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CROP PRODUCTION

Fuzzy modeling of biometric variables development of tomato crop under irrigation and water salinity effects

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ABSTRACT. Tomato is a demanding crop in terms of handling, mainly because irrigation has a strong influence on fruit production and quality. Salinity changes the absorption, transport, assimilation, and distribution of nutrients in the plant. In general, such effects are analyzed using statistical tests. However, fuzzy models allow simulations between points that are not verified in agricultural experimentation. Currently, systems with artificial intelligence have excelled in the field of applied sciences, particularly fuzzy systems applied to mathematical modeling. The objective of this research was to use fuzzy modeling to analyze the biometric variables during the development of hybrid tomatoes under two different conditions: the first concerning different water tensions in the soil and the second concerning different salinity doses in irrigation. To this end, two models were developed based on an experiment carried out at São Paulo State University (UNESP), School of Agriculture, Botucatu, São Paulo State, Brazil. Both models sought to estimate the values of biometric variables of the tomato crop. Thus, two models were developed: *Model 1* regarded water tensions and days after sowing (DAS), while *Model 2* featured salinity and DAS. Fuzzy models provided results that verified the effects of irrigation and salinity layers. Two Fuzzy Rule-Based Systems (FRBS), an input processor with two variables, a set of linguistic rules defined from statistical procedures with percentiles, the Mamdani fuzzy inference method, and the center of gravity method to defuzzification were elaborated for this purpose. The range between −25 and −10 kPa (for Model 1) and between 0.08 and 3 dS m^{-1} (for Model 2) provided the development within the ideal parameters for the complete development of the plant cycle. The use of fuzzy logic has shown effectiveness in evaluating the development of tomato crops, thus showing potential for use in agricultural sciences. Moreover, the created fuzzy models showed the same characteristics of the experiment, allowing their use as an automatic technique to estimate ideal parameters for the complete development of the plant cycle. The development of applications (software) that provide the results generated by the artificial intelligence models of the present study is the aim of future research.

Keywords: mathematical modeling; water potential; phytomass; artificial intelligence.

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Introduction

Tomatoes are present practically every day in Brazilian cuisine in their multiple forms of consumption: fresh or processed as juice, sauce, paste, dehydrated, and sweetened, among others (Ağaoğlu, Ayaz, Ayaz, & Yaman, 2022; Amin & Borchgrevink, 2022; Castro et al., 2021).

Tomato is a demanding crop in terms of handling, mainly because irrigation has a strong influence on fruit production and quality, as it is considered sensitive to water deficit (Khapte, Kumar, Burman, & Kumar, 2019; Lu, Shao, Cui, Wang, & Keabetswe, 2019; Valcárcel et al., 2020). Proper crop irrigation prevents fruit cracking, apical rot, the occurrence of hollow fruits, flower falling, and reduced fruit establishment (Ketsa, Wisutiamonkul, Palapol, & Paull, 2019; Simmons et al., 2018; Yahia et al., 2019).

The quality of water used for irrigation is a key factor for plants to express their maximum development and productive potential (Gomaa et al., 2021; Rosa et al., 2020; Ullah, Santiago-Arenas, Ferdous, Attia, & Datta, 2019; Wang & Xing, 2017). On the other hand, the use of water with moderate salinity levels has become a common practice, both due to the decrease in the availability of high-quality water and as a strategy to improve production (García-Caparrós & Lao, 2018; Nachshon, 2018; Yasuor, Yermiyahu, & Ben-Gal, 2020).

The effect of salinity is osmotic and can directly affect crop yields (Holanda, Amorim, Ferreira Neto, Holanda, & Sá, 2016). Tomato is considered a crop moderately sensitive to the effects of salt, with reductions in its potential yield by water with electrical conductivity above 1.7 dS m^{-1} (Bani, Daghari, Hatira, Chaabane, & Daghari, 2021; Bonachela, Fernández, Cabrera-Corral, & Granados, 2022; Feng, Zhang, Wan, Lu, & Bakour, 2017).

In the presently developed experiments, the effects are analyzed using statistical tests that aim to assist in interpreting the results and, thus, verify the real implications caused by the different adopted treatments. In this way, mathematical models seek to provide more accurate answers. Fuzzy models allow simulations between points that are not verified in agricultural experimentation to be more accurate than regression models.

According to Benini and Rinaldi (2015), fuzzy logic is the basis for developing methods and algorithms for modeling and process control, allowing the reduction of design and implementation complexity, and becoming the solution to identification problems hitherto intractable by classical techniques.

Generally, fuzzy modeling is used in several areas to better understand the observed phenomenon or find optimal points. As an example, Oliveira, Viais Neto, Maeda, and Gabriel Filho (2020) assessed the electricity consumption of a higher education institution to classify it over the months of the year for a better understanding of the phenomenon. Viais Neto et al. (2018) used fuzzy modeling to study the effects of different doses of polymers applied to the substrate with irrigation levels on the development of cherry tomato seedlings up to the transplanting stage, aiming to weave optimal points relative to seedling management. Also, Castro, Saad, and Gabriel Filho (2022) used artificial intelligence techniques applied to the optimization of micro-irrigation systems by the Zimmermann-Werner method for the resolution of fuzzy linear programming problems.

Several applications involving fuzzy logic can be found in agricultural sciences, such as crop yield improvement and fertilizer use efficiency (Prabakaran, Vaithiyanathan, & Ganesan, 2018), in which rules generated by experts have been used. It is also found in agrometeorological models for estimating yield (Luydmila, Mikhail, Imran, Tamara, & Anatoliy, 2017), in which the degree of agronomic suitability of the cultivation site of a given crop is expressed as a number between 0 and 1.

Specifically in research on irrigation, applications in water allocation in agriculture (Xie, Xia, Ji, & Huang, 2018; Elleuch, Anane, Euchi, & Frikha, 2019; Zhang & Guo, 2018; Zhang, Engel, & Guo, 2018) stand out in the assessment of soil suitability for irrigation (Hoseini, 2019) and water abstraction (Vema, Sudheer, & Chaubey, 2019).

Particularly, the use of fuzzy models aimed at mathematical modeling of agronomic experiments has proved to be highly necessary not only for analyzing the effects of variation in response variables but also for the creation of future applications/software to support researchers and farmers.

Therefore, this research aimed to study the effects of biometric variables during the development of the hybrid tomato (*Lycopersicum esculentum*) under two different conditions using fuzzy modeling: the first condition was about different soil water tensions and the second one was about different salinity doses in irrigation.

Material and methods

Description of the experiment

The experimental data used for the fuzzy modeling of this study were analyzed statistically (Silva Junior, 2018) and employed in the elaboration of the other fuzzy modeling used by Viais Neto et al. (2019a and b). The experiment was carried out between June and October 2011 in a protected environment installed in an area located in the Department of Rural Engineering of the São Paulo State University (UNESP), School of Agriculture, city of Botucatu, São Paulo State, Brazil, with an average altitude of 786 m, latitude 22°51′03″ South, and longitude 48°25′37″ West.

The used pots had a capacity of 15 dm^3 and were filled with the soil taken from the 0–0.20-m depth layer, classified as a medium-textured Rhodic Ferralsol. The soil was taken, sieved, and air-dried until it reached a water content of 4%. The method proposed by Klar (1998) was used to determine soil water content.

Liming and planting and topdressing fertilization were carried out based on the soil analysis, following the recommendation suggested by Trani and Raij (1996). The tomato variety used was the cultivar Katia. Seedlings were prepared by the Department of Horticulture and transplanted into pots 45 days after sowing.

Sodium chloride (NaCl) was used for water salinization. For this purpose, a 2 M solution (2 times the molecular weight of NaCl) was prepared to have a liter of solution. A conductivity meter was used to obtain the doses of 0.08, 3, and 5 dS m^{-1} of water salinity by diluting the respective proportions of 0, 31.07, and 53.96 mL of the solution in a liter of supply water.

A soil sample was collected in the 0-0.20-m layer and sent to the Laboratory of Soil Plant Water Atmosphere Relationship in the Department of Rural Engineering to determine the water content in the soil as a function of soil potentials (Ψ). The soil water retention curve points, adjusted by the Soil Water Retention Curve program (Dourado Neto, Lier, Botrel, & Libardi, 1990), allowed the determination of the soil water content as a function of soil potentials using the model proposed by van Genucinen (1980). Table 1 shows the equation parameters.

Table 1. Parameters of the Van Genuchten equation related to the soil water retention curve.

Soil	α	m	N	θr	θs
	0.07034	0.4610	1.8552	0.1922	0.3058

The following soil characteristic curve was generated after calculating the parameters:

$$\theta_{0-0.20} = 0.1922 + \frac{0.1136}{[1 + (0.07034|\Psi|)^{1.8552}]^{0.4610}}$$

Matric requirements (Ψ) of −60, −30, and −10 kPa was established to cause water stress and irrigation was determined based on the mass of the pot. Soil water content was inferred from the established Van Genuchten equation, and the amount of daily water to reach the established levels was calculated.

The biometric parameters of tomato measured by Silva Junior, Silva, Klar, Silva, and Tanaka (2018) throughout its cycle consisted of plant height (cm), stem diameter (cm), leaf area (cm^2), green phytomass (g), and dry phytomass (g).

According to Silva Junior (2018), plant height corresponded to the distance between the soil base and the plant apex; the stem diameter was determined in the basal region of the plant, close to the soil; the leaf area was calculated using an estimate using dry leaf phytomass; the calculation of both green and dry phytomass corresponded to the sum of the masses of leaflets, petioles, clutches, and stem; and the percentage of deficient fruits was calculated for the fruits that presented apical rot.

The evaluations were destructive seeking to meet the four analyses throughout the cycle (75, 90, 105, and 120 days after sowing) and 27 plants were used to assess the effects of irrigation and water salinity on the tomato crop. Thus, 108 plants (4 × 27) were required for the complete study.

Fuzzy modeling

Two fuzzy models were performed to evaluate the development characteristics of the experiment analyzed in this study, which used the management of different soil water tensions and salinity doses in irrigation throughout the tomato cycle.

The first modeling (Model 1) aimed to estimate the values of biometric variables of the tomato crop over the days after sowing (DAS) versus different soil water tensions (Irrigation) (Figure 1a). Model 2 also estimated the biometric variables over DAS, but now testing the effect of different doses of irrigation salinity (Salinity) (Figure 1b).

Analogously to the methodology proposed by Viais Neto et al. (2019a) for the elaboration of both Fuzzy Rule-Based Systems (FRBS), an input processor, a set of linguistic rules, a fuzzy inference method, and an output processor were defined so that a real number was generated in the end as an output.

Fuzzy sets of input variables

The variable DAS is an input variable for both models, defined using the evolution periods of the experiment (75, 90, 105, and 120 days), with four fuzzy sets named Very Low (VL), Low (L), Medium (M), and High (H). Specifically in Model 1, the other input variable is Irrigation, in which the fuzzy sets were defined according to Viais Neto et al. (2019a). In Model 2, the other variable is Salinity, in which the fuzzy sets were defined according to Viais Neto et al. (2019b) (Figure 2).

Fuzzy sets of output variables

Several biometric variables were analyzed according to the representative factors of both Models 1 and 2: Irrigation x DAS and Salinity x DAS (Table 2). Among the analyzed biometric variables, those that were considered for the models showed interactions between such factors and/or significant simultaneous differences between factors. The only variable that did not meet these criteria was Plant Height (Heig) and therefore not used in the models.

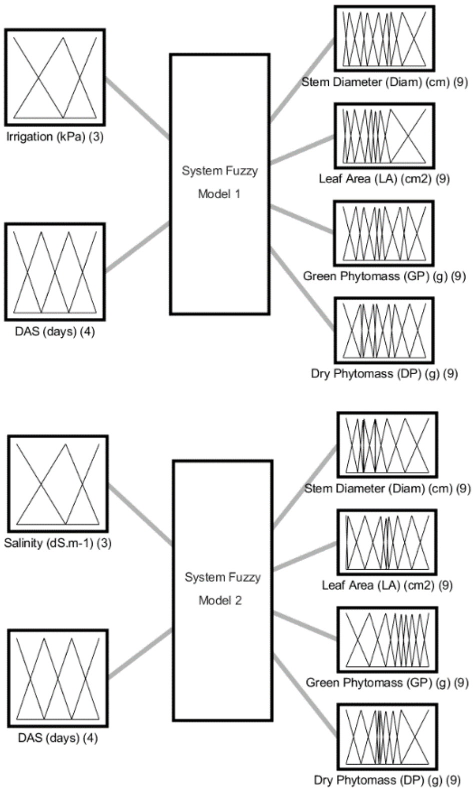

Figure 1. Tomato fuzzy systems with four output variables (biometric variables): stem diameter, leaf area, green phytomass, and dry phytomass. In both systems, days after sowing (DAS) is one of the input variables. In (a) Model 1, the other input variable is soil water tension. In (b) Model 2, the second input variable is salinity doses in irrigation.

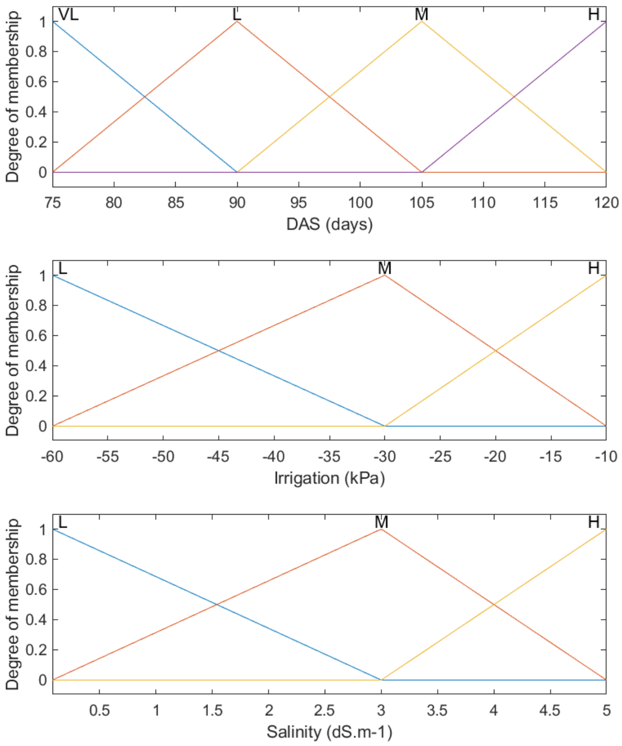

Figure 2. Triangular relevance functions of the Very Low (VL), Low (L), Medium (M), and High (H) fuzzy sets for the input variables DAS, Irrigation, and Salinity.

Table 2. Mean Squares (MS) and Coefficients of Variation (CV) of the Analysis of Variance (ANOVA) of the biometric variables to be the output variables of Models 1 and 2, labeled Plant Height (Heig), Stem Diameter (Diam), Leaf Area (LA), Green Phytomass (GP), and Dry Phytomass (DP), under a 3 × 4 Factorial Scheme.

Variation factor	MS									
	Model 1					Model 2				
	Heig	Diam	LA	GP	DP	Heig	Diam	LA	GP	DP
A	101.1	0.16*	10822.0*	7180.3*	327.0*	133.9	0.25*	4528.6*	3531.3*	153.3*
B	128.6	0.24*	64597.5*	1013.8*	67.3*	402.6*	0.06*	125682.8*	931.4	9.2
A × B	89.9	0.01	3197.8*	97.7	6.0	72.3	0.05*	2983.8*	1231.3*	52.0*
CV (%)	17.8	8.1	10.7	9.0	10.4	11.7	10.5	11.7	10.0	11.9

Legend: Factor A – Irrigation (−kPa) for Model 1 and Salinity (dS m^{-1}) for Model 2; Factor B – DAS (days); (*) Significant by the F-test with a 5% probability of error.

In Table 2, the variable Heig of Model 1 shows the absence of differences between the levels of analysis factors (Irrigation and DAS) and also the interaction between them. The variables Diam, GP, and DP had the same behavior, showing differences in the levels of each factor and an absence of interaction between analysis factors. Finally, there is an interaction between the analysis factors of the variable LA. In general, the coefficients of variation ranged from 8 to 18%.

The variable Hight of Model 2 shows differences between the levels of the factor DAS but has no differences between the factor Salinity as well as no differences of interaction between analysis factors (Salinity and DAS). The other variables show an interaction between analysis factors. In general, the coefficients of variation remained between 9 and 12%.

The methodology used to create the membership functions of the fuzzy sets of output variables in the modeling performed in this study was similar to that used by Viais Neto et al. (2019a) and is defined in Table 3, using percentiles varying at 12.5%. Importantly, one of the two disjunct intervals of the support, whose points have no degree of membership 1, was defined with an amplitude equal to 1 for the membership functions L1 and H3.

Table 3. Definition of delimiters of triangular membership functions of the fuzzy sets Low 1 (L1), Low 2 (L2), Low 3 (L3), Medium 1 (M1), Medium 2 (M2), Medium 3 (M3), High 1 (H1), High 2 (H2), and High 3 (H3) for the output variables of both Models 1 and 2, using percentiles of the data sets for each output variable.

Fuzzy Set	Delimiter
L1	[P(0%) - 1 , P(0%) , P(12.5%)]
L2	[P(0%) , P(12.5%) , P(25%)]
L3	[P(12.5%) , P(25%) , P(37.5%)]
M1	[P(25%) , P(37.5%) , P(50%)]
M2	[P(37.5%) , P(50%) , P(62.5%)]
M3	[P(50%) , P(62.5%) , P(75%)]
H1	[P(62.5%) , P(75%) , P(87.5%)]
H2	[P(75%) , P(87.5%) , P(100%)]
H3	[P(87.5%) , P(100%) , P(100%)+1]

Source: Viais Neto et al. (2019a).

Rules Base

Twelve (3 × 4) combinations between fuzzy sets of the two input variables were considered to obtain the rules base of the fuzzy system in both models. Thus, 12 pairs of the Irrigation × DAS form were created for Model 1 and 12 pairs of the Salinity × DAS form for Model 2, according to the methodology used by Viais Neto et al. (2019a), and similar to those adopted by Cremasco, Gabriel Filho, and Cataneo (2010), Gabriel Filho, Cremasco, Putti, and Chacur (2011), Gabriel Filho, Pigatto, and Lourenzani (2015), Gabriel Filho et al. (2016), Gabriel Filho, Silva Junior, Cremasco, Souza, and Putti (2022a), Gabriel Filho, Silva, Putti, and Cremasco (2022b), Pereira, Bighi, Gabriel Filho, and Cremasco (2008), Putti, Gabriel Filho, Silva, Ludwig, and Cremasco (2014), Putti et al. (2017a), Putti, Kummer, Grassi Filho, Gabriel Filho, and Cremasco (2017b), Putti et al. (2021), Putti, Cremasco, Silva Junior, and Gabriel Filho (2022), Martínez et al. (2020), Matulovic, Putti, Cremasco, and Gabriel Filho (2021), Góes, Goes, Cremasco, and Gabriel Filho (2022), Boso, Cremasco, Putti, and Gabriel Filho (2021a), Boso, Cremasco, Putti, and Gabriel Filho (2021b), and Maziero, Chacur, Cremasco, Putti, and Gabriel Filho (2022).

Similar to those studies, the highest degrees of relevance of each treatment median were calculated after the elaboration of the fuzzy output sets, associating the input variables with the output variables.

The association of combinations of fuzzy sets of the input variables with a fuzzy set of each output variable of both Models 1 and 2 was performed similarly to the model established by Viais Neto et al. (2019a and b).

Inference, defuzzification methods, and software

The inference method used in this study was the Mamdani (Mamdani, & Assilian, 1975). The center of gravity method was adopted for defuzzification. The value of the linguistic output variable inferred by the fuzzy rules is translated into real value.

The development of FRBS of the present study required the software Matlab®, licensed for the São Paulo State University (UNESP), School of Sciences and Engineering, Tupã campus, São Paulo State, Brazil. Specifically, the Fuzzy Logic Toolbox of the software was used to prepare three-dimensional graphs and contour maps.

Statistical analysis

The biometric variables were analyzed statistically using ANOVA (analysis of variance) in two ways: considering the factors irrigation and DAS (3 × 4) and later the factors salinity and DAS (3 × 4), thus consisting of 12 treatments in each analysis.

Each treatment had three repetitions. There was no need for a comparison between treatment means, as the purpose of the analysis was to identify variables with significant differences between their treatments. Thus, variables that did not present significant differences between their treatments were not mathematically modeled.

All statistical analyses were performed using the R software 4.2.0 (R Core Team, 2022), adopting a value of $p < 0.05$ as statistically significant.

Results and discussion

Both models were prepared, after calculating the percentiles of the measured data, with the definition of the membership functions of the fuzzy sets of the output variables stem diameter, leaf area, green phytomass, and dry phytomass (Figure 3).

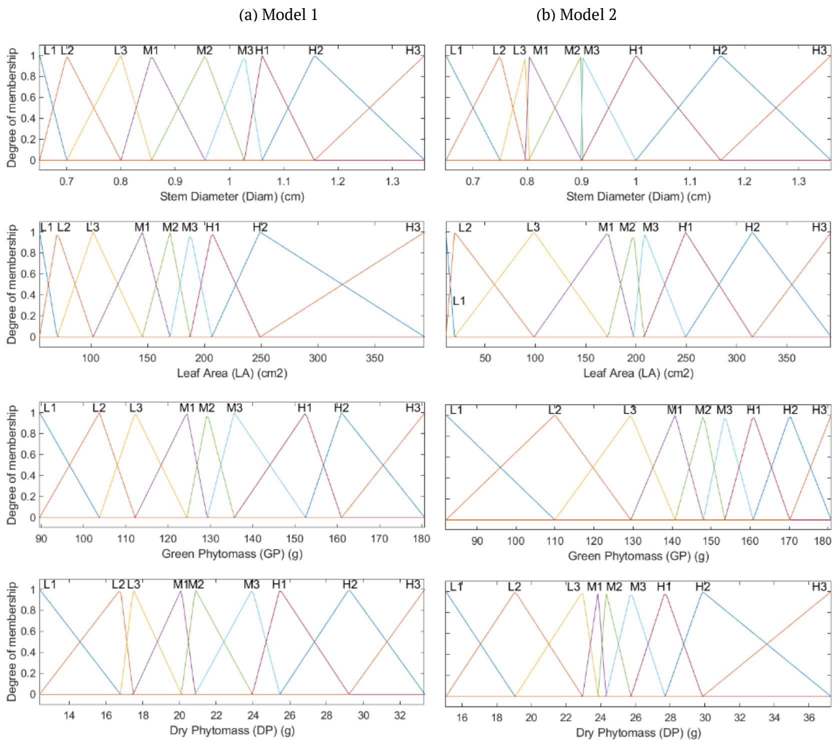

Figure 3. Membership functions of the fuzzy sets of the output variables of Stem diameter, Leaf area, Green phytomass, and Dry phytomass (a) for Model 1 and (b) Model 2.

Once the membership functions were defined, the highest pertinence degree was taken for each biometric variable analyzed, referring to the type of treatment applied during the tomato development. Thus, the situation that fits the variable under analysis could be assessed by comparing it with the other treatments, thus rating the rules base for the Models (Table 4).

Table 4. Rule-base of fuzzy systems relating all combinations of fuzzy sets of the input variables with those of the output variables (Diam - Stem Diameter, LA - Leaf Area, GP - Green Phytomass, and DP - Dry Phytomass). Input 1 is defined as "Irrigation" for Model 1 and "Salinity" for Model 2.

Input variable		Output variable							
Input 1	Input 2	Model 1				Model 2			
	DAS	Diam	AF	GP	DP	Diam	AF	GP	DP
L	VL	L3	M1	L2	L2	H1	M1	M3	M2
L	L	L2	H2	L2	L2	M1	H3	H1	H2
L	M	M2	M3	M2	M1	H3	M2	H2	H1
L	H	M3	L2	M2	M3	H2	L3	H1	H2
M	VL	M1	M2	M1	M1	M3	M3	M2	M1
M	L	L2	H1	L2	L3	M3	H2	L3	L3
M	M	H1	M1	M3	M1	H1	M1	M3	H1
M	H	H1	L2	M3	H1	L2	L2	M1	H2
H	VL	M3	M3	H1	H1	M3	H1	H1	M1
H	L	L3	H3	H2	H2	L2	H2	M1	M1
H	M	H3	H1	H2	H2	M1	L3	L2	L2
H	H	H2	L2	H2	H2	L1	L1	L1	L1

The power of analysis coming from the present mathematical modeling stands out, allowing a simultaneous comparison of all contour maps of the analyzed response variables.

Additionally, the way of obtaining the rules base contributes to performing the present method of creating Fuzzy Rule-Based Systems. Most fuzzy systems that use the Mamdani inference method are elaborated using expert interviews to create their rules base. The rules base is also an important result since the understanding of the present system with a table (rules base) becomes easier for many rural producers when faced with the interpretation of three-dimensional surfaces.

The Mamdani method was employed in this present study but without the use of interviews to create the rules base. It was generated from a specific methodology using percentiles and the association of fuzzy sets.

Therefore, Table 4 could be elaborated, which is an extremely important result for the practical use of the models developed in this paper.

The graphical results of the models are presented in the form of surfaces (Figure 4) and contour maps (Figure 5) for all biometric variables.

The Stem Diameter of Model 1 (Figure 5a) had the highest value at a soil water tension of −10 kPa and 105 DAS. Soil water tensions between −25 and −10 kPa led to a gradual increase in diameter until the end of the tomato cycle. In contrast, this development only occurred after 90 days for tensions between −30 and −60 kPa. Biomass allocation in stem diameter shows linear increases with increasing water depths, being associated with a reduction in phytomass production activity, as energy must be redirected to fruit production (Ullah et al., 2021; Zhou et al., 2019). In Model 2, Stem Diameter (Figure 5b) reaches its maximum at a salinity of 0.08 dS m^{-1} and 115 DAS. The minimum value was inferred at 90 DAS for a salinity of 5 dS m^{-1}. Salinity caused a reduction in stem diameter, as salts accumulate in this case, which affects the osmotic adjustment (Abdeldym, El-Mogy, Abdellateaf, & Atia, 2020; Feng et al., 2019).

The Leaf Area of Model 1 (Figure 5a) has a maximum value at a soil water tension of −10 kPa and 90 DAS. The leaf area size was similar at 120 DAS, regardless of the soil water tension. Water deficit decreases the number of leaves per plant, leaf area, and leaf longevity due to reduced soil water potential. The most visual effect of water deficit is the reduction in leaf area. It leads to reduced water loss and lower energy expenditure to control stoma opening and thus minimize impacts (Khapte et al., 2019; Ullah et al., 2021). For Model 2 (Figure 5b), Leaf Area had the highest value at 90 DAS and salinity of 0.08 dS m^{-1}. In general, the behavior of this variable is very similar throughout the tomato cycle according to the treatments, regardless of the salinity dose in irrigation. Morphological and anatomical changes in plants are common under salt stress conditions, which reflect in the reduction of transpiration as an alternative to maintain the low absorption of saline water; one of these adaptations is the reduction in leaf area (Pérez-Labrada et al., 2019; Sassine et al., 2020).

The Green Phytomass in Model 1 (Figure 5a) obtained a maximum at soil water tension of −10 kPa in the last evaluation period. There is no development of green phytomass between −60 to −30 kPa and 75 to 105 DAS. Similar effects have been observed in studies with the application of irrigation depths so that the reduction in green phytomass accumulation is linear as a function of the reduction in the applied depth (Hatamleh et al., 2022; Salgado et al., 2021). The highest development for Model 2 (Figure 5b) occurred throughout the cycle for the treatment with a salinity of 0.08 dS m^{-1}. The opposite of this situation occurred at 105 DAS for a salinity of 5 dS m^{-1}.

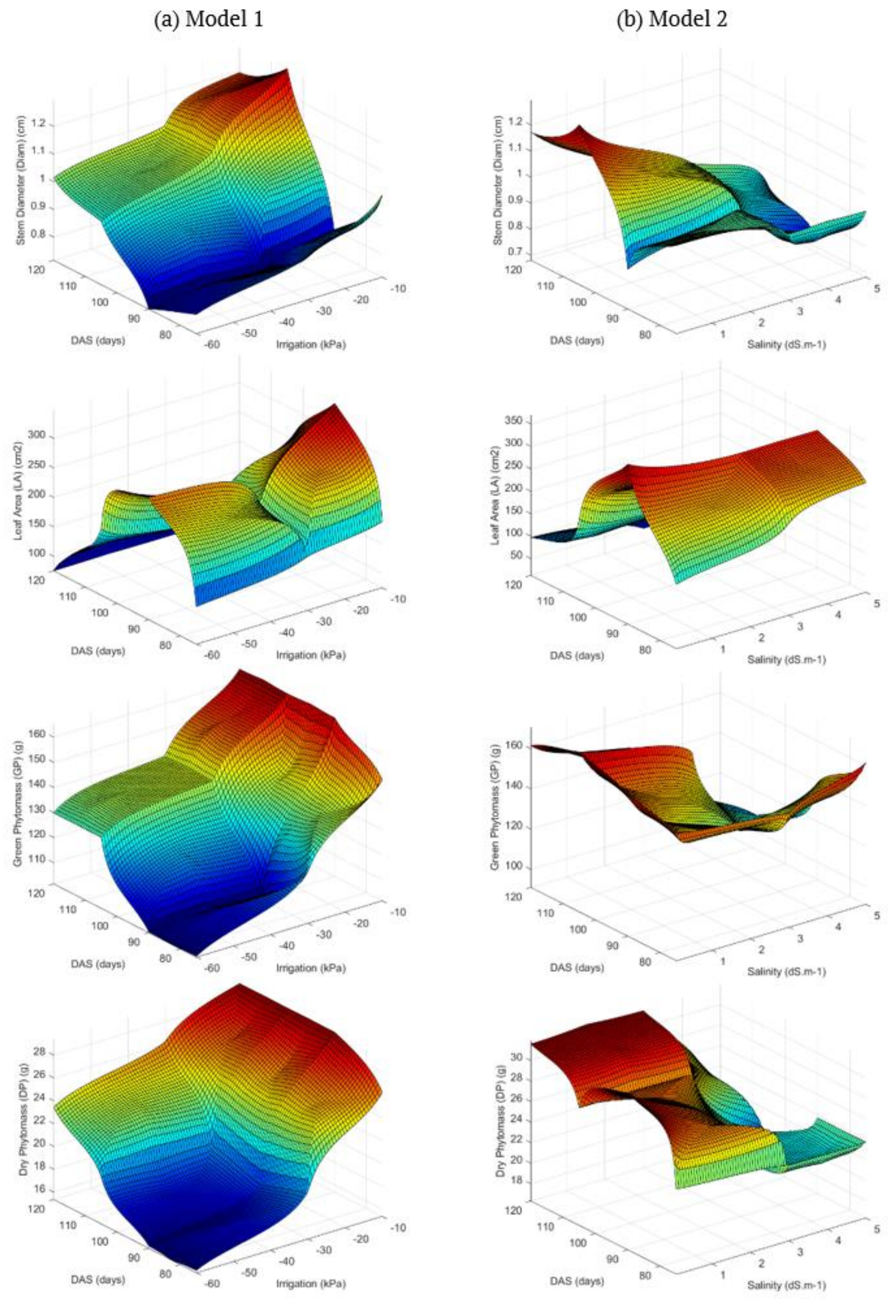

Figure 4. Surfaces generated by Models (a) 1 and (b) 2.

Finally, the Dry Phytomass behavior in Model 1 (Figure 5a) was similar to that of green phytomass. A similar phenomenon occurred in Model 2 (Figure 5b). However, salinity doses in Model 2 influenced the dry phytomass more intensely for values above 3 dS m^{-1}. In general, the inhibition in the growth and production of phytomass by plants is a response to nutritional imbalance and toxicity, which reflect in-breath loss, root expansion, water absorption, and CO_2 fixation (Alzahib et al., 2021; Martínez-Andújar et al., 2021; Sousa et al., 2022). The decrease in aerial phytomass production by plants irrigated with saline water is almost always the result of early senescence caused by the toxic effects of excess salts in the water, which limits leaf area expansion and, therefore, reduces dry matter yield (Huang, Zhang, Zhai, Lu, & Zhu, 2019; Okon, 2019; Zörb, Geilfus, & Dietz, 2019).

The normalization of references to the regions of each contour map of the biometric variables (Figure 5) was performed by defining as Region A the site with the highest values of the biometric variable (warmer colors or red), while Region B will be the one with the lowest values (cooler colors or blue).

Thus, Region A in Model 1 is partially or fully inserted between the irrigation levels 60 and −30 kPa for all variables. In contrast, Region B is fully inserted between the irrigation levels −25 and −10 kPa. Thus, water deficit negatively influences all the variables analyzed throughout the tomato cycle.

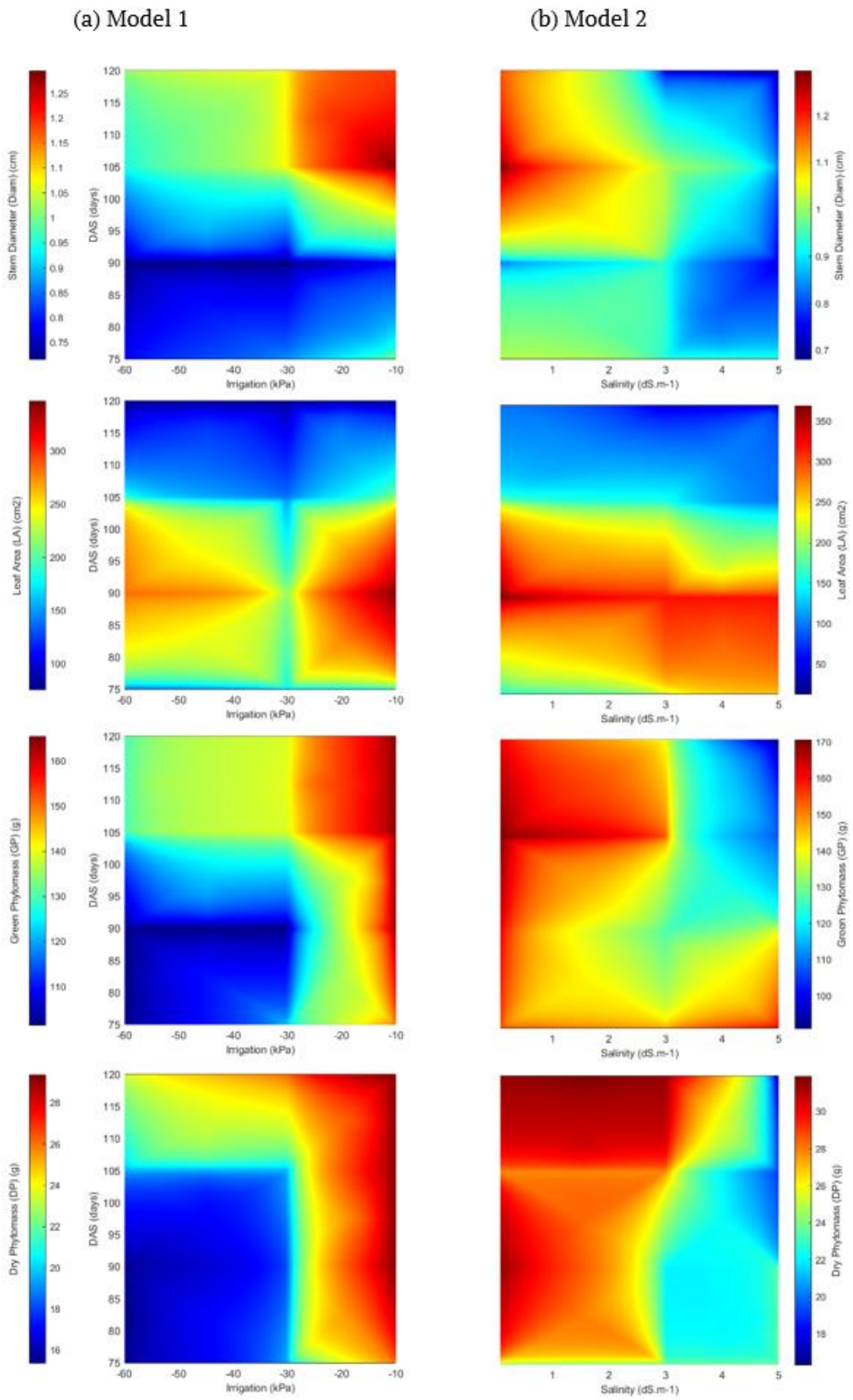

Figure 5. Contour maps by Models (a) 1 and (b) 2.

For Model 2, Region A represents the lowest values inferred for each variable, while Region B represents the highest values. The variables most affected by the increase in salinity doses in irrigation are stem diameter, green phytomass, and dry phytomass, as Region A of these variables is located between salinity doses in irrigation of 4 and 5 dS m^{-1}. In addition, Region B for all variables is partially or fully inserted between salinity doses in irrigation of 0.08 and 3 dS m^{-1}, which is in line with Ayres and Westcot (1976), who stated that tomato is considered moderately sensitive to salts, with the threshold for the crop at 2.5 dS m^{-1}.

Conclusion

All the biometric variables of the tomato crop analyzed in Model 1 showed a better development for high soil water tensions. Water deficit negatively influenced the variables analyzed throughout the tomato cycle. In addition, a certain homogeneity was observed in the effects caused by water stresses in the soil on the development of the variables stem diameter and green and dry mass. In Model 2, high salinity doses in irrigation severely affected the variables stem diameter, green phytomass, and dry phytomass throughout the tomato cycle. In addition, low amounts of salinity in irrigation provided the best development for all analyzed biometric variables. The use of fuzzy logic helped in modeling the behavior of the tomato crop under different management conditions whether due to water deficit or salinity, thus supporting the decision-making regarding the most appropriate management method. Thus, it proved to be an important tool to assist in the decision-making process of producers. It can be seen in the present mathematical model, which classified different conditions according to the development time, salinity, and irrigation conditions offered to the tomato crop. These different conditions proved to be favorable for the crop in certain cases but revealed situations not so favorable in other cases. Sometimes, these situations are characteristic of the planting site and therefore cannot be controlled. However, the model represents, even in such a scenario, an excellent decision-making support system, as the rural producer will be able to predict the biometric variables that tomato plants will have naturally before planting. The producer can carry out the most appropriate possible management for the crop regarding controllable factors, such as Irrigation, which is present in one of the models in this study. However, there are situations in which the amount of water is limited, and, in this case, the optimal point shown in the models cannot be obtained by the rural producer. Still in this case, the results of this study are useful, as the predictability of the behavior of biometric variables helps in the decision-making by the rural producer. Another conclusion is that the created fuzzy models showed the same characteristics of the experiment, allowing their use as an automatic technique to estimate the ideal parameters for the complete development of the plant cycle. The development of applications (software) that provide the results generated by the artificial intelligence models of the present study is the aim of future research.

References

Abdeldym, E. A., El-Mogy, M. M., Abdellateaf, H. R. L., & Atia, M. A. M. (2020). Genetic characterization, agro-morphological and physiological evaluation of grafted tomato under salinity stress conditions. *Agronomy*, *10*(12), 1-26. DOI: http://doi.org/10.3390/agronomy10121948

Ağaoğlu, M., Ayaz, B., Ayaz, Y., & Yaman, M. (2022). A historical and nutrition-dietetic analysis of food consumption habits in ottoman culinary culture in the light of travel books. *Food Science and Technology*, *42,* 1-10. DOI: http://doi.org/10.1590/fst.51721

Alzahib, R. H., Migdadi, H. M., Al Ghamdi, A. A., Alwahibi, M. S., Ibrahim, A. A., & Al-Selwey, W. A. (2021). Assessment of morpho-physiological, biochemical and antioxidant responses of tomato landraces to salinity stress. *Plants*, *10*(4), 1-18. DOI: http://doi.org/10.3390/plants10040696

Amin, S., & Borchgrevink, C. P. (2022). A Culinology® perspective of dry beans and other pulses. *Dry Beans and Pulses*, 453-480. DOI: http://doi.org/10.1002/9781119776802.ch18

Ayers, R. S., & Westcot, D. W. (1976). *Water quality for agriculture*. Rome, IT: FAO. (FAO Irrigation and Drainage Paper, No. 29).

Bani, A., Daghari, I., Hatira, A., Chaabane, A., & Daghari, H. (2021). Sustainable management of a cropping system under salt stress conditions (Korba, Cap-Bon, Tunisia). *Environmental Science and Pollution Research*, *28*(34), 46469-46476. DOI: http://doi.org/10.1007/S11356-020-09767-0

Benini, L., & Rinaldi, J. (2015). Modelagem para previsão/estimação: uma aplicação neuro-fuzzy. *Proceeding Series of the Brazilian Society of Computational and Applied Mathematics*, *3*(1), 1-5. DOI: http://doi.org/10.5540/03.2015.003.01.0264

Bonachela, S., Fernández, M. D., Cabrera-Corral, F. J., & Granados, M. R. (2022). Salt and irrigation management of soil-grown Mediterranean greenhouse tomato crops drip-irrigated with moderately saline water. *Agricultural Water Management*, *262*, 1-6. DOI: http://doi.org/10.1016/J.AGWAT.2021.107433

Boso, A. C. M. R., Cremasco, C. P., Putti, F. F., & Gabriel Filho, L. R. A. (2021a). Fuzzy modeling of the effects of different irrigation depths on the radish crop. Part I: Productivity analysis. *Engenharia Agrícola, 41*(3), 311-318. DOI: http://doi.org/10.1590/1809-4430-Eng.Agric.v41n3p311-318/2021

Boso, A. C. M. R., Cremasco, C. P., Putti, F. F., & Gabriel Filho, L. R. A. (2021b). Fuzzy modeling of the effects of different irrigation depths on the radish crop. Part II: Biometric variables analysis. *Engenharia Agrícola*, *41*(3), 319-329. DOI: http://doi.org/10.1590/1809-4430-Eng.Agric.v41n3p319-329/2021

Castro, E. R., Saad, J. C. C., & Gabriel Filho, L. R. A. (2022). Artificial intelligence techniques applied to the optimization of micro-irrigation systems by the Zimmermann-Werner method. *Engenharia Agrícola*, *42*(Supl. Especial), 1-12. DOI: http://doi.org/10.1590/1809-4430-Eng.Agric.v42nepe20210118/2022

Castro, T. A., Leite, B. S., Assunção, L. S., Jesus Freitas, T., Colauto, N. B., Linde, G. A., ... Ferreira Ribeiro, C. D. (2021). Red tomato products as an alternative to reduce synthetic dyes in the food industry: A review. *Molecules*, *26*(23), 1-24. DOI: http://doi.org/10.3390/molecules26237125

Cremasco, C. P., Gabriel Filho, L. R. A., & Cataneo, A. (2010). Methodology for determination of fuzzy controller pertinence functions for the energy evaluation of poultry industry companies. *Energia na Agricultura*, *25*(1), 21-39. DOI: http://doi.org/10.17224/EnergAgric.2010v25n1p21-39

Dourado Neto, D., Lier, Q. J. V., Botrel, T. A., & Libardi, P. L. (1990). Programa para confecção da curva característica de retenção de água do solo utilizando o modelo de Genuchten. *Engenharia Rural*, *1*(2), 92-102.

Elleuch, M. A., Anane, M., Euchi, J., & Frikha, A. (2019). Hybrid fuzzy multi-criteria decision making for solving the irrigation water allocation problem in the Tunisian case. *Agricultural Systems*, *176*, 102644. DOI: http://doi.org/10.1016/j.agsy.2019.102644

Feng, G., Zhang, Z., Wan, C., Lu, P., & Bakour, A. (2017). Effects of saline water irrigation on soil salinity and yield of summer maize (*Zea mays* L.) in subsurface drainage system. *Agricultural Water Management*, *193*, 205-213. DOI: http://doi.org/10.1016/j.agwat.2017.07.026

Feng, X., Guo, K., Yang, C., Li., J., Huanyu, C., & Liu, X. (2019). Growth and fruit production of tomato grafted onto wolfberry (*Lycium chinense*) rootstock in saline soil. *Scientia Horticulturae*, *255*, 298-305. DOI: http://doi.org/10.1016/j.scienta.2019.05.028

Gabriel Filho, L. R. A., Cremasco, C. P., Putti, F. F., & Chacur, M. G. M. (2011). Application of fuzzy logic for the evaluation of livestock slaughtering. *Engenharia Agrícola*, *31*(4), 813-825. DOI: http://doi.org/10.1590/S0100-69162011000400019

Gabriel Filho, L. R. A., Pigatto, G. A. S., & Lourenzani, A. E. B. S. (2015). Fuzzy rule-based system for evaluation of uncertainty in cassava chain. *Engenharia Agrícola*, *35*(2), 350-367. DOI: http://doi.org/10.1590/1809-4430-Eng.Agric.v35n2p350-367/2015

Gabriel Filho, L. R. A., Putti, F. F., Cremasco, C. P., Bordin, D., Chacur, M. G. M., & Gabriel, L. R. A. (2016). Software to assess beef cattle body mass through the fuzzy body mass index. *Engenharia Agrícola*, *36*(1), 179-193. DOI: http://doi.org/10.1590/1809-4430-Eng.Agric.v36n1p179-193/2016

Gabriel Filho, L. R. A., Silva Junior, J. F., Cremasco, C. P., de Souza, A. V., & Putti, F. F. (2022a). Fuzzy modeling of salinity effects on pumpkin (*Cucurbita pepo*) development. *Engenharia Agrícola*, *42*(1), 1-12. DOI: http://doi.org/10.1590/1809-4430-eng.agric.v42n1e20200150/2022

Gabriel Filho, L. R. A., Silva, A. O., Putti, F. F., & Cremasco, C. P. (2022b). Fuzzy modeling of the effect of irrigation depths on beet cultivars. *Engenharia Agrícola*, *42*(1), 1-11. DOI: http://doi.org/10.1590/1809-4430-Eng.Agric.v42n1e20210084/2022

García-Caparrós, P., & Lao, M. T. (2018). The effects of salt stress on ornamental plants and integrative cultivation practices. *Scientia Horticulturae*, *240*, 430-439. DOI: http://doi.org/10.1016/j.scienta.2018.06.022

Góes, B. C., Goes, R. J., Cremasco, C. P., & Gabriel Filho, L. R. A. (2022). Fuzzy modeling of vegetable straw cover crop productivity at different nitrogen doses. *Modeling Earth Systems and Environment*, *8*, 939-945. DOI: http://doi.org/10.1007/s40808-021-01125-4

Gomaa, M. A., Kandil, E. E., El-Dein, A. A. M. Z., Abou-Donia, M. E. M., Ali, H. M., & Abdelsalam, N. R. (2021). Increase maize productivity and water use efficiency through application of potassium silicate under water stress. *Scientific Reports*, *11*(1), 1-8. DOI: http://doi.org/10.1038/s41598-020-80656-9

Hatamleh, A. A., Danish, M., Munirah, B., Al-Dosary, A., El-Zaidy, M., & Ali, S. (2022). Physiological and oxidative stress responses of *Solanum lycopersicum* (L.) (tomato) when exposed to different chemical pesticides. *RSC Advances*, *12*(12), 7237-7252. DOI: http://doi.org/10.1039/d1ra09440h

Holanda, J. S., Amorim, J. R. A., Ferreira Neto, M., Holanda, A. C., & Sá, F. V. S. (2016). Qualidade da água para irrigação (2. ed.). In H. R. Gheyi, N. S., Dias, C. F. Lacerda, & E. G. Filho (Eds.), *Manejo da salinidade na agricultura*: estudos básicos e aplicados. Fortaleza, CE: INCTSal.

Hoseini, Y. (2019). Use fuzzy interface systems to optimize land suitability evaluation for surface and trickle irrigation. *Information Processing in Agriculture*, *6*(1). 11-19. DOI: http://doi.org/10.1016/j.inpa.2018.09.003

Huang, M., Zhang, Z., Zhai, Y., Lu, P., & Zhu, C. (2019). Effect of straw biochar on soil properties and wheat production under saline water irrigation. *Agronomy*, *9*(8), 1-5. DOI: http://doi.org/10.3390/agronomy9080457

Ketsa, S., Wisutiamonkul, A., Palapol, Y., & Paull, R. E. (2019). The Durian. *Horticultural Reviews*, 125-211. DOI: http://doi.org/10.1002/9781119625407.ch4

Khapte, P. S., Kumar, P., Burman, U., & Kumar, P. (2019). Deficit irrigation in tomato: Agronomical and physio-biochemical implications. *Scientia Horticulturae*, *248*, 256-264. DOI: http://doi.org/10.1016/j.scienta.2019.01.006

Klar, A. E. (1988). *A água no sistema solo-planta-atmosfera* (2. ed.). São Paulo, SP: Nobel.

Lu, J., Shao, G., Cui, J., Wang, X., & Keabetswe, L. (2019). Yield, fruit quality and water use efficiency of tomato for processing under regulated deficit irrigation: A meta-analysis. *Agricultural Water Management*, *222*, 301-312. DOI: http://doi.org/10.1016/j.agwat.2019.06.008

Luydmila, S., Mikhail, S., Imran, A., Tamara, A., & Anatoliy, C. (2017). Application of fuzzy set theory in agro-meteorological models for yield estimation based on statistics. *Procedia Computer Science*, *120*, 820-829. DOI: http://doi.org/10.1016/j.procs.2017.11.313

Mamdani, E. H., & Assilian, S. (1975). An experiment in linguistic synthesis with a fuzzy logic controller. *International Journal Man-Machine Studies*, *7*(1), 1-13. DOI: http://doi.org/10.1016/S0020-7373(75)80002-2

Martínez, M. P., Cremasco, C. P, Gabriel Filho, L. R. A., Braga Junior, S. S., Bednaski, A. V., Quevedo-Silva, F., ... Padgett, R. C. M. L. (2020). Fuzzy inference system to study the behavior of the green consumer facing the perception of greenwashing. *Journal of Cleaner Production*, *242*, 116064. DOI: http://doi.org/10.1016/j.jclepro.2019.03.060

Martínez-Andújar, C., Martínez-Pérez, A., Albacete, A., Martínez-Melgarejo, P. A., Dodd, I. C., Thompson, A. J., ... Pérez-Alfocea, F. (2021). Overproduction of ABA in rootstocks alleviates salinity stress in tomato shoots. *Plant, Cell & Environment*, *44*(9), 2966-2986. DOI: http://doi.org/10.1111/pce.14121

Matulovic, M., Putti, F. F., Cremasco, C. P., & Gabriel Filho, L. R. A. (2021). Technology 4.0 with 0.0 costs: fuzzy model of lettuce productivity with magnetized water. *Acta Scientiarum. Agronomy*, *43*(1), 1-15. DOI: http://doi.org/10.4025/actasciagron.v43i1.51384

Maziero, L. P., Chacur, M. G. M., Cremasco, C. P, Putti, F. F., & Gabriel Filho, L. R. A. (2022). Fuzzy system for assessing bovine fertility according to semen characteristics. *Livestock Science*, *256*, 104821. DOI: http://doi.org/10.1016/j.livsci.2022.104821

Okon, O. G. (2019). Effect of salinity on physiological processes in plants. In B. Giri, & A. Varma (Eds.), *Microorganisms in saline environments*: *Strategies and functions*. New York, NY: Springer. (Soil Biology, 56). DOI: http://doi.org/10.1007/978-3-030-18975-4_10

Oliveira, J. R. S., Viais Neto, D. S., Maeda, M. P. R, & Gabriel Filho, L. R. A. (2020). Modelo fuzzy de avaliação do perfil do consumo de energia elétrica de instituições de ensino superior. *Alomorfia*, *4*(2), 69-81.

Pereira, D. F., Bighi, C. A., Gabriel Filho, L. R. A., & Cremasco, C. P. (2008). Sistema fuzzy para estimativa do bem-estar de matrizes pesadas. *Engenharia Agrícola*, *28*(4), 624-633. DOI: http://doi.org/10.1590/S0100-69162008000400002

Pérez-Labrada, F., López-Vargas, E. R., Ortega-Ortiz, H., Cadenas-Pliego, G., Benavides-Mendoza, A., & Juárez-Maldonado, A. (2019). Responses of tomato plants under saline stress to foliar application of copper nanoparticles. *Plants*, *8*(6), 1-17. DOI: http://doi.org/10.3390/plants8060151

Prabakaran, G., Vaithiyanathan, D., & Ganesan, M. (2018). Fuzzy decision support system for improving the crop productivity and efficient use of fertilizers. *Computers and Electronics in Agriculture*, *150*, 88-97. DOI: http://doi.org/10.1016/j.compag.2018.03.030

Putti, F. F., Cremasco, C. P., Silva Junior, J. F., & Gabriel Filho, L. R. A. (2022). Fuzzy modeling of salinity effects on radish yield under reuse water irrigation. *Engenharia Agrícola*, *42*(1), 1-11. DOI: http://doi.org/10.1590/1809-4430-Eng.Agric.v42n1e215144/2022

Putti, F. F., Gabriel Filho, L. R. A., Cremasco, C. P., Bonini Neto, A., Bonini, C. S. B., & Reis, A. R. (2017a). A Fuzzy mathematical model to estimate the effects of global warming on the vitality of Laelia purpurata orchids. *Mathematical Biosciences*, *288*, 124-129. DOI: http://doi.org/10.1016/j.mbs.2017.03.005

Putti, F. F., Gabriel Filho, L. R. A., Silva, A. O., Ludwig, R., & Cremasco, C. P. (2014). Fuzzy logic to evaluate vitality of catasetum fimbiratum species (*Orchidacea*). *Irriga*, *19*(3), 405-413. DOI: http://doi.org/10.15809/irriga.2014v19n3p405

Putti, F. F., Kummer, A. C. B., Grassi Filho, H., Gabriel Filho, L. R. A., & Cremasco, C. P. (2017b). Fuzzy modeling on wheat productivity under different doses of sludge and sewage effluent. *Engenharia Agrícola*, *37*(6), 1103-1115. DOI: http://doi.org/10.1590/1809-4430-eng.agric.v37n6p1103-1115/2017

Putti, F. F., Lanza, M. H., Grassi Filho, H., Cremasco, C. P., Souza, A. V., & Gabriel Filho, L. R. A. (2021). Fuzzy modeling in orange production under different doses of sewage sludge and wastewater. *Engenharia Agrícola*, *41*(2), 204-214. DOI: http://doi.org/10.1590/1809-4430-eng.agric.v41n2p204-214/2021

R Core Team (2022). *R: A language and environment for statistical computing*. Vienna, AT: R Foundation for Statistical Computing. Retrieved on Jan. 10, 2022 from http://www.R-project.org/

Rosa, L., Chiarelli, D. D., Rulli, M. C., Dell'Angelo, J., & D'Odorico, P. (2020). Global agricultural economic water scarcity. *Science Advances*, *6*(18), 1-10. DOI: http://doi.org/10.1126/sciadv.aaz6031

Salgado, G. C., Ambrosano, E. J., Rossi, F., Otsuk, I. P., Ambrosao, G. M. B., Patri, P., ...Trivelin, P. C. O. (2021). Yield and nutrient concentrations of organic cherry tomatoes and legumes grown in intercropping systems in rotation with maize. *Biological Agriculture & Horticulture*, *38*(2), 94-112. DOI: http://doi.org/10.1080/01448765.2021.1992796

Sassine, Y. N., Alturki, S. M., Germanos, M., Shaban, N., Sattar, M. N., & Sajyan, T. K. (2020). Mitigation of salt stress on tomato crop by using foliar spraying or fertigation of various products. *Journal of Plant Nutrition*, *43*(16), 2493-2507. DOI: http://doi.org/10.1080/01904167.2020.1771587

Silva Junior, J. F., Silva, A. O., Klar, A. E., Silva, I. P. F., & Tanaka, A. A. (2018). Produção e desenvolvimento da cultura do tomate submetida a diferentes estratégias de irrigação e qualidade da água. *Irriga*, *23*(2), 298-313. DOI: http://doi.org/10.15809/irriga.2018v23n2p298-313

Simmons, A. M., Wakil, W., Qayyum, M. A., Ramasamy, S., Kuhar, T. P., & Philips, C. R. (2018). Lepidopterous pests: Biology, ecology, and management. In W. Wakil, G. E. Brust, & T. M. Perring (Eds.), *Sustainable management of arthropod pests of tomato* (p. 131-162). New York, NY: Academic Press. DOI: http://doi.org/10.1016/B978-0-12-802441-6.00006-1

Sousa, V. Q., Messias, W. F. S., Pereira, Y. C., Silva, B. R. S., Lobato, E. M. S. G., Alyemeni, M. N., ... Lobato, A. K. S. (2022). Pretreatment with 24-Epibrassinolide synergistically protects root sdtructures and chloroplastic pigments and upregulates antioxidant enzymes and biomass in Na+-stressed tomato plants. *Journal of Plant Growth Regulation*, *41*, 2869-2885. DOI: http://doi.org/10.1007/S00344-021-10481-5

Trani, P. E., & Raij, B. (1997). Vegetables. In B. Raij, H. Cantarella, J. A. Quaggio, & A. M. C. Furlani (Eds.), *Recommendations of fertilization and liming for the State of São Paulo*. Campinas, SP: Instituto Agronômico.

Ullah, H., Santiago-Arenas, R., Ferdous, Z., Attia, A., & Datta, A. (2019). Improving water use efficiency, nitrogen use efficiency, and radiation use efficiency in field crops under drought stress: A review. *Advances in Agronomy*, *156*, 109-157. DOI: http://doi.org/10.1016/bs.agron.2019.02.002

Ullah, I., Mao, H., Rasool, G., Gao, H., Javed, Q., Sarwar, A., & Khan, M. I. (2021). Effect of deficit irrigation and reduced n fertilization on plant growth, root morphology and water use efficiency of tomato grown in soilless culture. *Agronomy*, *11*(2), 1-15. DOI: http://doi.org/10.3390/agronomy11020228

Nachshon, U. (2018). Cropland soil salinization and associated hydrology: Trends, processes and examples. *Water*, *10*(8), 1-20. DOI: http://doi.org/10.3390/w10081030

Valcárcel, M., Lahoz, I., Campillo, C., Martí, R., Leiva-Brondo, M., Roselló, S., & Cebolla-Cornejo, J. (2020). Controlled deficit irrigation as a water-saving strategy for processing tomato. *Scientia Horticulturae*, *261*, 108972. DOI: http://doi.org/10.1016/j.scienta.2019.108972

Van Genuchten, M. T. (1980). A closed-from equation for predicting the conductivity of unsaturaded solis. *Soil Science Society of America Journal*, *44*(5), 892-898. DOI: http://doi.org/10.2136/sssaj1980.03615995004400050002x

Vema, V., Sudheer, K. P., & Chaubey, I. (2019). Fuzzy inference system for site suitability evaluation of water harvesting structures in rainfed regions. *Agricultural Water Management*, *218*, 82-93. DOI: http://doi.org/10.1016/j.agwat.2019.03.028

Viais Neto, D. S., Cremasco, C. P., Bordin, D., Putti, F. F., Silva Junior, J. F., & Gabriel Filho, L. R. A. (2019a). Fuzzy modeling of the effects of irrigation and water salinity in harvest point of tomato crop. Part I: Description of the method. *Engenharia Agrícola*, *39*(3), 294-304. DOI: http://doi.org/10.1590/1809-4430-eng.agric.v39n3p294-304/2019

Viais Neto, D. S., Cremasco, C. P., Bordin, D., Putti, F. F., Silva Junior, J. F., & Gabriel Filho, L. R. A. (2019b). Fuzzy modeling of the effects of irrigation and water salinity in harvest point of tomato crop. Part II: Application and interpretation. *Engenharia Agrícola*, *39*(3), 305-314. DOI: http://doi.org/10.1590/1809-4430-eng.agric.v39n3p305-314/2019

Viais Neto, D. S., Pradela, V. A., Gabriel Filho, L. R. A., Cremasco, C. P., Maria, A. C. G., & Oliveira, G. S. D. (2018). Fuzzy modeling for evaluation of cherry tomato seedlings production using different doses of polymers and irrigation levels. *Colloquium Agrariae*, *14*(3), 93-103. DOI: http://doi.org/10.5747/ca.2018.v14.n3.a231

Wang, X., & Xing, Y. (2017). Evaluation of the effects of irrigation and fertilization on tomato fruit yield and quality: a principal component analysis. *Scientific Reports*, *7*(1), 1-13. DOI: http://doi.org/10.1038/s41598-017-00373-8

Xie, Y. L., Xia, D. X., Ji, L., & Huang, G. H. (2018). An inexact stochastic-fuzzy optimization model for agricultural water allocation and land resources utilization management under considering effective rainfall. *Ecological Indicators*, *92*, 301-311. DOI: http://doi.org/10.1016/j.ecolind.2017.09.026

Yahia, E. M., Gardea-Béjar, A., Ornelas-Paz, J. D. J., Maya-Meraz, I. O., Rodríguez-Roque, M. J., Rios-Velasco, C., ... Salas-Marina, M. A. (2019). Preharvest factors affecting postharvest quality. In E. M. Yahia (Ed.), *Postharvest technology of perishable horticultural commodities* (p. 99-128). Amsterdam, NT: Elsevier. DOI: http://doi.org/10.1016/B978-0-12-813276-0.00004-3

Yasuor, H., Yermiyahu, U., & Ben-Gal, A. (2020). Consequences of irrigation and fertigation of vegetable crops with variable quality water: Israel as a case study. *Agricultural Water Management*, *242*, 106362. DOI: http://doi.org/10.1016/j.agwat.2020.106362

Zhang, C., & Guo, P. (2018) FLFP: A fuzzy linear fractional programming approach with double-sided fuzziness for optimal irrigation water allocation. *Agricultural Water Management*, *199*, 105-119. DOI: http://doi.org/10.1016/j.agwat.2017.12.013

Zhang, C., Engel, B. A., & Guo, P. (2018). An Interval-based Fuzzy Chance-constrained Irrigation Water Allocation model with double-sided fuzziness. *Agricultural Water Management*, *210*, 22-31. DOI: http://doi.org/10.1016/j.agwat.2018.07.045

Zhou, R., Kong, L., Yu, X., Ottosen, C. O., Zhao, T., Jiang, F., & Wu, Z. (2019). Oxidative damage and antioxidant mechanism in tomatoes responding to drought and heat stress. *Acta Physiologiae Plantarum*, *41*(2), 1-11. DOI: http://doi.org/10.1007/S11738-019-2805-1

Zörb, C., Geilfus, C. M., & Dietz, K. J. (2019). Salinity and crop yield. *Plant Biology*, *21*, 31-38. DOI: http://doi.org/10.1111/plb.12884