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Simultaneous Optimization of Water Usage Efficiency and Yield of Cucumber Planted in a Columnar Aeroponic System

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Abstract

The development of aeroponic cultivation technology has led to more efficient use of water and plant nutrients for producing high quality agricultural commodities. In this research, cucumbers were grown in columnar aeroponic systems for nine weeks and the effect of spraying rate and spraying duration on the cucumber average yield and water usage efficiency were investigated. The experiments were performed using factorial experiment based on completely randomized designs. The spraying rate had three levels of 125, 250 and 375 mL/min, and the spraying durations were 10, 15 and 20 min. During the experiment, the spraying pumps were turned off for 15 min between each spraying time. Then, the two factors were simultaneously optimized using response surface methodology to maximize fruit yield and water usage efficiency. The ANOVA results showed that both responses were significantly affected by the main effects of the factors ($\alpha = 0.01$) and by their interaction effects ($\alpha = 0.05$). The comparison of first and second-order models to show the average yield and water usage efficiency as functions of sparing rate and sparing time indicated that the second-order models fitted with higher accuracies (R^2> 80%) to the experimental data than the first-order model. Simultaneous optimization showed that the most suitable spraying rate was 233.37 mL/min and for the spraying duration, it was 16.06 min. At the optimum conditions, the average yield per plant yield was 2.96 kg and the water usage efficiency was 110.37 kg/m^3.

Keywords: Greenhouse, nutrient solution, cucumber, aeroponic, response surface methodology.

Introduction

Soil is the most available growing medium for plant roots that provides the main nutrients and water for plant growth. However, in some cases, the presence of soil-borne pathogens, inappropriate soil texture, poor drainage and soil degradation may pose serious limitations for soil plant growth. Thus, under such circumstances, soilless cultivation methods are proper

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alternatives (Sardare and Shraddha, 2013). Hydroponics and aeroponics are the main two soilless crop cultivations methods. In hydroponic method, water-soluble nutrients are delivered to the roots by the flow of water, and in the aeroponics method, soluble nutrients are provided to the plant roots through a spraying system.

Hydroponics and aeroponics cultivation systems both provide a precise flow of water and nutrition to the cultivated plants since the necessary nutrient reach directly the root network. Thus, yield per plant and per unit area are usually increased (Singh et al., 2019). Hydroponic and aeroponic systems have been successfully applied for commercial production of various vegetables such as lettuce, tomato, green peppers, maize and cucumber (Espinosa-Robles, 2009; Jamshidi et al., 2019). Some researchers have reported saving in water uptake to 99% and up to 50% savings in nutrients intake (Lakhiar et al., 2018). In particular, increase in yield of leafy vegetables/herbs (basil, chard, parsley, and red kale) and fruit crops (bell pepper, cherry tomatoes, cucumber, and squash) grown in aeroponic growing systems has been reported (Chandra et al., 2014).

The size of the water droplets that are sprayed over the root system is one of the main factors affecting the productivity efficiency of a cultivation in the aeroponics planting method (Lakhiar et al., 2018; Gao et al., 2016). Very coarse and very small droplets can cause less oxygen availability to the roots and thus resulting in yield decrease. Atomizer nozzles are designed from 10 to 100 microns for proper spraying of nutrient solutions in aeroponics systems (Lakhiar et al., 2018).

Duration of spraying and spraying intervals are also the factors that affect the growth and yield of the plant in the aeroponics system (Hayden et al., 2002). A research on aeroponic cultivation of cucumber concluded that the plant height and cucumber growth rate are significantly affected by both the duration and the amount of nutrient spraying (Zhang et al., 2011). In a study on the rate of nutrient solution uptake in cranberry aeropnic cultivation showed that spraying of a nutrient solution at the rate of 0.029 L/cm^2 from the root environment increases the availability of nutrients to the plants. On the other hand, continuous and intense spraying of nutrients causes plant root and foliage burnings (Barak et al., 2006).

Cucumber (*Cucumis sativa* L.) is one of the most important greenhouse crops and its soilless cultivation and yield have been studied by many previous reports (Singh et al., 2019, Zhang et al., 2011). In many countries, growing cucumber in greenhouses is an important agricultural business both for domestic usage and exports. Due to the advantages of soilless cultivation, many farmers are considering cultivation of cucumbers using hydroponic/aeroponic methods. There are many factors that affect the yield of cucumber under soilless growing environment (Singh et al., 2017). However, water availability is the most important factor limiting the cultivation of cucumbers in the regions with deficient water resources. Some researchers have considered water usage efficiency as a factor to for investigating water consumption by cucumber (Singh et al., 2019; Cakir et al., 2017). Due to increased drought periods, optimizing water usage for cucumber production is becoming increasingly important in the arid regions.

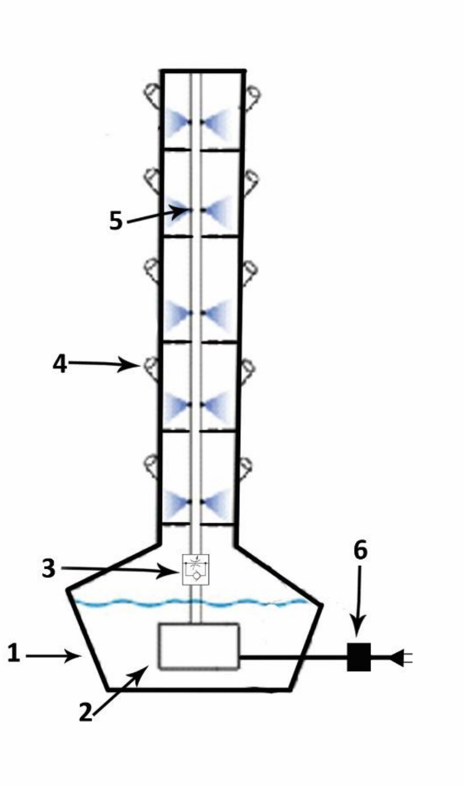
There are many approaches for optimizing a systems performance, among which the response surface methodology has been widely used in applied sciences. The response surface method is a set of mathematical and statistical techniques that initially helps in selecting the best combination of factors (independent variables) affecting one or more responses (dependent variables). Therefore, the method is applied for designing experiments, developing appropriate mathematical relationship between factors and responses and optimizing the considered factors to maximize or minimize the responses.

As mentioned earlier, spraying rates and the spraying duration are among the main factors that affect the yield of plants when cultivated in aeroponic system and effect of these two factors need to be investigated and optimized to maximize yield as well as minimize water consumption. Thus, the purpose of the present study was to apply the response surface methodology for investigating the effect of spraying rate and spraying duration for production of cucumber grown in a columnar aeroponic planting system as well as simultaneously optimizing these two factors in order to maximize the yield and water usage efficiency in cucumber.

Materials and Methods

Culturing system

The experiments were carried out at the Research Greenhouse of the College of Agriculture, Shahid Bahonar University of Kerman during the Fall of 2018. For this purpose, nine identical columnar aeroponics systems were built. Each of the column was a 20 cm diameter polyethylene tube with a height of 120 cm. On each column, there were five planting rows having four cavities for holding cucumber transplants. At the bottom of each column, an 80-L reservoir was mounted for holding nutrient solution. Inside the tank, a 350 W submerge pump was placed for pumping the nutrient solution through the sparing nozzles. Each pump was equipped with timer that was used to set the spraying time and spraying lag time. The amount of discharge through the nozzles was adjusted via a by-pass valve that was embedded after the pump. A photo of a typical used system along with its schematics diagram are shown in Figure 1.



A B

Fig. 1. Picture of a typical aeroponic system (A), Schematic diagram of the system (B)
1. Reservoir; 2. Pump 3. By-pass valve 4.Plant pots 5. Nozzle; 6. Timer

Yield and water usage

Response surface methodology was used in order to investigate the effects of the rate and the duration of spraying on the yield and water usage by the grown cucumber. Response surface methodology is a series of mathematical-statistical operations that examine the effects of independent variables (factors) on dependent variables (response/responses), usually followed by mathematical modeling an optimization of the independent variables. In this method, the required experiments were performed according to an experimental design to measure the effect of factors levels on the response. The experimental designs used in were: 1) factorial experiments, 2) the central composite design, or 3) Box-Behnken design, (4) Taguchi method, and (5) the Doehlert design (Bezerra et al., 2008). Each of these designs specifies a combination of experiments that should be performed for proper statistical analysis and modeling. In factorial designs, the experiments were a complete combination of factors. In this approach, if the number of factors was more than 3, the number of experiments strongly increased, and therefore in these cases other designs were recommended.

In the present study, the required experiments were performed using factorial experiments based on a completely randomized design. In these experiments, for each treatment, the independent variables were: 1) the rate of spraying (Q) at three levels of 125, 250, and 375 mL/min; and 2) spraying duration (T) at three levels of 10, 15, and 20 min. The dependent variables were: yield of each plant (YP) and water usage efficiency (WE). Thus, this investigation consisted of nine treatments and each treatment was performed using a columnar aeroponic system. We considered each horizontal row of the plant on an individual column as a replicates (a total of 5 replications for each treatment).

In order to carry out the experiments, initially the reservoirs were filled with Hoagland nutrient solution (Hoagland and Arnon, 1950). The cucumber seeds which were grown in polyethylene pots with rockwool media, after germination, the seedlings with their media were transferred to the column cavities and were immediately sprayed at specified spraying rates and durations. During the experiments the spraying pumps were turned off for 15 min between each spraying time. At the end of each week, after measuring the decrease in the volume of the reservoirs solutions, they were replaced with the original volumes of the solution.

At harvest time, nine weeks after transplanting, the average yield for plant in each treatment (YP, kg) was determined. To calculate the water usage efficiency (WE, kg/m^3), at the end of each week the volume of the consumed water (WU, m^3) in each reservoir was measured. Water usage efficiency was calculated using the following equation:

$$WE = \frac{YS}{\sum_{i=1}^{9} \mathrm{WU}_i} \tag{1}$$

where YS (kg) is the total yield of each treatment and i is the number of week after transplanting. All stages of the experimental design, estimation of model parameters and analysis of variances were performed using Minitab 2016 software.

Model development and evaluation

In the factorial experiments, it is assumed that the relationship between a response (y) and independent factors (X) is linear and it is expressed in by the general following model:

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k}\sum_{j=1}^{k} \beta_{ij} x_i x_j \tag{2}$$

where, x_i and x_j are independent variables, β_0 constant coefficient, β_i are linear coefficients, β_{ij} are the coefficients of interactions and k is the number of considered factors. However, in most cases linear models do not present a good relationship between factors and the response; in this cases, a second-order model with the following form is used (Bezerra et al., 2008):

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k}\sum_{j=1}^{k} \beta_{ij} x_i x_j + \sum_{i=1}^{k} \beta_{ii} x_i^2 \quad (3)$$

In this case, β_{ii} are coefficients of the degree effects on independent variables. After performing the experiments, the coefficients of equations (2) or (3) are estimated using least squares method and the power of the model is evaluated, i.e. determining the coefficient of determination (R^2) and performing the lack of fit test. The significances of coefficients are also evaluated through analysis of variances.

Model optimization

In this research, since the purpose of optimization was to find the values of Q and T for which YP and WE to be maximized, optimization process was performed using desirability function method (Bezerra et al., 2008). In this method, initially, a desirability function d_m was constructed for the response m. The scale of the individual desirability function ranges from 0, for a completely undesirable response, to 1, for a fully desired response. If the response m should be maximized, then an individual desirability functions is described by the following equation (Ramezanzade and Ghazanfari-Moghaddam, 2018):

$$d_m(Y_m(X)) = \begin{cases} 0 & Y_m(X) < L_m \\ \left(\dfrac{Y_m - L_m}{T_m - L_m}\right)^{S_m} & L_m \le Y_m(X) \le T_m \\ 1 & Y_m(X) > T_m \end{cases} \quad (4)$$

where, L_m, U_m and T_m are the lower boundary, the upper bound, the target value for the response m, and the value of each dependent variable, respectively. The parameter S_m has a value between 0 and 1, which specifies the curvature degree of the second-order function (Derringer and Suich, 1980). Using the individual desirability functions and assuming equal weight for responses, an overall desirability function D(Y) was developed by:

$$D(Y) = (d_1 \times d_2 \times \ldots \times d_n)^{\frac{1}{n}} \quad (5)$$

where *n* is the total number of responses. Thus, the simultaneous optimization process was reduced to find the values of independent variables that generate a maximum for overall desirability. In this investigation, the process of model optimization was performed using Design Expert software.

Results

Yield and water usage

The experimental design matrix, which was developed based on the complete factorial design, is presented in Table 1. The average values obtained for average plant yield (PA) and water usage efficiency (WE) for each system are presented in columns 4 and 6, and the numbers after the ± are the value of the calculated standard deviation, based on five replications.

Table 1. Mean values at different levels along with predicted values in the second-order model for aeroponic culture of cucumber

Experimental Number	Q (L/h)	T (s)	YP (Act.) (kg)	YP(Pred.) (kg)	WE (Act.) (kg/m^3)	WE (Pred.) (kg/m^3)
1	125	10	2.26±0.103	2.21047	94.4±4.0987	94.947
2	125	15	2.41±0.108	2.47122	98.8±3.0332	98.456
3	125	20	2.54±0.269	2.52231	98.2±4.494	97.997
4	250	10	2.66±0.139	2.74889	109.2±1.789	109.222
5	250	15	3.04±0.145	2.93789	111.8±2.168	110.256
6	250	20	2.90±0.250	2.91722	105.8±4.266	107.322
7	375	10	2.14±0.0783	2.09564	91.1±2.837	90.531
8	375	15	2.17±0.0758	2.21289	87.2±2.197	89.089
9	375	20	2.12±0.0594	2.12047	85.0±2.31840	83.681

Q: spraying rate; T: spraying time; YP: yield per plant; WE: water usage efficiency

Table 2 summarizes the results of analysis of variance performed on the data obtained using the factorial test. This Table shows that spraying rate (Q) and spraying duration (T) and the effect of these two factors on PA and WE are significant ($\alpha=0.05$). The comparison of the p-values shown in this Table shows that the effect of the spraying rate is greater than the effect of spraying time on both responses.

Table 2. Summary of the results of analysis of variance performed for yield per plant (PA) and water use efficiency (WE) for aeroponic culture of cucumber

Source of variation	df	YP		WE	
		MS	p value	MS	p value
Q	2	2.025	0.000^{**}	1687.51	0.000^{**}
T	2	0.161	0.003^{**}	33.21	0.048^{*}
$Q \times T$	4	0.063	0.049^{*}	44.12	0.005^{**}
Error	36	0.024	-	10.06	-

** Significant at 1% ; * Significant at 5% ; ns: not significant; YP: tield per plant, WE: water usage efficiency

Since the standard model for a randomized complete design is a first-order polynomial type, the equation (2) was fitted in the data obtained from the experiments and the following two models were obtained:

$$YA = 2.064 + 0.00069\,Q + 0.0455\,T - 0.0000115\,Q \times T \qquad R^2 = 14.91\% \tag{6}$$

$$WE = 95.3 + 0.0219\,Q + 0.800\,T - 0.00396\,Q \times T \qquad R^2 = 20.29\% \tag{7}$$

Figure 2 shows the interaction effect of spraying rate and spraying duration on the average PA for each of treatments. This graph shows that, for all three spraying durations at a spraying rate of 125 mL/min, the yield was low, but with increasing spraying rates to 250 mL/min, PA increased and the maximum yield was obtained when T was equal to 15 min. This figure also shows that the treatments with a spraying duration of 10 min had lower yields than other treatments. The yield, for all treatments, increased from the 125 mL/min spraying rate up to 250 mL/min and then it was decreased.

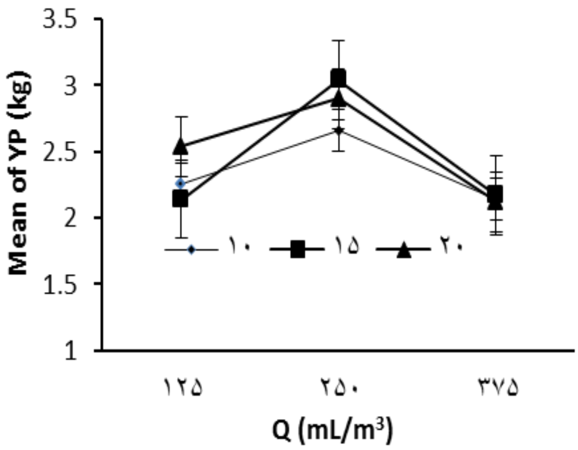


Fig. 2. Interaction of spraying rate (Q) and spraying duration (T) on average yield for different treatments including Q at three levels of 125, 250, and 375 mL/min; and T at three levels of 10, 15, and 20 min for aeroponic culture of cucumber

Equation (5) and analysis of Figure 2 show that a first-order model is not suitable for representing the average plant yield (YP), thus a second-order model, Equation 3, was fitted to the experimental data by least square method. The significance of the coefficients of the resulting model was verified by analysis of variance. A summary of the ANOVA test are presented in Table 4. Table 4 shows that for the mean yield, first-order coefficients and second-order coefficients were significant, but their second order interaction was not significant (α=0.05), and the following equation was presented to express the mean yield as the function of spraying time and spraying:

$$YA = -0.814 + 0.01976\,Q + 0.1713\,T - 0.000038\,Q^2 - 0.00419\,T^2 \quad R^2 = 81.78\% \tag{8}$$

The predicted values of the second-order model for YP are presented in Table 1. For further evaluation of this model, the predicted values of YP versus experimental data are plotted in Figure 3. The graph shows a uniform scatter of data around the diagonal line that indicates the model predictions can provide acceptable practical results. The scattering of the points around the diagonal line is also an indication that show a considerable variation among experimental data.

Table 3. Analysis of variance for the second-order models for evaluating the significant of calculated coefficients

		YP		WE	
	df	MS	p	MS	p
Model	5	0.89522	0.000^{**}	712.79	0.000^{**}
Q	1	2.92705	0.000^{**}	2263.80	0.000^{**}
T	1	0.19145	0.009^{**}	65.95	0.017^{*}
$Q\times T$	1	0.10296	0.052^{ns}	122.51	0.002^{**}
Q^2	1	3.55017	0.000^{**}	2717.00	0.000^{**}
T^2	1	0.10990	0.045^{**}	39.34	0.062^{ns}
Lack of Fit	3	0.04916	0.120^{ns}	17.99	0.167^{ns}
Pure Error	36	0.02360	-	10.06	-

** Significant at 1% ; * Significant at 5% ; ns: not significant; *YP*: tield per plant, *WE*: water usage efficiency

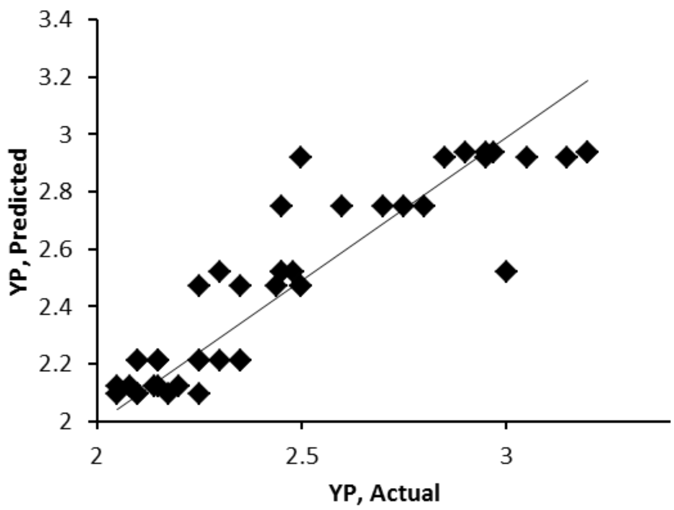


Fig. 3. Difference between the actual and expected values for yield per plant (YP) for aeroponic culture of cucumber

Figure 4 shows the interaction effect of spraying rate and spraying duration on WE for the nine studied treatments. This Figure shows that WE is low in all spraying durations and the spraying rate of 125 mL/min, but with increasing spraying rates to 250 mL/min, WE increased and the maximum WE was obtained for 15 min spraying duration. Treatments with spraying time of 20 min had lower WE than the other treatments.

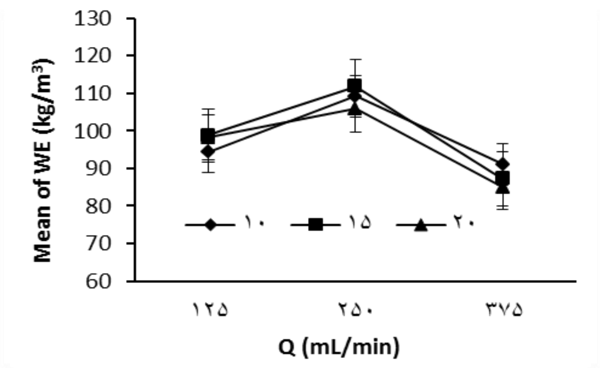


Fig. 4. Interaction effect of spraying rate (Q) and spraying duration (T) on water use efficiency (WE) for aeroponic culture of cucumber. Q at three levels of 125, 250, and 375 mL/min; and T at three levels of 10, 15, and 20 min for aeroponic culture of cucumber

A second order polynomial, Equation 3, was fitted to the experimental data by least square method and significance of the coefficients of the model was verified by analysis of variance. A summary of the ANOVA tests are presented in Table 3. This table shows that for the WE, all of the calculated coefficient, except for the second order spraying time (T^2), were significant (α=0.05), and the following equation was presented to express the WE as the function of spraying time and spraying:

$$WE = 23.8 + 0.5494\,Q + 3.18\,T - 0.001055\,Q^2 - 0.00396\,Q \times T \quad R^2 = 89.54\% \tag{9}$$

The high value of R^2 and the lack of fit test (Table 3) indicate that this model is adequate for predicting WE. The predicted values for WE using this equation are given in Table 1. Figure 5 shows the graph of the predicted WE data against the experimental data. The scatter of the data around the diagonal line have close similarity to Figure 3.

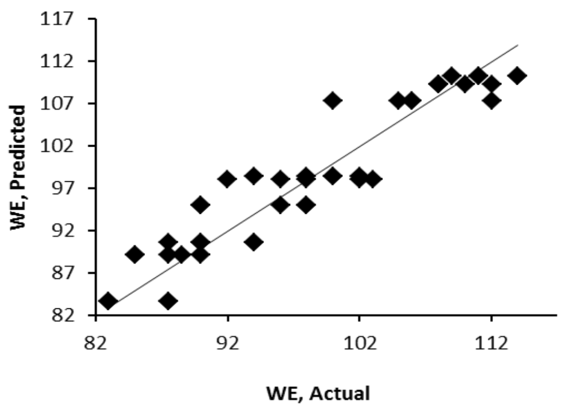


Fig. 5. Difference between the actual and expected values for water use efficiency (WE) for aeroponic culture of cucumber

Table 4. Summary of optimization results for spraying rate (*Q*) and spraying duration (*T*) for aeroponic culture of cucumber

Response	Optimized factors		YP	WE
Factors	Q (mL/min)	T (min)	(kg)	(kg/m^3)
Optimum	233.59	16.06	2.96	110.37
di			0.88	0.79

YP: yield per plant; WE: water usage efficiency

Optimization

The results of the optimization of spraying duration (T) and spraying rate (Q) for simultaneous maximizing YP and WE, which were performed using the desirability function method, are presented in Table 4. As shown, the optimized spraying rate was equal to 233.59 mL/min and the optimized spraying duration of 16.06 min.

Discussion

The minimum YP belonged to the treatment having a spraying rate of 375 mL/min and a spraying duration of 20 min (Table 1), indicating that, by these treatments the plant was exposed for longer time to the nutrient solution. In general, plants that were exposed to the spraying rate of 375 mL/min had a lower YP and the best PA were related to treatments with a spraying rate of 250 mL/min.

The experimental values for WE as was shown in Table 2 indicated the best WE was for the treatment with a spraying rate of 250 mL/min and a spraying duration of 15 min. The experiments performed at a spraying rate of 125 and 375 mL/min had a low WE, which indicates that 375 spraying rate is high and 125 mL/min was not enough, and therefore the optimum spraying rate (Q) for this system should be somewhere between 125 and less than 375 mL/min.

The fitted first order equation for predicting YP and WE had low coefficient of determinations, indicating that first-order models are not suitable for mathematically expressing the relationship between YP and WE as functions of the Q and T. This was also confirmed by results presented in Figure 2, which showed that the variation of the yield does not linearly follow the spraying rate and duration. The variation trend in all treatments was incremental from the spraying rate of 125 mL/min to 250 mL/min, and then it decreased, which is very similar to the variation trend observed for YP (Fig. 2). This suggests that variations in WE are not linear in terms of spraying time and rates, and a second-order model is more justified for developing a model. The determination coefficient for a second order model for predicting YP (Equation 4) was equal to 81.78%, which shows a better fit over the first-order model (Equation 5). Since for this equation lack of fit test was not significant (Table 3), therefore the model was adequate. The same discussion applies to the second order model for predicting WE. For this model since the coefficient of determination was 89.54%, this model also resulted in a better fit. Generally, both second order proposed models could depict the experimental results with acceptable accuracy.

The optimum values for spraying rate and duration were 233.59 mL/min and 16.06 minutes, respectively. The optimum spraying rate was close to 250 mL/min, which was the proper spraying rate and distanced away from 375 mL/min, which based on the experimental results, was too high. The optimum spraying duration, 16.06 min, is very close to the most suitable experimental spraying time (15 min). The desirability value, for yield and water usage efficiency were equal to 0.88 and 0.79, respectively and the overall desirability value (D) was 0.84, which indicates the obtained optimized value were desirable. Using the developed models (Equations 8 and 9) and optimal values for Q and T, the average yield was 2.96 kg and water usage efficiency was 110.30 kg/m^3, both are higher than the values listed in Table 1.

Conclusion

In the present study, cucumbers were cultivated in columnar aeroponic systems and the effect of the sparing duration (T) and sparing rate (Q) on average yield of plants (YP) and water usage efficiency (WE) were investigated using response surface methodology. It was concluded that both considered independent variables significantly affected the two considered responses, however, the effect of Q was greater than the effect of T on both responses. Second order polynomial models were suitable for describing PA and WE as functions of the T and Q. The optimum values for the spraying rate and spraying time were 233.59 mL/min and 16.06 min, respectively.

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Conflict of interest

There is no conflict of interest for this research.

References

1. Barak P, Smith J.D, Krueger A.R, Peterson L.A. 2006. Measurement of short-term nutrient uptake rates in cranberry by aeroponics. Plant Cell Environment 19(2), 237–242.

2. Bezerra M.A, Santelli R.E, Oliveira E.P, Villar L.S, Escaleira L.A. 2008. Response surface methodology (RSM) as a tool for optimization in analytical chemistry. Talanta 76(5), 965-977.

3. Cakir R, Kanburoglu U¸ Altintas S, Ozdemir A. 2017. Irrigation scheduling and water use efficiency of cucumber grown as a spring-summer cycle crop in solar greenhouse. Agricultural Water Management 180, 78-87.

4. Chandra S, Khan S, Avula B, Lata H, YP M.H, Elsohly M.A,and Khan I.A. 2014. Assessment of total phenolic and flavonoid content, antioxidant properties, and yield of aeroponically and conventionally grown leafy vegetables and fruit crops: A comparative study. Evidence-Based Complementary and Alternative Medicine 2014(4), 1-9.

5. Derringer G, Suich R. 1980. Simultaneous optimization of several response variables. Journal of Quality Technology 12(4), 214-219.

6. Espinosa-Robles P, Espinosa-Mendoza L, Perez-Mercado C, Agustin-Martinez J. 2009. Hydroponics maize forage production. Acta Horticulturae 843(37), 283-286

7. Gao J, Zhang J, Lu D. 2016. Design and atomization experiments of an ultrasonic atomizer with a levitation mechanism. Applied Engineering in Agriculture 32(4), 353-360.

8. Hayden, A. L., T. N. Yokelsen, G. A. Giacomelli, and J. J. Hoffmann. "Aeroponics: An alternative production system for high-value root crops." In XXVI International Horticultural Congress: The Future for Medicinal and Aromatic Plants 629, 207-213. 2002.

9. Hoagland D.R, and Arnon D.I. 1950. The water-culture method for growing plants without soil. Circular 347. Agricultural Experiment Station, University of California, Berkeley.

10. Jamshidi A.R, Ghazanfari Moghaddam A, Ommani A.R. 2019. Effect of ultrasonic atomizer on the yield and yield components of tomato grown in a vertical aeroponic planting system. International Journal of Horticultural Science and Technology 6(2), 237-246. doi: 10.22059/ijhst.2019.278366.284

11. Lakhiar I.A, Gao J, Syed T.N, Chandio F.A, Buttar N.A. 2018. Modern plant cultivation technologies in agriculture under controlled environment: A review on aeroponics. Journal of Plant Interactions 13(1), 338–352.

12. Ramezanzadeh M, Ghazanfari-Moghaddam A. 2018. Optimizing the production parameters for pellets made from pistachio tree pruning using multi-response optimization. Waste and biomass valorization 9(7), 1213-1221.

13. Sardare M., Shraddha V.A. 2013. A review on plant without soil – hydroponics. International Journal of Research in Engineering and Technology 2(3), 299-304.

14. Savvas D, Gruda N. 2018. Application of soilless culture technologies in the modern

greenhouse industry – A review. European Journal of Horticultural Science 83(5), 280-293

15. Singh M.C, Singh K.G, Singh J.P. 2019. Nutrient and water use efficiency of cucumbers grown in soilless media under a naturally ventilated greenhouse. Journal of Agricultural Science and Technology 21(2), 193-207

16. Singh M.C, Singh J.P, Pandey S.K, Mahay D, Shrivastva V. 2017. Factors affecting the performance of greenhouse cucumber cultivation-A review. International Journal of Current Microbiology and Applied Sciences 6(10), 2304-2323.

17. Zhang H, Chi D, Wang Q, Fang J, Fang X. 2011. Yield and quality response of cucumber to irrigation and nitrogen fertilization under subsurface drip irrigation in solar greenhouse. Journal of Integrative Agriculture 10(6), 921–930.