Modeling tomato evapotranspiration and yield responses to salinity using different macroscopic reduction functions

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Abstract

Plant responses to salinity can be used to manage irrigation with brackish water. This study evaluated effects of brackish water irrigation on tomato (\textit{Solanum lycopersicum} L.) plants, proposed a new model to describe plant relative evapotranspiration (ET) and relative yield as a function of electrical conductivity of soil saturated paste extract (ECe), and compared the estimations of the new model with four other models (linear model of Mass and Hoffman, and three nonlinear models of van Genuchten, Dirksen, and Homae). A greenhouse experiment was conducted with five salinity treatments: tap water of EC 0.6, brackish groundwater of EC 2 and 3, and reverse osmosis (RO) of EC 4 and 6 dSm\(^{-1}\). Results indicated no changes in leaf photosynthesis rate (\(P_\text{n}\)), transpiration rate (\(T_\text{r}\)), and stomatal conductance (\(G_\text{s}\)) up to 2 dSm\(^{-1}\) irrigation water salinity. Nonlinear models better described tomato yield and seasonal ET. The proposed new model performed best when compared with four previous models to predict tomato yield and ET responses to salinity. The calculated soil salinity threshold values (ECe\textsuperscript{*}) from the new model were 1.73 dSm\(^{-1}\) for yield and 2.52 dSm\(^{-1}\) for ET. Data from published studies on effects of irrigation water salinity (ECw) on tomato yield and ET were analyzed to validate models. The results showed that the new model was simpler and superior in estimating plant responses to ECw. Tomato is a salt-sensitive crop, and irrigation with brackish waters adversely influences growth and ET.

1 | INTRODUCTION

Soil salinization is a growing trend due to the continual use of brackish irrigation water and the accumulation of salt with time because of low rainfall and high evapotranspiration in arid and semiarid areas. This problem is expected to worsen with increasing population and industries and the associated demand for good-quality water (Massaretto et al., 2018). Low rainfall and drought in many areas of the world are also diminishing the supply of surface water for irrigation. Thus, brackish groundwater is frequently used for irrigation, which could further increase salt buildup near the soil surface (Duan & Fedler, 2013). Consequently, abiotic stresses and associated nutritional imbalances induced in plants can adversely affect yield and growth (Baath, Shukla, Bosland, Steiner, & Walker, 2017).

Abbreviations: EC, electrical conductivity; ECe, electrical conductivity of soil saturated paste extract; ET, evapotranspiration; RO, reverse osmosis.

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About 1,100 million ha of land are affected by salt worldwide, and about 1.5 million ha are becoming unusable for agricultural production due to high salinity levels every year (Hossain, 2019). Thus, clarifying the mechanisms of plant responses to salt stress and providing solutions for improving crop acclimation to abiotic stresses are critical to meet the increasing food demand across sustainable agriculture when saline water is increasingly used for irrigation, especially in arid and semiarid areas of the world (Baath et al., 2017; Flores, Shukla, Schutte, Picchioni, & Daniel, 2017).

Tomato (Solanum lycopersicum L.), with a global annual production of > 1.78 x 10^8 tons (FAOSTAT, 2016), is one of the most important vegetable crops worldwide. It is moderately sensitive to salinity and can tolerate up to 2.0 dS m^{-1} at a soil saturation extract electrical conductivity (EC_s); growth and yield decline above this level (Shalhevet & Yaron, 1973). Short-term exposure of plants to high salt concentration in the soil makes it difficult for roots to extract water due to the osmotic stress (Munns & Tester, 2008). Tomato plants irrigated with nutrient solution (9.1 dS m^{-1}) consumed 40% less water than control irrigated plants, and reductions in plant water uptake with increasing salinity ranged from 3.5 to 5% per 1 dS m^{-1} among different cultivars (Reina-Sánchez, Romero-Aranda, & Cuartero, 2005). Salinity-induced water uptake loss was regulated by plant transpiration through decreased stomatal density and aperture (Albaladejo et al., 2017), which were derived from decreased soil water potential (Ghanem et al., 2008; Li, Wang, Xiao, & Xu, 2015; Poór et al., 2019). For tomato grown in pots where salts were mixed with soil, yield per plant decreased by 27.3% at soil salt content of 0.3%, corresponding to an EC_e of 1.03 dS m^{-1} (Yang, Shukla, Mao, Kang, & Du, 2019). A different study found 10% yield decline for every 1.5 dS m^{-1} increase when EC_s was above 2.0 dS m^{-1} (Shalhevet & Yaron, 1973).

Salt toxicity takes time to accumulate in plants before it reduces plant productivity and induces leaf senescence in the second phase of salt stress (Farooq, Hussain, Wakeel, & Siddique, 2015; Munns & Tester, 2008). Because salinity stress develops over time, the rate at which old leaves die is greater than the rate at which new leaves grow, and the plant growth rate further decreases because of the insufficient supply of photosynthetic assimilation (Munns & Tester, 2008), consequently causing yield reductions. It was reported that tomato yield was linearly correlated with transpiration for short time periods; linear yield to transpiration relationships have been used in crop or water uptake models to estimate yield based on predicted transpiration values (Ben-Gal, Karlberg, Jansson, & Shani, 2003; Shani & Dudley, 2001). However, in previous research, positive relationships between tomato yield and seasonal evapotranspiration were also fitted using nonlinear models (Patané, Tringali, & Sortino, 2011; Yang et al., 2017). Although tomato plants are inhibited by increasing salinity, evapotranspiration and yield might not respond in the same way to salt stress. Response of evapotranspiration to an increase of 1 dS m^{-1} in salinity is not the same as yield’s response to the same increase. Different responses of evapotranspiration and yield to osmotic and ionic stresses are not clearly understood.

Plant response to salinity is mathematically expressed in terms of relative transpiration or relative yield as a function of EC_s or irrigation water salinity. Skaggs, van Genuchten, Shouse, and Poss (2006) demonstrated macroscopic simulating approaches, which are based on the Richards equation with a sink term of water uptake, and estimated uptake reduction parameters from alfalfa (Medicago sativa L.) databases. There are several macroscopic water uptake functions proposed by different researchers (Dirksen, Kool, Koorevaar, & van Genuchten, 1993; Homae, Dirksen, & Feddes, 2002; Homae, Feddes, & Dirksen, 2002a, 2002b, 2002c; Maas & Hoffman, 1977; van Genuchten & Hoffman, 1984). Some researchers evaluated plant transpiration sensitivity to salinity using these four functions (for alfalfa, Homae, Dirksen, & Feddes, 2002; and for basil [Ocimum basilicum L.], Babazadeh, Tabrizi, & Homae, 2016). Others modeled the relationships between salinity and plant yield of durum wheat (Triticum durum Desf.; Jalali, Kapourchal, & Homae, 2017) and sorghum [Sorghum bicolor (L.) Moench; Saadat & Homae, 2015] using these functions. Maggio, Raimondi, Martino, and De Pascale (2007) identified yield response of tomato to salinity with piecewise linear functions. The slope was 6% per 1 dS m^{-1} in the first stage of 2.5 and 9.6 dS m^{-1} of Hoagland solution, whereas after 9.6 dS m^{-1}, the yield decrease per unit increase in salinity was 1.4%. Among the four models, only the linear model of Maas and Hoffman (1977) and nonlinear model of van Genuchten and Hoffman (1984) were used to model tomato yield and evapotranspiration under saline rootzones (Letey & Dinar, 1986; Steppuhn, van

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**Core Ideas**

- Moderate salinity (2 dS m^{-1}) stimulates leaf $P_n$, $T_r$, and $G_s$ of tomato plant.
- Nonlinear models performed better than linear model.
- The new model was compared with models of Maas and Hoffman, van Genuchten, Dirksen, and Homae.
- The new model provided the best estimation of both yield and ET under saline conditions.
Genuchten, & Grieve, 2005a, 2005b). However, to the best of our knowledge, the Dirksen et al. (1993), Homae, Dirk-

sen, and Feddes (2002), and Homae et al. (2002a, 2002b, 2002c) models have not been used to evaluate the influ-
ences of irrigation water salinity on tomato yield and evap-
otranspiration.

The aims of this research were (a) to investigate the impacts of irrigation with chosen brackish waters on gas exchange, evapotranspiration, and yield of tomato; (b) to propose a new reduction function to evaluate tomato water uptake and yield response to irrigation water salinity; and (c) to compare the proposed model with existing linear (Maas & Hoffman, 1977) and nonlinear models (Dirksen et al., 1993; Homae, Dirksen, & Feddes, 2002; Homae et al., 2002a, 2002b, 2002c; van Genuchten & Hoffman, 1984).

## 2 MATERIALS AND METHODS

A greenhouse experiment was conducted at the Fabian Garcia Science Center of New Mexico State University, Las Cruces (32.28° N, 106.77° W, elevation 1,186 m asl) from 24 Jan. to 18 May 2018, to quantify the influences of salinity on tomato yield and root water uptake. The average values of photosynthetically active radiation (PAR), vapor pressure deficit (VPD), and reference evapotranspiration (ET₀) in the greenhouse during the entire experiment were 640.2 ± 119.6 μM m⁻² s⁻¹, 1.40 ± 0.15 kPa, and 2.40 ± 0.60 cm, respectively (Figure 1). Tomato seed (cv. ‘Sow easy’) was sown in cylindrical polyvinyl chloride (PVC) pots with a height of 33 cm and a diameter of 17 cm. Four holes were punched in the bottom of the pots, and cheesecloth and 500 g of gravel were added for leaching and to prevent soil loss. The pots were filled with 9 kg of soil with a bulk density of 1.36 ± 0.5 g cm⁻³. The sandy loam soil, collected from the upper 30 cm of soil at the Fabian Garcia Science Center, was air dried and sieved through a 4-mm sieve; 14 g of Miracle-Gro fertilizer was homogeneously mixed with soil prior to packing into pots. The texture and chemical properties of the experimental soil prior to packing are given in Table 1. Two tomato seeds were sown within a soil depth of 1–2 cm in each pot on 24 Jan. 2018. After the germination and seedling stages, only one healthy plant was kept from 28 Feb. 2018 on.

The treatments consisted of a nonsaline water treat-
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ment of EC 0.6 dS m⁻¹ (S0) and four irrigation water salinity treatments of EC 2 (S1), 3 (S2), 4 (S3), and 6 dS m⁻¹ (S4). Final seasonal ECₑ was 1.73, 2.50, 3.41, 4.11, and 8.38 dS m⁻¹ for the S0, S1, S2, S3, and S4 treatments, respectively. Each treatment had four replicates. The tap water in the greenhouse was used as the control (S0). The brackish groundwater (EC of 4 dS m⁻¹) and reverse osmosis (RO) concentrate (EC of 8 dS m⁻¹) were provided by the Brackish Groundwater National Desalination and Research Facility (BGNDRF) in Alamogordo, NM. The control water and brackish water were appropriately mixed to create S1 and S2, and RO concentrates were mixed to create S3 and S4. The chemical analysis of irrigation water included measurements of EC, Mg²⁺, K⁺, Ca²⁺, Na⁺, and Cl⁻ ion concentrations and is given in Table 2. The whole growth of tomato plants was divided into

![Figure 1](https://example.com/fig1.png)

**Figure 1** Greenhouse (a) photosynthetic active radiation (PAR, μM m⁻² s⁻¹), (b) vapor pressure deficit (VPD, kPa), and (c) reference evapotranspiration (ET₀, cm) from 1 Jan. to 1 June 2018.

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TABLE 1 Concentrations of Na⁺, K⁺, Mg²⁺, Ca²⁺, Zn²⁺, and Cl⁻ ions; cation exchange capacity (CEC); pH; and electrical conductivity (EC) in the sandy loam soil. Results are means and SD

| Parameter | Value |
|-----------|-------|
| Texture   | Sandy loam |
| Na, mg kg⁻¹ | 115.3 ± 14.43 |
| K, mg kg⁻¹  | 163.7 ± 17.67 |
| Mg, mg kg⁻¹  | 123.0 ± 13.00 |
| Ca, mg kg⁻¹  | 2,233.0 ± 132.86 |
| Zn, mg kg⁻¹  | 1.03 ± 0.06 |
| Cl, mg kg⁻¹  | 105.3 ± 1.53 |
| CEC        | 13.1 ± 0.87 |
| pH         | 8.10 ± 0.00 |
| EC, dS m⁻¹  | 1.06 ± 0.09 |

3 | ROOT WATER UPTAKE FUNCTIONS

3.1 | Model description

To describe water flow in a soil root zone, Richards’ equation with the sink term is commonly used to quantify root water uptake (Richards, 1931):

\[
\frac{\partial \theta}{\partial t} = C(h) \frac{\partial h}{\partial z} = \frac{\partial}{\partial z} \left[ k(h) \frac{\partial h}{\partial z} + k(h) \right] - S(h) \quad (3)
\]

where \( \theta \) is volumetric soil water content \([L⁻³ L⁻³]\), \( t \) is time, \( C \) \([L⁻¹]\) is the slope \( \Delta \theta/\Delta h \) of the soil water retention curve, \( z \) is gravitational head taken positively upward \([L]\), \( h \) is water pressure head \([L]\), \( k \) is hydraulic conductivity of unsaturated soil \([L T⁻¹]\), and \( S \) is the root water uptake rate \([L³ L⁻³ T⁻¹]\).

Feddes, Kowalik, and Zaranyi (1978) introduced a macroscopic water uptake term depending on soil water pressure head \( h \) as

\[
S = \alpha(h) S_{max} \quad (4)
\]

where \( S_{max} \) is water uptake under non-stress conditions and \( \alpha(h) \) is a function of soil water pressure head. Homae, Dirksen, and Feddes (2002) modified this macroscopic function using a soil salinity reduction term, \( \alpha(h_0) \) instead of \( \alpha(h) \):

\[
S = \alpha(h_0) S_{max} \quad (5)
\]

As Homae, Dirksen, and Feddes (2002), Homae et al. (2002a, 2002b, 2002c), and Jalali et al. (2017) reported, the reduction equation \( \alpha(h_0) \) can be defined as relative yield \( Y/Y_{max} \) and relative transpiration \( T_r/T_p \) for the same species and growth stage. The common reduction functions used in the simulations were proposed by Dirksen et al. (1993), Maas and Hoffman (1977), van Genuchten and Hoffman (1984), Homae, Dirksen, and Feddes (2002), and Homae et al. (2002a, 2002b, 2002c).

The piecewise linear function in the form of the Maas and Hoffman (1977) model can be written as

\[
\alpha(h_0) = 1 - \frac{\alpha}{360}(h_0^* - h_0) \quad (6)
\]

where \( h_0^* \) \([L]\) is the salinity threshold value after which the uptake linearly decreases with decreasing \( h_0 \) \([L]\), \( \alpha \) is the slope of yield or transpiration (decrease per one unit of salinity), and 360 is the constant that converts the salinity-dependent slope into osmotic head.

Although the Maas and Hoffman (1977) model was a significant breakthrough toward quantifying plant response to salinity, some studies also reported a nonlinear...
TABLE 2 Chemical composition of irrigation water used in the experiment: water from the greenhouse (control), brackish groundwater from the Brackish Groundwater National Desalination and Research Facility (BGNDRF, diluted), and reverse osmosis (RO) concentrate from BGNDRF (diluted). Results are means and SD

| Irrigation water | Na       | K        | Mg       | Ca        | Cl        | EC<sup>a</sup> |
|------------------|----------|----------|----------|-----------|-----------|--------------|
| Control          | 77.8 ± 1.77e | 12.06 ± 0.14b | 12.52 ± 1.68e | 55.0 ± 2.0e | 65.7 ± 3.1e | 0.62         |
| Brackish 1 conc. | 166.3 ± 7.11d | 14.79 ± 0.45a | 73.26 ± 2.59d | 173.0 ± 17.8d | 300.5 ± 6.5d | 2            |
| Brackish 2 conc. | 270.2 ± 44.2c | 15.25 ± 0.71a | 135.20 ± 20.00c | 307.6 ± 20.7c | 514.5 ± 16.5c | 3            |
| RO1 conc.        | 332.9 ± 13.2b | 14.82 ± 0.57a | 172.00 ± 6.44b | 366.5 ± 20.7b | 620.5 ± 14.5b | 4            |
| RO2 conc.        | 510.3 ± 16.5a | 15.29 ± 0.27a | 283.60 ± 8.99a | 606.7 ± 10.4a | 1031.0 ± 49.0a | 6            |

Note. Different letters within a column correspond to Duncan’s multiple range tests at P ≤ .05.

<sup>a</sup>EC, electrical conductivity.

relationship under salinity stress. Therefore, van Genuchten and Hoffman (1984) were the first to propose a nonlinear function as

\[ \alpha(h_0) = \frac{1}{1 + (h_0/h_{050})^\alpha} \]  

(7)

where \( h_{050} \) is osmotic head at which the relative uptake is declined by 50% [L], and \( p \) is a unitless parameter related to climate, crop, and soil.

Dirksen et al. (1993) modified Equation 7, incorporating the threshold value \( (h_0^*) \), and defined the following:

\[ \alpha(h_0) = \frac{1}{1 + [(h_0^* - h_0)/(h_0^* - h_{050})]^p} \]  

(8)

This equation can model plant response to salinity more realistically than Equation 6, but it is difficult to obtain \( h_{050} \) and \( p \) parameters. Therefore, Homae et al. (2002a, 2002c) defined the shape parameter \( p \) as a function of \( h_{050} \) and \( h_0^* \) and proposed the following:

\[ p = \frac{h_{050}}{h_{050} - h_0^*} \]  

(9)

To resolve the limitation of obtaining \( h_{050} \), Homae et al. (2002a, 2002c) used \( h_{0\text{max}} \) instead of \( h_{050} \), beyond which relative uptake is not significantly affected by salinity increase. This indicates that at \( h_0 \leq h_{0\text{max}} \), the plant is still alive with a minimal rate of biological activities. The modified nonlinear two-threshold reduction function was written as

\[ \alpha(h_0) = \frac{1}{1 + ([1-a_0]/a_0)(h_0^* - h_0)/(h_0^* - h_{0\text{max}}))^p} \]  

(10)

where \( a_0 \) is the relative uptake at \( h_{0\text{max}} \). The empirical parameter, \( p \), similar to Equation 9, can be obtained from Homae et al. (2002a, 2002c):

\[ p = \frac{h_{0\text{max}}}{h_{0\text{max}} - h_0^*} \]  

(11)

The three models of Dirksen et al. (1993), Maas and Hoffman (1977), and Homae et al. (2002a, 2002c) demonstrated a threshold \( (h_0^*) \) after which the yield began to decline. However, Maggio et al. (2007) found that there existed another break point after which the slope of yield reduction function to salinity was reduced. To better describe plant adaptation to salinity higher than the break point and avoid the limitation of obtaining the parameters \( (e.g., h_{050}, h_0^*, \text{and} h_{0\text{max}}) \), we proposed a new model based on an inverse function as

\[ \alpha(\text{EC}_w) = \frac{1}{A(\text{EC}_w - B) + C} \]  

(12)

where \( A \) is a shape parameter, \( B \) is the asymptote (parallel to the y axis, dS m<sup>-1</sup>), and \( C \) is the asymptote (parallel to the x axis), which is the potential lowest value for relative yield and relative ET. When \( \alpha(\text{EC}_w) = 1 \), the calculated \( \text{EC}_w \) from this equation is the salinity threshold value \( (\text{EC}_w^*) \).

The new model was proposed based on the relationship between \( \text{EC}_w \), and plant relative yield and relative ET. Electrical conductivity of irrigation water \( (\text{EC}_w) \) was linearly correlated to \( \text{EC}_w \) (Figure 2):

\[ \text{EC}_w = m\text{EC}_w + n \]  

(13)

where \( \text{EC}_w \) is irrigation water salinity (dS m<sup>-1</sup>), \( \text{EC}_w \) is soil solution salinity (dS m<sup>-1</sup>), and \( m \) and \( n \) are slope and intercept, respectively.

According to Equations 12 and 13, when used under saline irrigation water conditions, the model can be expressed as

\[ \alpha(\text{EC}_w) = \frac{1}{\frac{A}{m}(\text{EC}_w - n - mB) + C} \]  

(14)
When $A/m = A'$ and $n + mB = B'$, Equation 14 can be written as

$$\alpha(\text{EC}_w) = \frac{1}{A'}(\text{EC}_w - B') + C \quad (15)$$

where $A'$ is the shape parameter, $B'$ is the asymptote (parallel to the y axis, dS m$^{-1}$), and $C$ is the potential minimal value of relative yield or ET.

### 3.2 Data analysis

The experimental data were analyzed by one-way ANOVA using SPSS version 23.0 (IBM Statistics). Differences among treatments were evaluated using Duncan’s multiple range test at $P = .05$. The estimated parameters in Maas and Hoffman, van Genuchten, Dirksen, and the proposed new model were calibrated by nonlinear least squares regression using R; the estimated parameters in Homaeae were calibrated by minimizing the sum of squared deviations using a solver program in Microsoft Excel.

Some statistics, including the $r^2$, RMSE, normalized RMSE (NRMSE), Willmott index of agreement ($d$), coefficient of residual mass (CRM), and modeling efficiency (EF), were used to evaluate the differences between measured and simulated values (Kobayashi & Salam, 2000; Nash & Sutcliffe, 1970; Willmott, 1981; Willmott & Matsuura, 2005).

### 4 RESULTS

#### 4.1 Evapotranspiration, yield, and gas exchange for tomato under different salinity conditions

The parameters of water consumption for tomato plants under different irrigation water salinity during the whole growth stage are given in Table 3. A total of 94.9 cm of irrigation water was applied to each treatment, but decreases in total ET were observed with increasing salinity, and consequently increases in DP and LF were recorded with increasing irrigation water salinity. The control treatment (S0) had the highest ET and consequently the lowest DP and LF among different salinity levels ($P < .05$). Furthermore, differences in ET, DP, and LF among treatments S1, S2, and S3 were not significant, but significant decreases in ET, DP, and LF were found for treatment S4 compared with S3. Tomato yield decreased with increasing salinity; compared with S0, yield for treatments S1, S2, S3, and S4 showed decreases of 12.2, 26.5, 32.5, and 45.5%, respectively. The positive nonlinear relationship between ET and yield for salt treatments was best fitted using a nonlinear curve (Figure 3). Compared with the S0 treatment, average $P_n$, $T_r$, and $G_s$ for S1 showed an increase of 3.9, 7.9, and 23.9%, respectively, whereas up to the S4 treatment, average $P_n$, $T_r$, and $G_s$ decreased with increasing salinity, but the differences among the five treatments were not significant (Table 4). Foliar chlorophyll content and fruit number also did not reveal significant differences among the five treatments; foliar chlorophyll content for S1, S2, S3, and S4...
### Table 3

| Treatment | IR (cm) | ET (g) | DP (g) | LF (%) | Yield per plant (g) |
|-----------|---------|--------|--------|--------|---------------------|
| S0        | 94.9 ± 0.0 | 83.2 ± 1.7a | 11.7 ± 1.7c | 0.1 ± 0.0c | 305.9 ± 35.8a |
| S1        | 94.9 ± 0.0 | 77.2 ± 0.8b | 17.7 ± 0.8b | 0.2 ± 0.0b | 268.5 ± 34.0ab |
| S2        | 94.9 ± 0.0 | 75.7 ± 0.5b | 19.2 ± 0.5b | 0.2 ± 0.0b | 224.9 ± 19.4bc |
| S3        | 94.9 ± 0.0 | 75.5 ± 1.5b | 19.4 ± 1.5b | 0.2 ± 0.0b | 206.5 ± 29.2cd |
| S4        | 94.9 ± 0.0 | 71.4 ± 0.6c | 23.6 ± 0.6a | 0.3 ± 0.0a | 166.7 ± 33.6d |

Note. Different letters within a column indicate significant differences according to Duncan’s multiple range tests at P ≤ .05.

### Table 4

| Treatment | $P_n$ (μmol m$^{-2}$ s$^{-1}$) | $T_r$ (mmol m$^{-2}$ s$^{-1}$) | $G_s$ (mol m$^{-2}$ s$^{-1}$) | Chl (SPAD value) | Fruit no. |
|-----------|-------------------------------|-------------------------------|-------------------------------|------------------|-----------|
| S0        | 11.10 ± 1.97a                 | 2.65 ± 0.38a                  | 0.092 ± 0.02a                 | 39.81 ± 0.62a    | 25.5 ± 2.38a |
| S1        | 11.53 ± 0.46a                 | 2.86 ± 0.21a                  | 0.114 ± 0.01a                 | 38.16 ± 1.31a    | 25.8 ± 3.60a |
| S2        | 10.70 ± 1.38a                 | 2.60 ± 0.34a                  | 0.105 ± 0.02a                 | 37.64 ± 2.48a    | 21.3 ± 1.50a |
| S3        | 9.78 ± 1.16a                  | 2.53 ± 0.49a                  | 0.098 ± 0.03a                 | 39.00 ± 1.47a    | 24.8 ± 2.36a |
| S4        | 8.86 ± 2.85a                  | 2.26 ± 1.01a                  | 0.098 ± 0.05a                 | 37.74 ± 2.78a    | 23.8 ± 3.92a |

Note. Different letters within a column correspond to Duncan’s multiple range tests at P ≤ .05.

### 4.2 Modeling yield and evapotranspiration responses to $EC_e^*$

Maas and Hoffman (Figures 4a and 5a), van Genuchten (Figures 4b and 5b), Dirksen (Figures 4c and 5c), Homae (Figures 4d and 5d), and the new model (Figures 4e and 5e) were fitted to the measured relative yield and relative ET. The threshold value was designated as $EC_e^*$. The model estimations performed better as $d$, $EF$, and $r^2$ came closer to 1. An RMSE close to 0 indicates that the simulated and measured values are close (Homae, Dirksen, & Feddes, 2002). An NRMSE value <10% represents excellent model performance, 10–20% represents a good performance, 20–30% represents a fair performance, and >30% reveals a poor model performance (Bannayan & Hoogenboom, 2009). The statistics for these models showed that the $r^2$ values for Maas and Hoffman, van Genuchten, Dirksen, Homae, and the new model were .590, .688, .863, .864, and .894 for estimating relative yield (Table 5), whereas $r^2$ values were .644, .638, .689, .834, and .855 for estimating relative ET (Table 6), respectively. Dirksen and Homae models were superior to other models. However, the new model proposed in this study performed the best for estimating relative yield and relative ET responses to salinity among all the tested models. The CRM value of Maas and Hoffman (1977) was −0.187 and indicated that this model slightly overestimated the relative yield compared to other models. The CRM value of the

### Table 5

| Model                  | $r^2$ | RMSE | $d$ | CRM | $EF$ |
|------------------------|-------|------|-----|-----|------|
| Maas and Hoffman       | 0.590 | 0.008| 0.991| −0.187| 0.957|
| van Genuchten and Hoffman| 0.688 | 0.016| 0.937| 0.011| 0.838|
| Dirksen et al.         | 0.863 | 0.008| 0.992| 0.012| 0.962|
| Homae et al.           | 0.864 | 0.008| 0.992| 0.006| 0.962|
| New                    | 0.894 | 0.055| 0.999| 0.002| 0.994|

Note. $d$, Willmott index of agreement; CRM, coefficient of residual mass; $EF$, modeling efficiency.
FIGURE 4  Comparison between the measured and estimated relative fruit fresh weight using different equations: (a) Mass and Hoffman, (b) van Genuchten and Hoffman, (c) Dirksen et al., (d) Homae et al., and (e) our new model. EC*, the salinity threshold value after which the relative fruit fresh weight decreases; EC<sub>50</sub>, electrical conductivity of soil saturated paste extract (EC<sub>e</sub>) at which the relative fruit fresh weight is declined by 50%; EC<sub>max</sub>, EC<sub>e</sub> beyond which relative fruit fresh weight is not significantly affected by salinity increase; A, shape parameter; B, the asymptote (parallel to the y axis, dS m<sup>-1</sup>); C, the asymptote (parallel to the x axis), which is the potential lowest value for relative fruit fresh weight.
FIGURE 5  Comparison between the measured and estimated relative evapotranspiration (ET) using different equations: (a) Mass and Hoffman, (b) van Genuchten and Hoffman, (c) Dirksen et al., (d) Homae et al., and (e) our new model. EC*, the salinity threshold value after which the relative ET decreases; EC50, electrical conductivity of soil saturated paste extract (ECe) at which the relative ET is declined by 50%; ECmax, ECe beyond which relative ET is not significantly affected by salinity increase; A, shape parameter; B, the asymptote (parallel to the y axis, dS m⁻¹); C, the asymptote (parallel to the x axis), which is the potential lowest value for relative ET.
new model was closer to 0 than that of the other four models, and the estimated relative yield of the new model was closer to the measured data. Despite the higher RMSE for the new model, $d$ and EF were larger than that of the other four models. These results showed that the new model was more efficient in predicting relative yield response to salinity than other models. Dirkseen and Homaeae models had similar RMSE, $d$, and EF, but the CRM value for the Homaeae model was much larger than that of the Dirkseen model. Similarly, in spite of higher RMSE, the new model resulted in larger $d$ and EF values than the other four models in estimating relative ET response to salinity. The CRM values indicated that all models except Homaeae’s overestimated the relative ET.

### 4.3 Modeling yield and evapotranspiration responses to $EC_w$

The proposed new model was based on the responses of tomato ET and yield to $EC_w$. To further identify the model applicability, data of relative ET and relative yield of different tomato cultivars, as well as $EC_w$, were collected from published literature (Ben-Gal & Shani, 2002; El-Mogy, Garchery, & Stevens, 2018; Magán, Gallardo, Thompson, & Lorenzo, 2008; Maggio et al., 2007; Ragab, Malash, Gawad, Arslan, & Ghaibeh, 2005; Reina-Sánchez et al., 2005; Wan, Kang, Wang, Liu, & Feng, 2007). The relationships between $EC_w$ and relative ET and relative yield were plotted in Figure 6 for (a) observed data and collected data of relative ET, and (b) observed data and collected data of relative yield, respectively. Because tomato responses to salinity were influenced by differences in varieties, the data of tomato ET and yield observed from our experiment and data collected from literature were categorized into four salt tolerance levels, denoted as I, II, III, and IV. The five models were used to estimate tomato relative ET and relative yield with increasing salinity of irrigation water. Results showed that of the five models, the new model gave the best estimate of relative ET and relative yield for four salt-tolerant varieties, having the largest values of $r^2$ and the smallest values of RMSE and NRMSE (Tables 7 and 8). Moreover, the model parameters of $A'$ and $C$, indicating the shape of the curve and the potential minimal relative ET or yield, respectively, could reflect the salt tolerance of different tomato cultivars. Table 9 shows that parameters $A'$ and $C$ decreased for the salt tolerance levels ranging from I to IV.

### 5 DISCUSSION

#### 5.1 Driving factors of tomato yield reduction under salt stress

The salinity-induced yield reductions of tomato vary depending upon the sensitivity of a cultivar. In our experiment, we observed 12.2 and 32.5% decreases in tomato yield for $EC_w$ of 2.50 and 4.11 dS m$^{-1}$, respectively, in sandy loam soil (Table 3). The salinity level had no significant impact on fruits number, and at $EC_w$ of 2.50 dS m$^{-1}$, fruit numbers remained almost unchanged (Table 4), indicating that smaller fruit size was the main cause of yield reduction. Moderate saline conditions stimulated photosynthesis (Maggio, De Pascale, Angelino, Ruggiero, & Barbieri, 2004; Schwarz, Klarling, van Iersel, & Ingram, 2002; Xu, Gauthier, & Gosselin, 1995). Compared with the control, $P_n$ and $G_s$ of tomato plants under $EC_w$ of 2.50 dS m$^{-1}$ were 3.9 and 23.9% higher, respectively (Table 4). Increasing irrigation water salinity diminished yield by reducing leaf growth and inducing leaf senescence by limiting the photosynthetic capacity and possibility of accumulating further harvestable biomass growth (Nebauer et al., 2013). Chlorophyll content in leaves was an indicator of the photosynthetic rate (Leidi, Silberbush, & Lips, 1991), and the differences between the salt and control treatments were not significant, indicating that the toxic effect of salt on chlorophyll synthesis was not associated with a reduction of photochemical activity. We even found an increase of chlorophyll content on plants at $EC_w$ of 4.11 dS m$^{-1}$ (Table 4). In contrast, da Silva Lima et al. (2020) applied 3 dS m$^{-1}$ of nutrient solution to two different passion fruit (Passiflora L.) species and found that saline stress had a negative effect on chlorophyll contents and net photosynthetic

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**TABLE 6** The calculated statistics for the comparison between measured relative evapotranspiration (ET) and those simulated by various models

| Model             | $r^2$ | RMSE | $d$  | CRM   | EF   |
|-------------------|-------|------|------|-------|------|
| Mass and Hoffman  | 0.644 | 0.005| 0.964| −0.044| 0.778|
| van Genuchten and Hoffman | 0.638 | 0.001| 0.998| −0.0002| 0.994|
| Dirkseen et al.   | 0.689 | 0.005| 0.966| −0.007| 0.793|
| Homaeae et al.    | 0.834 | 0.005| 0.966| 0.0008| 0.793|
| New               | 0.855 | 0.021| 0.999| −0.002| 0.999|

Note. $d$, Willmott index of agreement; CRM, coefficient of residual mass; EF, modeling efficiency.
### TABLE 7  Comparative analysis of observed relative evapotranspiration (ET) and estimated relative ET using the five models (the linear model of Maas and Hoffman; three nonlinear models of van Genuchten, Dirksen, and Homae; and our new proposed model)

| Salt tolerance | Data source | Index   | Model | Mass | van Genuchten | Dirksen | Homae | New |
|----------------|-------------|---------|-------|------|---------------|---------|-------|-----|
| I              | Wan et al. (2007) | $r^2$   | 0.447 | 0.444 | 0.464 | 0.46 | 0.482 |
|                |             | RMSE    | 0.076 | 0.076 | 0.077 | 0.075 | 0.073 |
|                |             | NRMSE (%) | 8.7 | 8.7 | 8.9 | 8.6 | 8.4 |
| II             | experimental data | $r^2$   | 0.951 | 0.962 | 0.967 | 0.966 | 0.983 |
|                |             | RMSE    | 0.011 | 0.011 | 0.01 | 0.009 | 0.007 |
|                |             | NRMSE (%) | 1.2 | 1.1 | 1.1 | 1.0 | 0.7 |
| III            | Reina-Sánchez et al., (2005); Ben-Galand Shani (2002) | $r^2$   | 0.857 | 0.883 | 0.905 | 0.903 | 0.913 |
|                |             | RMSE    | 0.058 | 0.054 | 0.055 | 0.049 | 0.045 |
|                |             | NRMSE (%) | 7.7 | 7.1 | 7.3 | 6.5 | 6.0 |
| IV             | Reina-Sánchez et al. (2005) | $r^2$   | 0.890 | 0.886 | 0.914 | 0.910 | 0.915 |
|                |             | RMSE    | 0.051 | 0.053 | 0.069 | 0.050 | 0.045 |
|                |             | NRMSE (%) | 6.7 | 6.9 | 9 | 6.5 | 5.9 |

*NRMSE, normalized RMSE.

### TABLE 8  Comparative analysis of observed relative yield and estimated relative yield using the five models (the linear model of Maas and Hoffman; three nonlinear models of van Genuchten, Dirksen, and Homae; and our new proposed model)

| Salt tolerance | Data source | Index   | Model | Mass | van Genuchten | Dirksen | Homae | New |
|----------------|-------------|---------|-------|------|---------------|---------|-------|-----|
| I              | Experimental data | $r^2$   | 0.902 | 0.956 | 0.960 | 0.960 | 0.998 |
|                |             | RMSE    | 0.029 | 0.020 | 0.021 | 0.019 | 0.004 |
|                |             | NRMSE (%) | 4.3 | 2.9 | 3.1 | 2.8 | 0.6 |
| II             | El-Mogy et al. (2018) | $r^2$   | 0.892 | 0.954 | 0.934 | 0.937 | 0.984 |
|                |             | RMSE    | 0.025 | 0.016 | 0.022 | 0.019 | 0.010 |
|                |             | NRMSE (%) | 3.1 | 2.1 | 2.7 | 2.4 | 1.2 |
| III            | Ragab et al. (2005) | $r^2$   | 0.763 | 0.792 | 0.794 | 0.794 | 0.799 |
|                |             | RMSE    | 0.057 | 0.053 | 0.054 | 0.053 | 0.052 |
|                |             | NRMSE (%) | 9.6 | 9.0 | 9.1 | 9.0 | 8.9 |
| IV             | Magán et al. (2008); Maggio et al. (2007) | $r^2$   | 0.896 | 0.936 | 0.977 | 0.976 | 0.986 |
|                |             | RMSE    | 0.048 | 0.038 | 0.084 | 0.023 | 0.018 |
|                |             | NRMSE (%) | 6.9 | 5.4 | 12.1 | 3.3 | 2.6 |

*NRMSE, normalized RMSE.

### TABLE 9  The parameters of our new model when simulating relative evapotranspiration (ET) and yield, respectively, for different salt-tolerant varieties of tomato

| Trait          | Parameter | Salt tolerance |
|----------------|-----------|----------------|
|                |           | I             | II            | III           | IV            |
| Relative ET    | $A'$      | 1.337         | 0.437         | 0.246         | 0.152         |
|                | $B'$      | -1.159        | -6.155        | -4.626        | -6.118        |
|                | $C$       | 0.669         | 0.662         | 0.302         | 0.176         |
| Relative yield | $A'$      | 1.060         | 0.365         | 0.334         | 0.226         |
|                | $B'$      | -0.358        | -5.279        | -2.817        | -2.230        |
|                | $C$       | 0.411         | 0.581         | 0.215         | 0.207         |

Note. $A'$, $B'$, and $C$ are model parameters; $A'$ represents shape parameter, $B'$ represents the asymptote parallel to the y axis, and $C$ is the lowest value that relative yield and relative ET could reach. I, II, III, and IV are four salt-tolerant levels of tomato cultivars.
rate of passion fruit with significant reductions of 31.0 and 44.0%, respectively.

5.2 Yield relationship modeling

The relationship between biomass yield and evapotranspiration has been demonstrated for a number of crops under drought and salinity. Tomato has a complicated relationship between vegetative and reproductive growth, and conflicting accounts are available. It was reported that tomato yield and seasonal ET were fitted by linear models under conditions of salinity (Ben-Gal et al., 2003) and conditions of water deficit (Kuşçu, Turhan, & Demir, 2014), as well as by nonlinear models under conditions of drought (Renquist & Reid, 2001). The positive relationships of linear yield to ET were previously used by modelers to estimate crop yield based on predicted seasonal ET (Jansson et al., 1999); however, our study found that the relationship between tomato yield and ET was best fitted by a nonlinear curve under salinity (Figure 3). For this reason, plant responses to salinity need to be described as a function of root zone salinity (EC$_e$) and tomato yield, as well as EC$_e$ and plant ET, separately. For tomato yield and ET responses to salinity, similar results were obtained. The van Genuchten, Dirksen, and Homaei models had higher accuracy than the linear model of Maas and Hoffman; however, the new model had the highest $r^2$, $d$, and EF among all the models, suggesting that the new model was superior in estimating relative yield and relative ET responses to EC$_e$.

5.3 Model applicability

We want to emphasize that the proposed new model had no EC$_e^*$ value in the equation. In the four previous models, except for van Genuchten and Hoffman, EC$_e^*$ was regarded as a specific scatter on the model fitting line. Generally, the EC$_e^*$ value was measured or estimated along with the EC$_e$ value, and differentiating between these two was challenging. Moreover, EC$_e^*$ value of plant response to salinity varied with crop species as well as varieties. Since the EC$_e^*$ value was not an indispensable input parameter, it could make the model easily applicable and reliable. Compared with the van Genuchten and Hoffman model of no EC$_e^*$, the new model had higher $r^2$, $d$, and EF; however, both models underestimated the relative yield but overestimated the relative ET. Furthermore, the new model could better describe plant response under conditions of high salinity, since the curve gradually stabilized to a constant, which reflected a more realistic plant adaptation to salinity (Maggio et al., 2007).

Since water is limited in arid and semiarid areas, high-salinity water is widely used for crop irrigation (Baath et al., 2017; Flores et al., 2016, 2017). Therefore, the direct descriptions of plant yield and ET as a function of EC$_w$ could achieve timely feedback for irrigation management and provide plant growth modelers highly available relationships between plants and salinity. Among the five models, the new model performed best with the highest $r^2$ and lowest RMSE and NRMSE for estimations of both

![Figure 6: Relationships between electrical conductivity of irrigation water (EC$_w$), relative evapotranspiration (ET), and relative yield, respectively, for (a) observed data of relative ET from the experiment and collected data of relative ET from the literature, and (b) observed data of relative yield from the experiment and collected data of relative yield from the literature. The curves are fitted using our new model.](image-url)
relative yield and relative ET (Tables 7 and 8). The new model can also be used to describe the relationships between EC, tomato yield, and ET.

The parameters $A$, $B$, and $C$ of the new model for predicting plant response to EC, and $A'$, $B'$, and $C$ for predicting plant response to EC, have biological significance. The parameter $C$ indicated that the potential minimal relative yield under different EC was 0.45 and the corresponding minimal relative ET was 0.82 in our study. The calculated salinity threshold values (EC*) from Equation 12 were 1.73 dS m$^{-1}$ for relative yield and 2.52 dS m$^{-1}$ for relative ET when $\alpha(\text{EC}) = 1$, suggesting that a decrease of tomato yield under salinity was more sensitive than a decrease of ET. Correspondingly, the shape parameter $A$ also reflected the sensitivity of plant response to salinity; the larger the value of $A$, the better the tolerance could be. When the relationships between plant responses and EC were evaluated using the new model, the differences in model parameters of $A'$ and $C$ for four salt-tolerant levels of tomato cultivars (Table 9) also indicated that decreases in plant yield and ET under saline conditions were cultivar specific and cannot be generalized. In addition, it was found that $A'$ and $C$ decreased from salt tolerance Level I to Level IV, indicating that the tomato cultivars were decreasingly salt tolerant. This study demonstrated the applicability of a new model in several tomato cultivars; future experiments should quantify the relationship between crop salt tolerance and model parameters.

6 | CONCLUSION

In this study, tomato yield and ET responses to EC and EC data obtained from a pot experiment and published research were analyzed. The results showed that increasing irrigation water salinity reduced evapotranspiration and consequently increased deep percolation and leaching fraction, which therefore allowed plants to maintain a favorable water status. Photosynthetic and transpiration rates decreased slightly with increasing salinity. Yield decreased with increasing salinity, and the relationship between yield and ET was nonlinear. A comparison of five models of Maas and Hoffman, van Genuchten, Dirksen, Homae, and our new model with observed data showed that the new model provided the best estimation of both yield and ET under saline conditions. When describing responses of tomato yield and ET to root zone salinity, the new model could be easy to use, could be representative, and could achieve wide applicability.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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