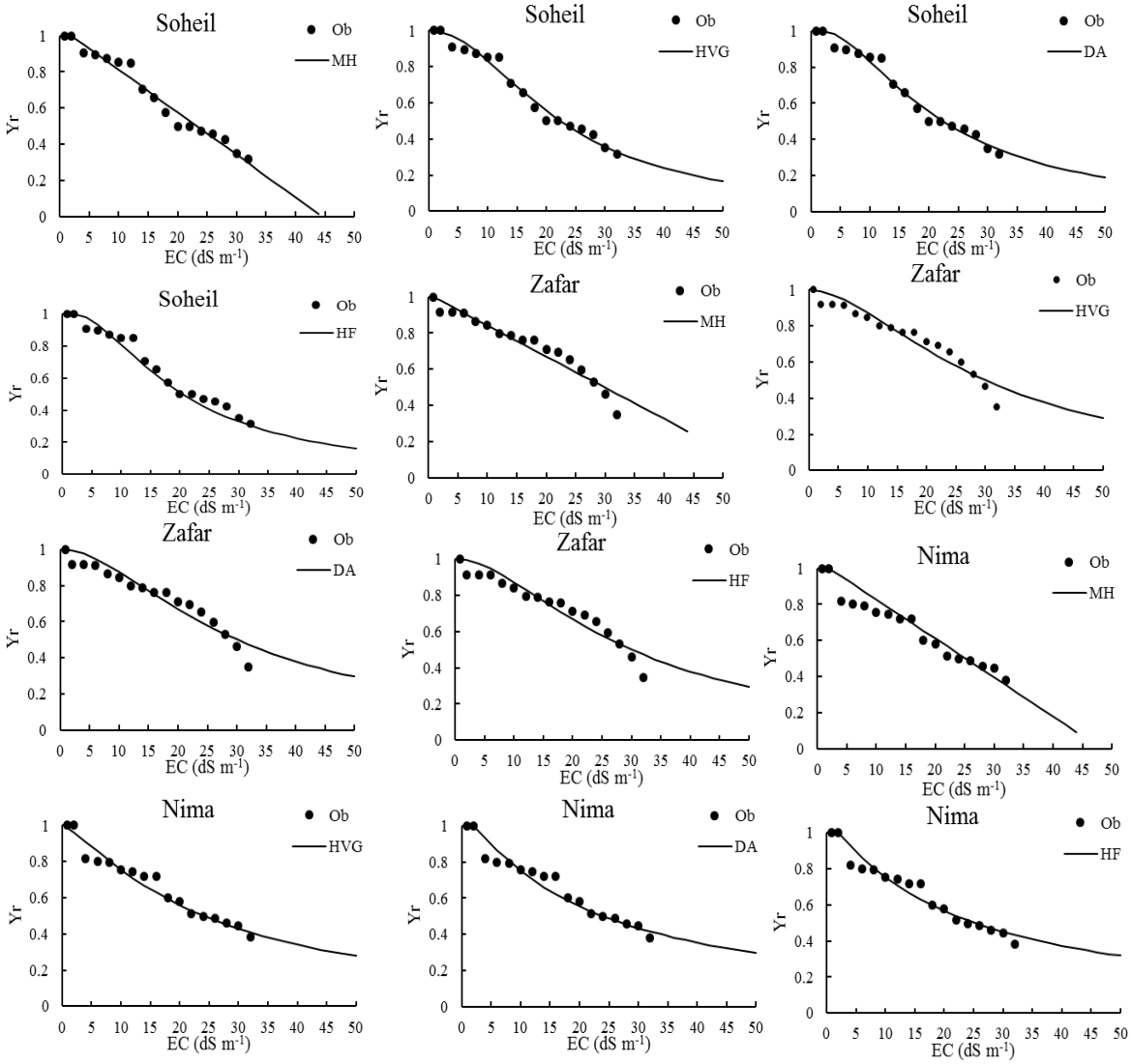


Fig. 2. Different predictive models fitted to GSI for Nima and Zafar rapeseed cultivars, and Soheil camelina cultivar

4.3 Modeling of seed vigor index

Table 6 presents the measured and predicted electrical conductivity of seed vigor index under salinity stress using various predictive models for Nima and Zafar rapeseed cultivars, as well as Soheil camelina cultivars. Based on the data presented in this table for Soheil, Nima and Zafar cultivars, the predicted values of salinity tolerance threshold of seed vigor index by MH model were equal to 12, 8 and 4 dS/m, respectively. The predicted threshold values for Soheil, Nima and Zafar cultivars by DA and HF models are 12, 5 and 2 dS/m, respectively. However, the measured threshold values for these models are equal to 12, 8 and 4 dS/m.

The difference between predicted and measured salinity tolerance threshold values can be considered data trend. The predicted values by the MH model are equal to the measured values. The EC_{50} and EC_{max} values are critical in determining salinity tolerance because the lower the slope and, subsequent, the higher the

electrical conductivity of EC_{50} and EC_{max}, the greater the resistance to salinity stress. The measured values of seed vigor reduction slope in Soheil, Nima and Zafar were 7.7, 1.7 and 3.5%, respectively. The predicted values of reduction slope for the studied cultivars using MH model are equal to 5.6, 5.2 and 3.9%, respectively. Also, the measured values of EC_{50} of seed vigor index for Soheil, Nima and Zafar are equal to 18.5, 17.6 and 9.4 dS/m, respectively. EC_{max} of seed vigor index for Soheil, Nima and Zafar cultivars was 24, 27.5 and 24.8 dS/m, respectively. Based on seed vigor index, Soheil, Nima and Zafar cultivars are tolerant, tolerant and moderately tolerant to salinity, respectively.

Table 6: Measured electrical conductivity of seed vigor index under salinity stress based on different predictive models for the studied cultivars

Model	Index Parameter		Soheil	Nima	Zafar
MH	h_0^*	(cm)	12	8	4
	Slope	(%)	7.7	1.7	3.5
HVG	h_{050}	(cm)	18.5	17.6	9.4
	P		2.84	1.8	1.75
DA	h_0^*	(cm)	12	8	4
	h_{050}	(cm)	18.5	17.6	9.4
	P		2.8	1.2	1.75
HF	h_{0max}	(cm)	24	27.5	24.8
	α_0		0.25	0.25	0.25
	h_0^*	(cm)	12	17.6	4
	P		0.99	1.41	1.19

The calculated statistical performance evaluation criteria for different predictive models fitted to the seed vigor index under salinity stress for Nima and Zafar rapeseed cultivars and Soheil camelina cultivar are given in Table 7. Based on the data presented in this table, R^2 of the models fitted to Soheil, Nima and Zafar ranged from 0.962 to 0.988, 0.947 to 0.984 and 0.646 to 0.954, respectively. Also, the RMSE values of MH, HVG, DA and H models that fitted to seed vigor in Soheil cultivar were equal to 0.05, 0.03, 0.029 and 0.029, respectively. The RMSE for salinity models of MH, HVG, DA and H in Nima cultivar were equal to 0.077, 0.056, 0.046 and 0.043, respectively, and in Zafar cultivar were equal to 0.173, 0.076, 0.062 and 0.062, respectively. In Soheil and Zafar cultivars, the lowest SSR value was obtained by DA and HF models and in Nima cultivar was obtained by HF model. The HVG model provided the highest EF values for the Soheil and Nima cultivars, whereas the DA and HF models provided the highest EF values for the Zafar cultivar. These values indicate that the simulation values correspond to the measurement values. Also, the minimum ME value of the models fitted to Soheil and Zafar cultivars was obtained by HVG, MH and HVG models, respectively. According to CRM values, the values predicted by MH and HVG models in Soheil cultivar tend to overestimate. Due to the positive CRM values, the values predicted by all models except MH in Nima cultivar and HVG in Zafar cultivar were higher than the measured values; and other models tended to underestimate. All of the models provided results that were satisfactory and acceptable. However, the MH linear model provided weakest perfromance compared to other models. The performance of HF model in Soheil, Nima and Zafar cultivars is better than other models due to RMSE, SSR and ME smaller and larger R^2 and EF.

Table 7: Calculated statistical performance evaluation criteria for different predictive models fitted to seed vigor index under salinity stresses for studied cultivars

Soheil						
Model/Parameter	R^2	RMSE	SSR	EF	ME	CRM
MH	0.962	0.05	0.090	0.962	0.169	0.011
HVG	0.987	0.03	0.031	0.987	0.007	0.012
DA	0.988	0.029	0.030	0.988	0.010	-0.002
HF	0.988	0.029	0.030	0.988	0.010	-0.002
Nima						
Model/Parameter	R^2	RMSE	SSR	EF	ME	CRM
MH	0.947	0.077	0.103	0.947	0.047	-0.040
HVG	0.972	0.056	0.054	0.972	0.005	0.052
DA	0.981	0.046	0.036	0.981	0.021	0.030

HF	0.984	0.043	0.031	0.984	0.029	0.009
			Zafar			
Model/Parameter	R^2	RMSE	SSR	EF	ME	CRM
MH	0.646	0.173	0.511	0.646	0.178	-0.168
HVG	0.931	0.076	0.099	0.931	0.046	0.078
DA	0.954	0.062	0.066	0.954	0.063	-0.002
HF	0.954	0.062	0.066	0.954	0.063	-0.002

Figure 3 illustrates salinity models fitted to the seed vigor index of the Soheil, Nima, and Zafar cultivars. According to the figure, the approximate values of the EC^*, EC_{50}, and EC_{max} for the Soheil cultivar are 12, 19, and 24 dS/m, respectively. The EC^*, EC_{50}, and EC_{max} for Nima cultivar were 8, 18, and 28 dS/m, respectively, as shown in Fig.3. These parameters have values of 4, 9, and 25 dS/m for the Zafar cultivar, respectively. The good performance of nonlinear models compared to the linear model, as well as the weakest performance of the linear model are clearly visible in the figure. Among the nonlinear models fitted to the seed vigor index, the HF model provided the best performance. Because of the overlap of the nonlinear models, choosing the best model is difficult, and should be based on the performance evaluation statistics presented in Table 7. In general, according to the figure, the proper performance of all models, especially nonlinear models, is known.

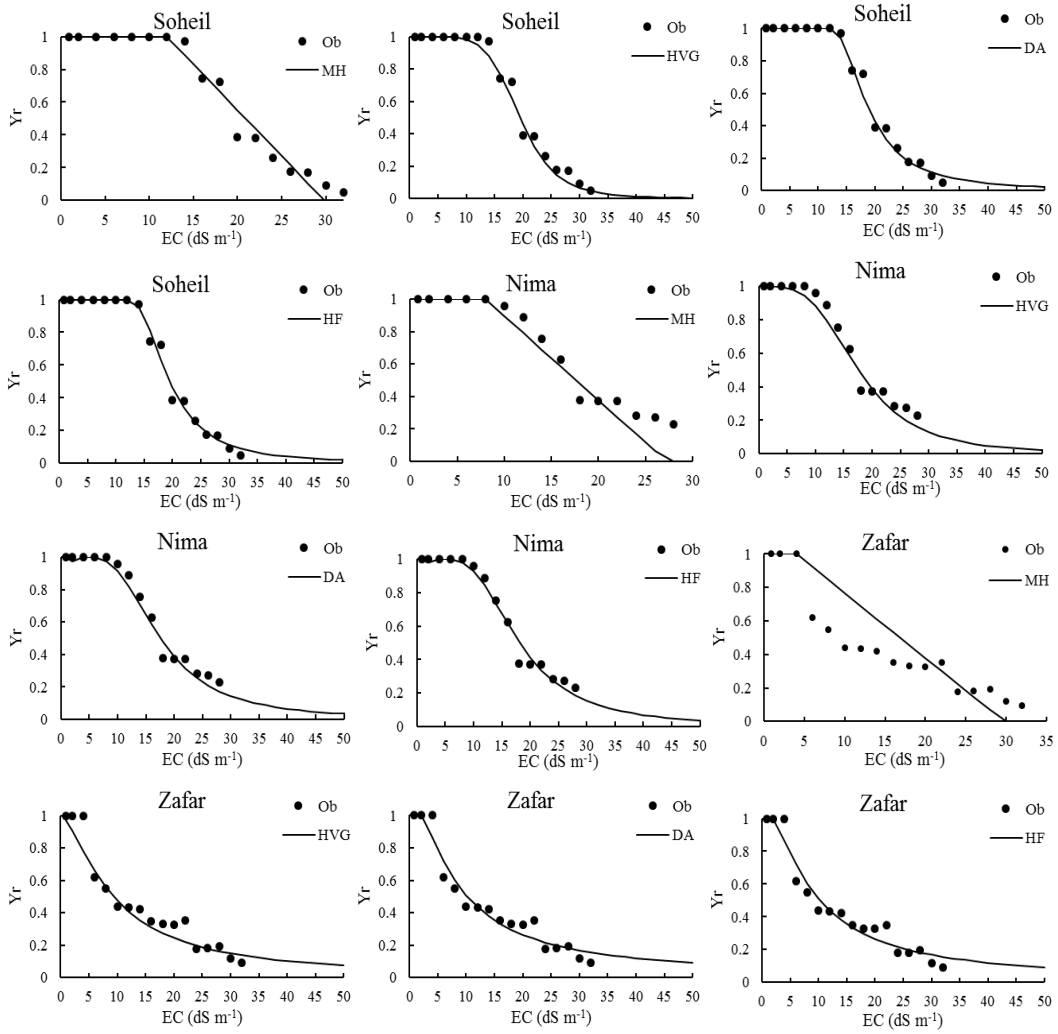


Fig. 3. Different predictive models fitted to seed vigor index for Nima and Zafar rapeseed cultivars, and Soheil camelina cultivar

Figure 4 depicts the germination percentages for Soheil, Nima and Zafar cultivars at different salinity levels. As can be seen, Soheil has a maximum final germination percentage of 100 and a germination delay of only 1-3 days at high salinity levels. Meanwhile, in salinities of 2 and 4 dS/m, the maximum final germination percentage in Nima and Zafar rapeseed cultivars was 77.33 and 92 percent, respectively. according to FGP data, FGP modeling revealed a 50 percent and a 25% reduction in FGP of Nima cultivar in higher electrical conductivity, respectively. Soheil, Nima, and then Zafar cultivars are more salinity resistant and suitable for cultivation under salinity stress.

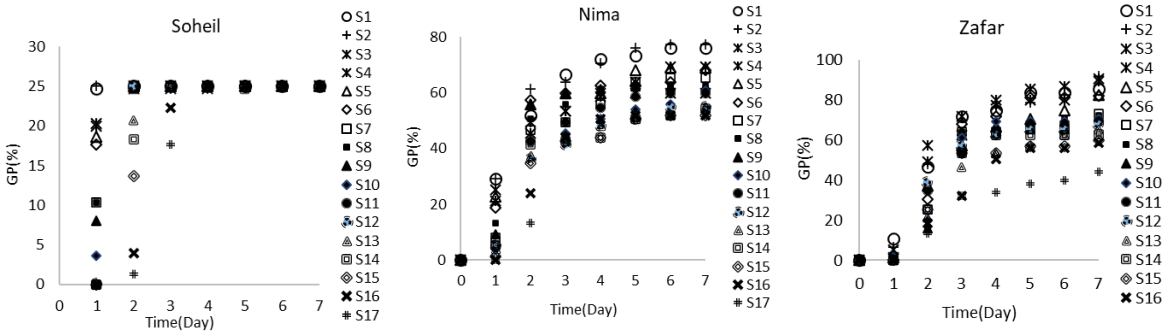


Figure 4- Germination percentage at different salinity levels for Soheil, Nima and Zafar

5. *Conclusion*

Cultivation of salinity-tolerant cultivars is an effective strategy for reducing the impacts of salinity stress. Quantitative evaluation of germination and seed vigor indices showed that the camelina cultivar Soheil exhibited higher salinity tolerance than the rapeseed cultivars Nima and Zafar. Nonlinear models consistently outperformed linear models in describing the response of final germination percentage, germination speed index, and seed vigor to salinity stress, reflecting the sigmoid nature of the response curves. Among the evaluated models, the HF and HVG models provided the most accurate predictions across cultivars and indices, highlighting their suitability for modeling germination responses under saline conditions.

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