Application of logistic model to estimate eggplant yield and dry matter under different levels of salinity and water deficit in greenhouse and outdoor conditions

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Eggplant is an important product in greenhouse cultivation in the world. However, much of its production is done on the farm. Few studies have been conducted on modelling of its growth and yield. Considering the simplicity of the logistic models, only the temperature and dry matter data during the growing season are needed to calibrate them. Hence, we evaluated the performance of the logistic model in growth and yield prediction of eggplant in greenhouse and farm conditions. Eggplants were planted in 2012 and 2013 under different treatments of irrigation and salinity with a complete randomized block statistical design. Irrigation frequency treatments consisted of: daily (I_1), weekly, (I_2) and every 2 weeks of irrigation (I_3). Each pot was irrigated to field capacity level. Four levels of salinity treatments are as follows: electrical conductivities (EC) of 0.8 (J_1); 2.5 (J_2); 5.0 (J_3) and 7.0 (J_4) dS·m^{-1}. The amount of plant dry matter was measured during the growing season (DM) and the amount of product (Y) at the end of the growing season. The logistic model was calibrated with the first-year data and validated with the second-year data. Logistic equation coefficients and harvest index were estimated as a function of the depth and electrical conductivity of irrigation water. The results showed that the accuracy of the logistic model for estimating DM during the growing season was good and predicted the product at the end of the growing season with acceptable accuracy. Also, the model's agreement with the measured DM and Y was good.

INTRODUCTION

Crop modelling has been gaining momentum over the past decade; partly due to the necessity of sustainable agriculture under environmental degradation along with population growth (Overman and Martin, 2001; Overman et al., 2003; Sepaskhah et al. 2011; Du et al., 2014; Camargo et al., 2015; Ramírez-Pérez et al., 2018). Such models help to assess the most appropriate planning in agro-environmental systems, through optimization of water and fertilizer application and finally maximizing returns to farmers. However, crops are highly dynamic systems emerging from an interface between cultivar factors, environmental conditions and management practices. The interaction of these determinants induces various stress patterns, resulting in different yield and growth patterns (Casadebaig et al., 2016). Deficiency in irrigation water quantity and quality leads to a reduction of water uptake and therewith significant evapotranspiration and yield limitation. Crop yield prediction according to water requirement or evapotranspiration is important in irrigation system design and evaluation (Ünlükara et al., 2010).

However, prearranged reduction of water application at certain stages of the growing season, called deficit irrigation, has been extensively studied and considered as a suitable irrigation strategy in dry regions (Rodrigues and Pereira, 2009; Geerts and Raes, 2009; Ghaemi and Rafiee, 2016). To obtain a precise description of crop growth features, a large number of variables have to be simultaneously taken into consideration, of which many are usually not available. Accordingly, crop models are divided into two general categories: dynamic and empirical (simple) models. Dynamic models simulate plant growth and development processes in relation to environmental factors and the movement of water in the soil. Consequently, these models require a large number of inputs, as model calibration is needed in various segments of such models. Measurement of some environmental factors and the calibration process are financially expensive and time-consuming (Kasampalis et al., 2018). A number of models, namely, WOFOST (Van Diepen et al., 1989), STICS (Brisson et al., 2003), APSIM (Keating et al., 2003), DSSAT (Jones et al., 2003), have been employed by researchers since they were first presented (Jin et al., 2018). In contrast, in empirical models, a detailed look at the mechanism of the environmental factors affecting plant growth is not considered. Instead, these models require fewer inputs. Further, they can be easily calibrated for a given location. Some examples of well-validated models in the country of the present study are presented by Ziaei and Sepaskhah (2003), Pirmoradan and Sepaskhah (2006), and Shabani et al. (2015). Simple models are still quite attractive to researchers (Basso and Ritchie. 2015), as they require fewer parameters and allow researchers to use literature or limited crop data to provide reasonable estimates of crop components (Dzotsi et al., 2015). Simple crop growth simulation models can be outlined as non-linear functions of a dependent variable (plant height, biomass accumulation or fruit growth dynamics) and an independent variable (time or growing degree days) (Lopez et al., 2000; Ruiz et al., 2012). One commonly used model is the logistic model, based on a sigmoid function of cumulative heat units (Shabani et al., 2015, 2018a, 2018b).

Sepaskhah et al. (2011) developed a logistic model based on cumulative heat units, considering the effect of seasonal water and nitrogen application on maize dry matter and grain yield. The harvest
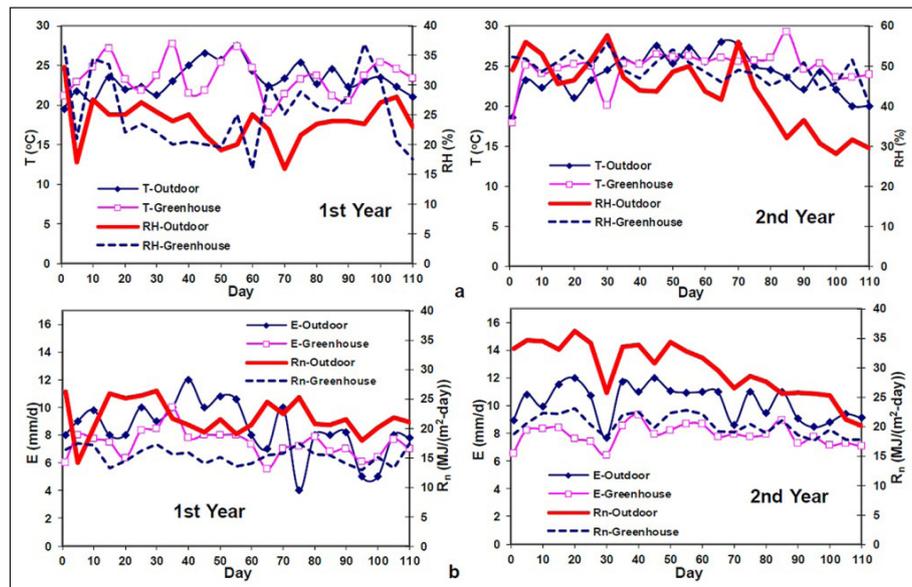
Figure 1. (a) Temperature (T) and relative humidity (RH) and (b) net radiation (Rn) and pan evaporation (E) at different days after planting in outdoor and greenhouse conditions

Table 1. Soil physical and chemical characteristics

Field capacity, θ_{FC} (g·g^{-1})	Wilting point, θ_{WP} (g·g^{-1})	Bulk density, ρ_b (g·cm^{-3})	pH	Ece (dS·m^{-1})	N$_{total}$ (%)	K (mg·kg^{-1}$_{soil}$)	P (mg·kg^{-1}$_{soil}$)	Organic matter (%)
0.305	0.11	1.03	7.72	0.55	0.2	600	12.5	1.65

index (HI) was also related to the applied water and nitrogen as another empirical model. Wardhani and Kusumastuti (2013) showed the superiority of logistic models in describing maize growth height in comparison with the Gompertz model. They suggested two different models for the two distinct stages of plant growth, i.e., vegetative and generative stage. Mahbod et al. (2015) estimated yield and dry matter of winter wheat with the logistic model under different irrigation water regimes and nitrogen application rates. The total irrigation water, rainfall and nitrogen, plus residual soil mineral nitrogen, applied in the logistic model coefficients and the harvest index, predicted above-ground dry matter and grain yield with good accuracy.

Eggplant is an important vegetable crop, produced as 35.3 million tons from 1.9 million ha worldwide. Eggplant is ranked third within the greenhouse products, after tomato, pepper and cucumber. Around 94% of eggplant is produced in Asia (FAOSTAT, http://www.fao.org/faostat/). Despite extensive investigations on cereal crop growth modelling, few researchers have investigated vegetable crops such as eggplant (Keating et al., 2014; Zurayk et al., 1993). However, it is important that the use of low-quality water and its effect on crop growth dynamics should be taken into consideration, given ever-increasing water supply limitations throughout the world. For example, Assaha et al. (2013) assessed the salinity tolerance of eggplant under two levels of salinity stress. Abd El-Azeem et al. (2012) elucidated the effects of inoculation with plant growth–promoting rhizobacteria on eggplant growth, yield, and mineral content under salt stress. Therefore, this study aims to use the logistic model to simulate the effect of salinity and drought stresses on eggplant yield and above-ground dry matter in greenhouse and outdoor cultivation environments.

MATERIALS AND METHODS

Experimental procedure

On 5 May 2012 and 18 May 2013, uniform seedlings of eggplant (Anamur RZ cultivar) were transplanted to both the field and plastic pots in the adjacent greenhouse located in Badjgah (29°36'N, 52°32'E), College of Agriculture, Shiraz University, Shiraz, Iran.

Each pot (with 35 cm diameter and 60 cm height), filled with the same field soil from the same depth, functioned as a microlysimeter. Some physical and chemical properties of the soil are presented in Table 1. Before transplanting, 1 g mono-ammonium phosphate was added to each soil pot, and 1 g, 0.5 g and 0.5 g potassium nitrate was applied to each pot, respectively, in the three different stages of the growth period (i.e. transplant, beginning of flowering and start of harvest). Weather parameters including net radiation (R_n), air temperature (T_a) and relative humidity (RH) were collected simultaneously from two automatic stations installed inside and outside the greenhouse. Changes of such parameters during the experimental periods are shown in Fig. 1.

Irrigation and salinity treatments were initiated after the establishment of plants (14 days after transplanting). The experiment was laid out according to a complete randomized design with 3 replicates per treatment. Irrigation frequency treatments consisted of: daily (I_1), weekly (I_2) and every 2 weeks of irrigation (I_3). Each pot was irrigated to the soil field capacity level. Four levels of salinity treatments were as follows: electrical conductivities (EC) of 0.8 (J_1); 2.5 (J_2); 5.0 (J_3) and 7.0 (J_4) dS·m^{-1}. Pots were weighed prior to each irrigation, and the weight of irrigation water amount (W_I) was computed as:

$$W_I = \frac{W_{FC} - W}{1 - LF} \quad (1)$$

where W and W_{FC} are each pot weight (g) just before irrigation and at field capacity, respectively. W_{FC} is calculated as the weight summation of plastic pots ($W_{plastic\ pots}$), dry soil ($W_{dry\ soil}$), water at field capacity ($W_{\theta FC}$) and plant (W_{plant}).

$$W_{FC} = W_{plastic\ pots} + W_{dry\ soil} + W_{\theta FC} + W_{plant} \quad (2)$$

$W_{plastic\ pots}$, $W_{dry\ soil}$ and $W_{\theta FC}$ ($\rho_b \times \theta_{FC} \times$ soil volume) were defined at the beginning of the experiment and W_{plant} was assessed using pot weight (W_{total}) and soil moisture (θ_{i-1}) a day before irrigation as:

$$W_{plant} = W_{total} - (W_{plastic\ pots} + W_{dry\ soil} + W_{\theta_{i-1}}) \quad (3)$$

where $W_{\theta_{i1}}$ is mass of soil water 1 day before irrigation, calculated as $\rho_b \times \theta_{i-1} \times$ soil volume.

Table 2. Number of irrigation and total water applied (mm) in outdoor and greenhouse treatments

Treatment		I_1J_1	I_1J_2	I_1J_3	I_1J_4	I_2J_1	I_2J_2	I_2J_3	I_2J_4	I_3J_1	I_3J_2	I_3J_3	I_3J_4
Number of irrigation		110	110	110	110	16	16	16	16	8	8	8	8
Outdoor irrigation water applied	1st year	924.3	758.6	682.1	610.4	662.8	539.1	482.5	447.1	481.5	356.6	308.8	277.6
	2nd year	1036.3	870.8	756.9	634.5	769.3	630.0	548.0	471.0	531.2	401.3	323.2	271.8
Greenhouse irrigation water applied	1st year	676.2	573.7	521.0	463.5	460.8	363.7	345.7	313.1	293.1	236.2	235.4	213.8
	2nd year	738.9	670.3	575.6	513.2	541.4	448.0	393.8	374.2	375.2	308.6	282.8	256.9

Leaching fraction (LF) of 0.15 was considered for efficient irrigation as proposed by Ayers and Westcot (1985). Leachate was gathered and weighed after irrigation using empty pans placed underneath each pot. Table 2 shows the number of irrigations and total water applied in the outdoor and greenhouse treatments.

Crop dry matter (DM) was determined during 7 stages at 2-week intervals including harvest time. Seven extra pots were reserved for each treatment, the plants from which were used to measure dry matter at 6 stages during the growing season. Fruits per plant were gathered and weighed during August and September. Shoot and root dry weights were determined next. It should be noted that in eggplant cultivation there is the possibility of periodic and continuous harvests after the first crop. Therefore, harvest index values were calculated as the ratio of fruit weight at the first harvest to weight of above-ground dry matter.

Model theory

Logistic models using 'calendar days after planting' as the independent variable, may provide unsatisfactory estimates in regions with different climatic conditions (Mahbod et al., 2015). On the other hand, temperature is one of the most important factors governing plant growth (Sadek et al., 2013). Growing degree-days is considered as an important factor for all biological development due to its simple estimations of the accumulated heat energy available over the growing season or life cycle of an organism. The rate of growth and phenological development of individual plants has been found to increase almost linearly from a base to a limiting temperature threshold (Cesaraccio et al., 2001; Fealy, 2008). Therefore, to designate variable environmental conditions during growing season and planting dates, cumulative heat unit (GDD) was calculated as follows:

$$GDD = \sum \left(\frac{T_{max_i} + T_{min_i}}{2} - T_b \right) \qquad (4)$$

where T_{min} and T_{max} are the daily minimum and maximum air temperature at Day i (°C), T_b is the base temperature of 11°C according to Rouphael et al. (2010). No degree days were considered for days with average temperatures equal or below T_b.

Distinct plant features such as crop height, canopy, population and biomass growth can be modelled by 'S-shaped' logistic functions of GDD as below (Shabani et al., 2018a):

$$Y = \frac{K}{C + A \exp(-B \times GDD)} \qquad (5)$$

In this study, Y is considered as eggplant DM, and K, A, B and C are coefficients of the equation. In the calibration phase, K, A, B and C were determined using DM values measured in the first year of the experiment by Solver tool in MS Excel. These coefficients were then fitted to quadratic functions of seasonal applied water (I) and water salinity (EC) via stepwise multiple regression analysis. The calibrated experimental logistic model was then used to estimate eggplant DM for the second year. Finally, the predicted DM values were compared with the measured values in order to validate the model in the greenhouse and outdoor environments.

Statistical evaluation

Statistical parameters used to describe the model accuracy were coefficient of determination (R^2) (interpreted as the proportion of the variance in the dependent variable that is predictable from the independent variable, indicating the extent to which the dependent variable is predictable), normalized root mean square error (*NRMSE*), index of agreement (*d*) and F-test (Willmott et al., 1985):

$$R^2 = \left(\frac{\sum_{i=1}^{n}(P_i - \bar{P})(O_i - \bar{O})}{\sqrt{\sum_{i=1}^{n}(P_i - \bar{P})^2 \sum_{i=1}^{n}(O_i - \bar{O})^2}} \right)^2 \qquad (6)$$

$$NRMSE = \frac{\sqrt{\dfrac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}}}{\bar{O}} \qquad (7)$$

$$d = \frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(|P_i - \bar{O}| + |O_i - \bar{O}|)^2} \qquad (8)$$

where P_i and O_i are the predicted and observed values, respectively, n is the data number, $\bar{O}$ and $\bar{P}$ are the observed and predicted mean values, respectively. The simulation is considered excellent with a NRMSE less than 0.1, good if the NRMSE is greater than 0.1 and less than 0.2, fair if the NRMSE is greater than 0.2 and less than 0.3, and poor if the NRMSE is greater than 0.3 (Jamieson et al., 1991; Mahbod et al., 2015). According to the d-index, the closer the index value is to 1, the better the agreement between the two variables that are being compared and vice versa.

RESULTS AND DISCUSSION

Table 3 indicates some eggplant growth traits, including final fruit yield per plant (*Y*), fruit size and shoot dry matter weights (shoot DM). As designated in Table 3, both irrigation and salinity significantly affected eggplant fruit yield. Nevertheless, the yield values were not significantly different in I_1 and I_2 treatments in either environment, except for outdoor cultivation in the second year (Table 4). Moreover, the deleterious effects of salt stress were reinforced by the prolongation of irrigation intervals, as has been reported by Rameshwaran (2015). Table 3 also shows EC$_e$ values for each irrigation and water salinity treatment. Such values ranged from 2.7 (I_1J_1) to 18.8 (I_3J_4) and 1.6 to 16.4 dSm^{-1} for outdoor and greenhouse pots, respectively. As the salinity of irrigation water (EC$_w$) increased, EC$_e$ tended to increase significantly for all watering frequency treatments in both outdoor and greenhouse environments. The higher EC$_e$ value observed in the outdoor treatments in comparison to the greenhouse pots was due to the higher evaporation occurring from the surface, as reported by Aragüés et al. (2005).

Table 3. Effect of different levels of water application and salinity on the experimental soil and plant properties in outdoor and greenhouse conditions

Treatment	ET_c (mm) 1st year		2nd year		EC_e (dS·m⁻¹) 1st year		2nd year		Y (g·plant⁻¹) 1st year		2nd year		Fruit diameter (cm) 1st year		2nd year		Shoot DW (g·plant⁻¹) 1st year		2nd year	
									Outdoor											
I_1J_1	846.6	a	954.6	a	2.7	e	3.1	g	2 490.1	ab	2 587.4	a	6.5	a	7.1	a	38.7	a	43.5	a
I_1J_2	680.9	b	789.0	b	8.5	d	7.2	ef	1 713.2	cd	1 748.2	bc	5.9	ab	6.0	abc	34.1	ab	36.6	a
I_1J_3	604.4	bc	675.1	c	10.6	cd	9.3	d	1 690.8	cd	1 714.1	bc	5.2	abc	5.2	abcd	29.4	bc	27.7	bc
I_1J_4	532.7	cd	552.8	d	11.4	cd	9.5	d	1 536.4	cde	1 429.7	cd	3.8	cde	4.9	bcd	26.0	bc	28.0	b
I_2J_1	604.7	bc	707.5	c	3.2	e	6.7	f	2 720.3	a	2 019.3	b	6.1	a	6.5	ab	41.0	a	41.7	a
I_2J_2	476.6	cde	564.2	d	9.8	d	9.9	d	1 723.2	cd	1 658.4	bc	5.5	ab	6.1	abc	38.4	a	39.2	a
I_2J_3	417.9	def	478.5	e	12.8	bc	13.2	c	1 282.4	cdef	1 351.6	cd	5.0	abcd	6.0	abc	28.0	bc	26.5	bc
I_2J_4	380.3	efg	400.1	f	15.2	ab	15.7	b	806.8	def	993.4	de	3.5	de	4.2	cd	25.0	bcd	24.4	bc
I_3J_1	439.2	de	482.6	e	4.3	e	7.9	e	1 909.9	bc	1 878.2	bc	4.4	bcd	5.1	abcd	27.9	bc	25.5	bc
I_3J_2	299.6	fgh	344.7	f	14.4	b	14.7	b	1 165.4	cdef	1 376.7	cd	3.8	cde	3.8	d	20.6	cd	22.0	bc
I_3J_3	251.4	gh	261.0	g	14.4	b	15.2	b	956.2	def	963.7	de	3.3	de	4.2	cd	22.3	cd	23.4	bc
I_3J_4	215.7	h	205.0	g	17.4	a	18.8	a	527.9	f	598.9	e	2.7	e	3.5	d	16.6	d	19.7	c
									Greenhouse											
I_1J_1	598.5	a	657.2	a	1.6	d	2.0	h	2 405.3	ab	2 510.0	a	6.0	a	6.6	a	36.7	a	40.8	a
I_1J_2	495.9	b	588.6	b	9.9	c	6.8	f	1 849.7	c	1 869.1	b	5.2	ab	5.6	abc	31.2	ab	32.0	bc
I_1J_3	443.3	bc	493.8	c	11.6	bc	10.6	c	1 141.5	de	1 424.5	d	4.5	bc	5.0	bcd	28.1	bc	28.5	bcd
I_1J_4	385.8	cd	431.4	de	13.9	ab	11.0	c	1 006.4	def	1 210.2	de	4.2	bc	4.5	cde	25.7	bcd	31.3	bc
I_2J_1	394.2	cd	475.0	cd	2.1	d	3.3	g	2 679.0	a	2 290.3	a	6.0	a	6.4	a	37.2	a	39.3	a
I_2J_2	294.3	de	379.7	e	11.7	bc	8.4	e	1 590.0	cd	1 516.7	cd	5.5	ab	6.2	ab	32.1	ab	34.8	ab
I_2J_3	275.9	e	323.0	f	11.6	bc	10.3	cd	962.1	ef	1 411.1	d	5.2	ab	5.5	abc	29.3	ab	27.4	bcd
I_2J_4	242.2	ef	301.2	fg	14.0	ab	12.6	b	779.3	ef	1 184.7	de	3.0	cd	3.6	de	26.8	bcd	28.2	bcd
I_3J_1	233.4	ef	318.0	f	2.7	d	5.5	F	2 080.6	bc	1 781.6	bc	4.3	bc	4.8	bcde	31.1	ab	21.4	d
I_3J_2	171.4	f	249.1	gh	11.9	bc	9.0	De	914.0	ef	1 212.0	d	3.2	cd	3.4	e	23.9	bcd	24.5	cd
I_3J_3	169.3	f	217.4	hi	12.5	bc	12.7	B	779.3	ef	893.0	ef	3.6	cd	3.9	de	20.9	bcd	25.6	cd
I_3J_4	145.3	f	187.3	i	16.4	a	16.3	A	497.9	f	789.0	f	2.7	d	3.3	e	19.1	d	22.0	d

Values followed by the same letter are not significantly different according to Duncan's multiple range test at 0.05 significance level

Table 4. Duncan's multiple range test for yield

Year			Outdoor			Greenhouse		
	I	n	M	G	EMS	M	G	EMS
1st year	1	12	1 857.6	A	96 611.62	1 600.73	A	43 230.75
	2	12	1 633.2	A		1 502.6	A	
	3	12	1 139.9	B		1 067.95	B	
2nd year	1	12	1 869.9	A	82 440.89	1 753.46	A	37 281.75
	2	12	1 505.7	B		1 600.71	A	
	3	12	1 204.4	C		1 168.91	B	
1st year	1	9	2 373.5	A	96 611.62	2 388.3	A	43 230.75
	2	9	1 533.9	B		1 451.22	B	
	3	9	1 309.8	B		960.98	C	
	4	9	957	C		761.22	C	
2nd year	1	9	2 161.6	A	82 440.89	2 193.99	A	37 281.75
	2	9	1 594.4	B		1 532.6	B	
	3	9	1 343.1	B		1 242.85	C	
	4	9	1 007.3	C		1 061.31	C	

M: mean (g/plant), G: Duncan grouping, EMS: error mean square, α = 0.05, error degrees of freedom = 24

As shown in Table 3, longer irrigation intervals from I_1 to I_3, escalate EC_e values in both outdoor and greenhouse environments. Both water deficit and salinity significantly affected EC_e values according to ANOVA analysis.

Considering the environment as a cause of variations, a compound analysis of variance was exercised to compare the results of I and J treatments on greenhouse yields with the outdoor ones.

As shown in Table 5, no significant effect of environment was met on Y and EC_e values, while it significantly affected ET_C at 5%.

Given that the obtained results showed no significant difference in salinity of the saturated extract in the greenhouse and the outdoor conditions, EC_e could not be considered as the effective factor for obtaining quadratic equations for estimation of B, C, and K, whereas irrigation water salinity was considered as an effective

Table 5. Source of variation, related *F*-ratios and Pr-values calculated from compound ANOVA from SAS software for the ET_c, Y and EC_e

Source	DF	1st year						2nd year					
		ET_C		Y		EC_e		ET_C		Y		EC_e	
		F value	Pr > F	F value	Pr > F	F value	Pr > F	F value	Pr > F	F value	Pr > F	F value	Pr > F
Environment	1	181.52	<.0001*	6.04	0.0177	1.82	0.1837	330.18	<.0001*	0.11	0.744	2.12	0.1521
I	2	268.66	<.0001*	36.17	<.0001*	34.22	<.0001*	638.06	<.0001*	39.54	<.0001*	30.13	<.0001*
Environment × I	2	2.62	0.0835	0.77	0.47	7	0.0022	18.92	<.0001*	1.14	0.3281	9	0.0017
J	3	54.83	<.0001*	112.87	<.0001*	310.06	<.0001*	175.65	<.0001*	72.37	<.0001*	299.01	<.0001*
I × J	6	1.39	0.2388	2.46	0.0372	1.79	0.1209	3.26	0.009	0.35	0.9087	3.22	0.09743
Environment × J	3	3.93	0.0138	1.57	0.2083	1.43	0.246	15.12	<.0001*	0.41	0.7458	2.07	0.177
Environment × I × J	6	0.14	0.991	1.01	0.429	1.65	0.1548	0.24	0.9621	0.92	0.4917	1.99	0.1128

Values are significant at 5%

Table 6. Coefficients of calibrated logistic equation (*K*, *B*, *A* and *C*) based on GDD for each *I* and *J* treatment in outdoor and greenhouse conditions (calibration)

Environment	Treatment	K	A	B	C
Outdoor	I_1J_1	284 472.53	100 000	0.0028	5 126.16
	I_1J_2	287 317.25	100 000	0.0029	6 664.01
	I_1J_3	301 683.12	100 000	0.0031	8 663.21
	I_1J_4	316 767.27	100 000	0.0032	11 262.18
	I_2J_1	298 696.16	100 000	0.0029	5 382.47
	I_2J_2	313 630.96	100 000	0.0030	6 458.96
	I_2J_3	316 767.27	100 000	0.0032	8 719.60
	I_2J_4	332 605.64	100 000	0.0033	10 463.52
	I_3J_1	209 087.31	100 000	0.0030	5 651.59
	I_3J_2	229 996.04	100 000	0.0032	7 912.23
	I_3J_3	252 995.64	100 000	0.0033	8 703.45
	I_3J_4	265 645.43	100 000	0.0035	12 184.84
Greenhouse	I_1J_1	224 472.53	100 000	0.0031	5 126.16
	I_1J_2	231 206.70	100 000	0.0032	6 664.01
	I_1J_3	242 767.04	100 000	0.0034	7 996.81
	I_1J_4	267 043.74	100 000	0.0035	10 395.86
	I_2J_1	235 696.16	100 000	0.0031	5 638.78
	I_2J_2	259 265.77	100 000	0.0032	7 330.41
	I_2J_3	311 118.93	100 000	0.0033	10 262.58
	I_2J_4	357 786.76	100 000	0.0034	12 315.09
	I_3J_1	238 053.12	100 000	0.0032	6 202.66
	I_3J_2	249 955.77	100 000	0.0033	9 303.98
	I_3J_3	312 444.72	100 000	0.0034	13 955.98
	I_3J_4	374 933.66	100 000	0.0035	19 538.37

factor for its simplicity. On the other hand, due to the difference in the mean DM in the greenhouse and outdoor conditions, independent and separate logistic functions were fitted for the mentioned conditions.

Crop growth modelling

Model calibration

First-year values of total plant dry matter accumulation (DM) and GDD were used to obtain the coefficients of Eq. 4 that are presented in Table 6 for greenhouse and outdoor conditions. As reported by Sepaskhah et al. (2011), the calibration coefficients are affected by agronomic management parameters. A similar trend was observed for this study, so that, *K* and *B* values increased with increasing levels of water and salinity. Furthermore, *B* values increased with higher water application levels and decreased at

higher salinity levels. Thus, the calibrated *K*, *B* and *C* coefficients were fitted to quadratic functions based on seasonal applied water (*I*) and water salinity (EC) using stepwise multiple regression analysis. Such functions are given as follows:

$$K_{Outdoor} = -393749 + 1560.6(I) + 108500(EC) - 4661(EC^2)$$
$$- 0.87(I^2) - 124.9(EC \times I) + 4.62 \times 10^{-3}(EC^2 \times I^2)$$

$n = 12, R^2 = 0.92, p = 0.009$ (9)

$$B_{Outdoor} = 3.73 \times 10^{-3} - 1.9 \times 10^{-6}(I) - 4.6 \times 10^{-5}(EC)$$
$$+ 5.9 \times 10^{-6}(EC^2) + 9.2 \times 10^{-10}(I^2) + 1.3 \times 10^{-7}(I \times EC)$$
$$- 1 \times 10^{-11}(I^2 \times EC^2)$$

$n = 12, R^2 = 0.97, p < 0.001$ (10)

$$C_{Outdoor} = 11876 - 16.2(I) - 459.8(EC) + 92.3(EC^2)$$
$$+ 8.9 \times 10^{-3}(I^2) + 1.19(I \times EC) - 4 \times 10^{-5}(I \times EC)^2$$
$$n = 12, R^2 = 0.96, p = 0.0012 \tag{11}$$

$$K_{Greenhouse} = 167266 - 300.3(I) - 5703(EC) - 0.35(EC^2)$$
$$+ 2982.6(I^2) + 13.16(EC \times I) + 1.8 \times 10^{-2}(EC^2 \times I^2)$$
$$n = 12, R^2 = 0.96, p = 0.001 \tag{12}$$

$$B_{Greenhouse} = 3.46 \times 10^{-3} - 1.4 \times 10^{-6}(I) + 1.6 \times 10^{-5}(EC)$$
$$- 1.07 \times 10^{-9}(EC^2) - 2.3 \times 10^{-7}(I^2) + 7.48 \times 10^{-8}(I \times EC)$$
$$+ 6.94 \times 10^{-12}(I^2 \times EC^2)$$
$$n = 12, R^2 = 0.97, p < 0.001 \tag{13}$$

$$C_{Greenhouse} = 8437.2 - 20.37(I) + 3451.9(EC) + 0.0256(EC^2)$$
$$- 72.8(I^2) - 5.97(I \times EC) + 4.25 \times 10^{-4}(I \times EC)^2$$
$$n = 12, R^2 = 0.95, p = 0.003 \tag{14}$$

where n is the number of observations and p is the probability level. Values of A were not noticeably different at different levels of salinity and applied water, which agreed with the results of Mahbod et al. (2015), in which the values of A were assumed constant at different irrigation levels and nitrogen rates. Therefore, A was considered as a constant value of 100 000 according to the average of calculated A in each treatment.

Figure 2 demonstrates sample results of measured and predicted DM changes with GDD for I_1 irrigation water level under different salinity levels. According to the results, the developed logistic equations properly predicted DM values in both environments. Shabani et al. (2014) reached the same results estimating yield and dry matter of rapeseed. According to their study, statistical parameters indicated that logistic equation was fitted very accurately for all irrigation and water salinity treatments. To investigate the model accuracy over all treatments, measured DM values during the growing season (DM_m) are compared with the estimated ones (DM_P) with the 1:1 line in Fig. 3. The satisfying values of d (0.96, 0.97); NRSME (0.13, 0.11) and R^2 (0.91, 0.89) in outdoor and greenhouse conditions, respectively, along with regression line slopes close to 1 (1.02, 0.89), statistically confirm that the calibrated empirical models accurately estimated eggplant dry matter.
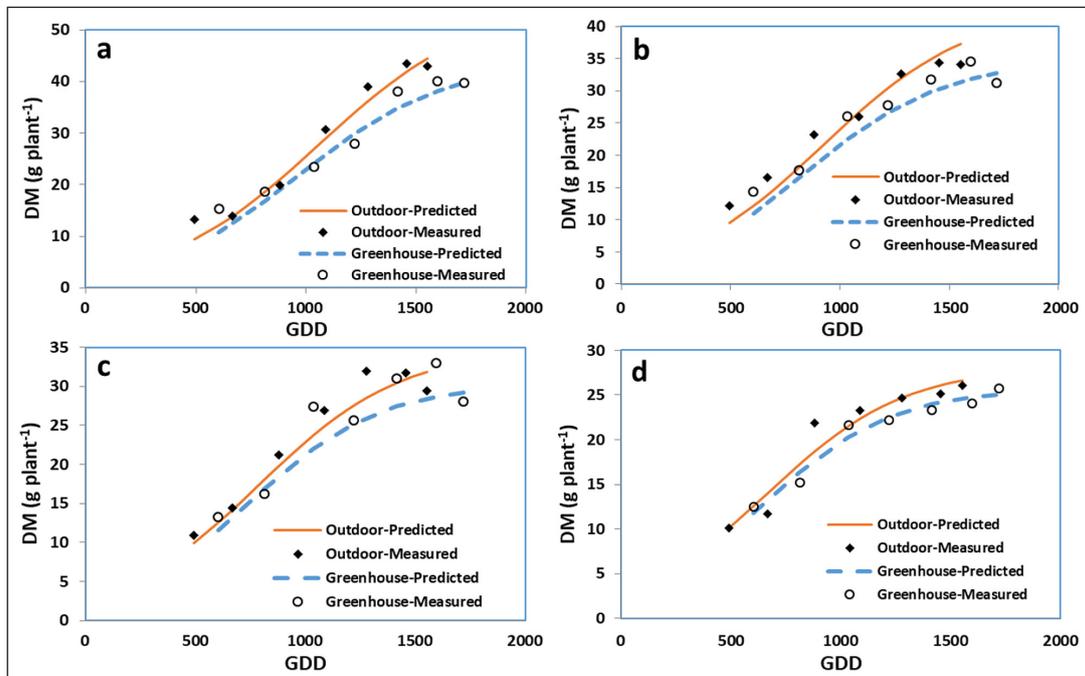
Figure 2. Changes of measured and predicted eggplant dry matter (*DM*) with cumulative growing degree days (*GDD*) for I_1J_1(a), I_1J_2(b), I_1J_3(c), and I_1J_4(d) treatments (2012, calibration)
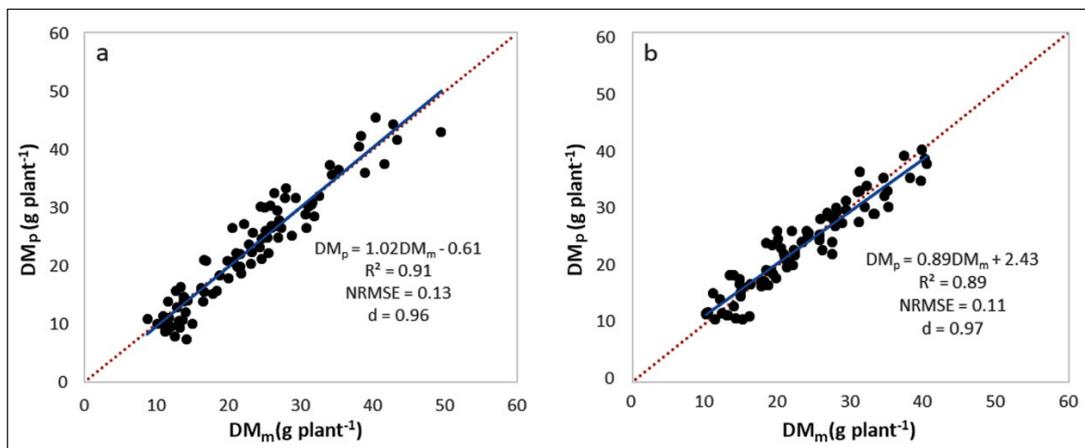
Figure 3. Relationship between measured and predicted values of dry matter in (a) outdoor and (b) greenhouse eggplants during the first growing experiment (2012, calibration)

Harvest index and yield

Using multiple regression analysis, harvest index (HI) as a function of seasonal irrigation water and water salinity, is determined as follows:

$$HI = 0.8 + 1.41 \times 10^{-4} (I) - 0.021 (EC) - 1.60 \times 10^{-7} (EC^2)$$
$$- 1.2 \times 10^{-7} (I^2) - 2.2 \times 10^{-5} (I \times EC) + 1.01 \times 10^{-8} (I \times EC)^2$$

$$n = 12, R^2 = 0.84, p < 0.001 \tag{15}$$

Eggplant dry fruit yield (Y_P) was estimated from HI equation (Eq. 15) multiplied by predicted DM values at harvest time in 2012. The relationship between predicted (Y_P) and measured (Y_M) dry fruit yields in the first year are shown in Fig. 4. Low scatter of data, shown by high values of R^2 along with statistical factors d and NRSME close to 1 and 0, respectively, indicates high accuracy of the calibrated model in prediction of fruit yield.

Model validation

Total dry matter

Measured values of irrigation water in the second year of experiment (2013), along with water salinity, were applied to estimate K, B and C coefficients using Eqs 9–14 for 2013. The obtained values are presented in Table 7. Total dry matter (DM_p) values for the second year were then obtained using the developed logistic model and GDD data. Such values were compared with the measured DM during the second growing season (DM_m) in order to validate the model.
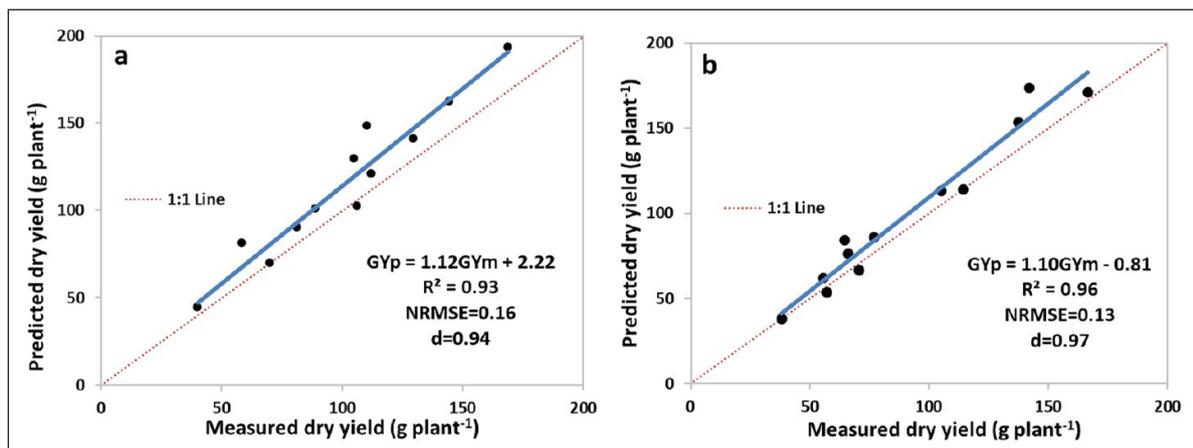
Figure 4. Relationship between measured and predicted values of dry yield (DY) in (a) outdoor and (b) greenhouse eggplants during the first growing experiment (2012, calibration)

Table 7. Coefficients of logistic equation (K, B, A and C) based on GDD for each I and J treatment in outdoor and greenhouse conditions (validation)

Environment	Treatment	K	A	B	C
Outdoor	I_1J_1	301 342.09	100 000	0.0028	5 113.98
	I_1J_2	312 636.14	100 000	0.0030	6 296.72
	I_1J_3	320 828.70	100 000	0.0031	8 616.16
	I_1J_4	317 434.74	100 000	0.0033	11 007.69
	I_2J_1	278 305.09	100 000	0.0029	5 394.51
	I_2J_2	277 569.53	100 000	0.0031	6 716.97
	I_2J_3	308 817.85	100 000	0.0032	8 807.50
	I_2J_4	316 080.48	100 000	0.0033	11 078.66
	I_3J_1	192 892.27	100 000	0.0030	6 304.86
	I_3J_2	186 852.73	100 000	0.0032	7 704.21
	I_3J_3	249 594.68	100 000	0.0033	9 489.09
	I_3J_4	278 510.29	100 000	0.0035	11 546.35
Greenhouse	I_1J_1	206 403.24	100 000	0.0031	6 725.35
	I_1J_2	215 527.45	100 000	0.0032	5 666.48
	I_1J_3	214 692.96	100 000	0.0034	6 975.48
	I_1J_4	227 981.19	100 000	0.0035	9 354.59
	I_2J_1	236 263.28	100 000	0.0031	5 136.01
	I_2J_2	256 547.03	100 000	0.0032	6 477.18
	I_2J_3	289 842.56	100 000	0.0033	9 716.47
	I_2J_4	326 473.91	100 000	0.0034	12 267.20
	I_3J_1	239 574.94	100 000	0.0031	5 366.07
	I_3J_2	258 918.23	100 000	0.0032	8 412.04
	I_3J_3	309 586.46	100 000	0.0034	12 568.88
	I_3J_4	372 268.43	100 000	0.0034	16 120.25
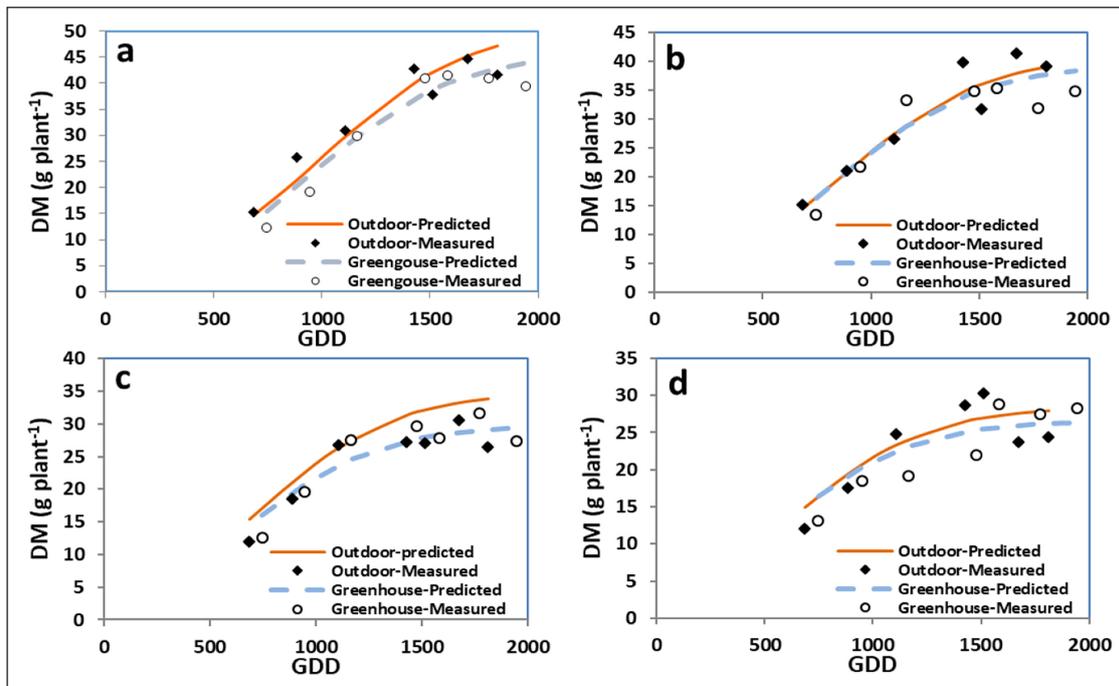
Figure 5. Changes of measured and predicted eggplant dry matter (DM) with cumulative growing degree days (GDD) for I_2J_1, I_2J_2, I_2J_3, and I_2J_4 treatments, 2013 (2013, validation)
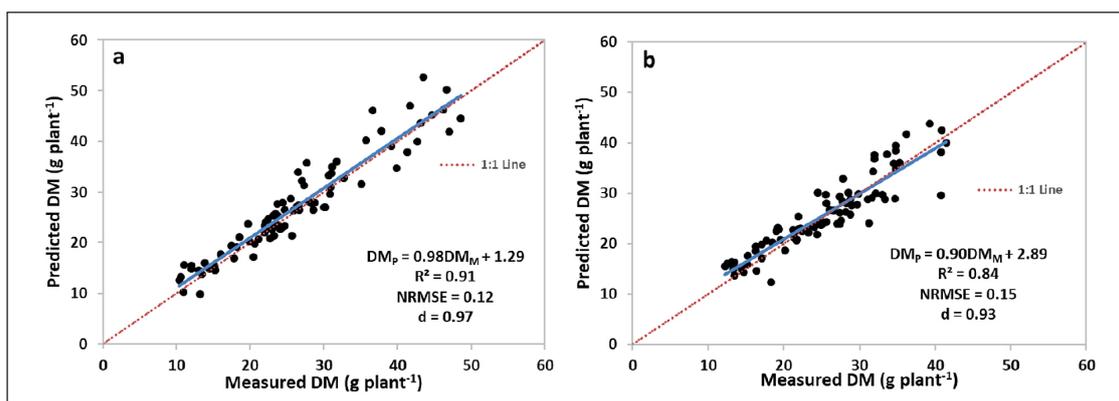
Figure 6. Relationship between measured and predicted values of dry matter in (a) outdoor and (b) greenhouse eggplants during the second growing experiment (2013, validation)

Figure 5 indicates the comparison between DM_P and DM_m during the growing season for I_2 treatments in outdoor and greenhouse conditions. Satisfying agreement between the measured and predicted values of DM was also obtained for other treatments with good accuracy. The linear relationship between measured and estimated values of DM was compared with the 1:1 line to evaluate the model in Fig. 6. The slopes were close to 1.0 in both environmental conditions and the values of NRMSE (0.12, 0.15) and d (0.97, 0.93) and R^2 (0.91 and 0.84 for outdoor and greenhouse, respectively) indicated accurate estimations in either environment. Xiangxiang et al. (2014) predicted DM values of winter wheat under different irrigation treatments in China's Loess Plateau using logistic function and obtained relative errors from 2–15%. Mahbod et al. (2015) and Shabani et al. (2015) found similar results for wheat and winter sorghum under different water and nitrate fertilization treatments, with NRMSE values of 0.11 and 0.02, respectively. Results of the present study alongside previous investigations indicate that logistic functions can properly predict DM values during the growing season.

Fruit yield (Y)

Fruit yield was predicted using the estimated DM values (Eqs 5 and 9–14) and HI values obtained from Eq. 15 in the second year of experiment. The relationship between predicted and measured values of final DM, HI and DY are shown in Fig. 7, for outdoor (a), greenhouse (b) and total (c) treatments. NRMSE values in Fig. 7 show proper estimations of dry matter at the end of cropping season, inside and outside of the greenhouse. The outdoor value of the d index was close to 1 (0.9) indicating model accordance with measured values; however, the value obtained in the greenhouse was smaller (0.69). Despite the high value of R^2 in outdoor conditions, a considerably lower value was obtained for greenhouse conditions, implying that the fitted function in greenhouse conditions could not predict the variation of changes in total DM. On the other hand, accuracy in HI estimations was uppermost, obtaining NRMSE values of 0.04 in both conditions. Shabani et al. (2015) also found 0.02 for NRMSE in HI estimations and, according to Mahbod et al. (2015), HI values were predicted with proper precision. Errors of Y estimation in outdoor and greenhouse estimations increased up to 0.22 and 0.27, respectively, due to integration of total HI and DM estimation errors. Similar results were found by Mahbod et al. (2015) in which NRMSE values of crop estimation were 0.11 higher than those of DM. Generally, the logistic model precision was acceptable for eggplant crop yield estimation in both greenhouse and outdoor conditions.
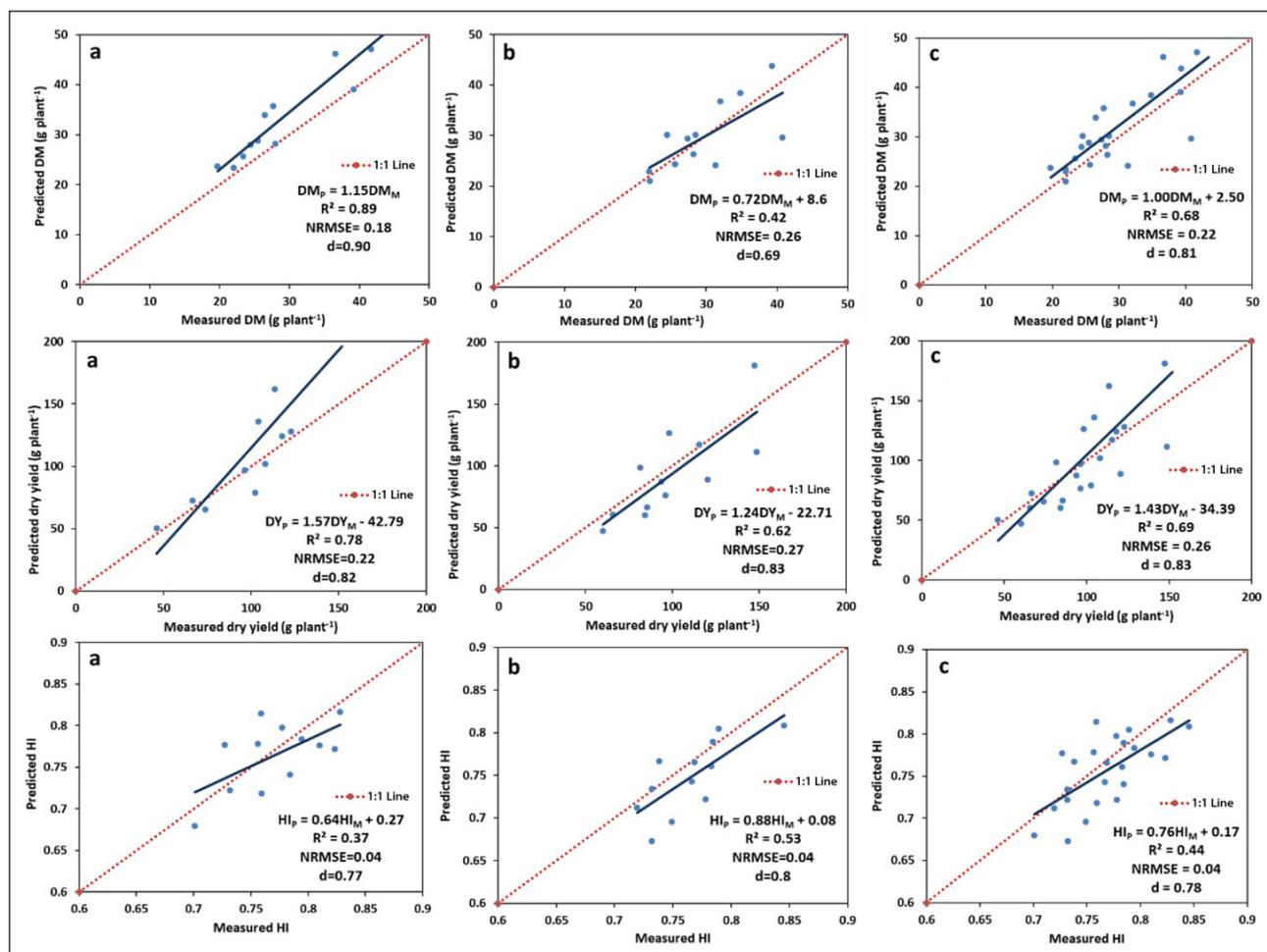
Figure 7. Relationship between predicted and measured values of final DM, HI and DY in (a) outdoor, (b) greenhouse and (c) total treatments (2013, calibration)

CONCLUSIONS

The effect of irrigation regimes and water salinity on eggplant evapotranspiration, dry matter, and yield was studied in greenhouse and outdoor conditions, during two 110-day experiments conducted in two successive years (2012 and 2013). Final dry matter and fruit yield of eggplant were simulated with an empirical logistic growth model based on GDD under different levels of water deficit and salinity. Such models can only be applied for the same weather conditions under which models were developed. Therefore, the model was first calibrated using the measured DM values during the first year of experiment. Logistic function coefficients and the harvest index were related to total irrigation water application and water salinity. Finding acceptable accuracy in the calibrated model, the model was validated according to the DM and fruit yield data collected during the second year. Statistical analysis indicated that the accuracy of the model in DM, HI and *Y* estimations was fair, excellent and fair, respectively. *d* index values showed good accordance of the model with measured data. Hence, the logistic model can be used to predict eggplant DM and fruit yield.

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