Modelling the Richards function using Evolutionary Algorithms on the effect of electrical conductivity of nutrient solution on zucchini growth in hydroponic culture

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Abstract

The effect of two levels of electrical conductivity (EC) in two nutrient solutions was studied in a hydroponic cultivation of zucchini, during the growing period using the Richards function. The equations for each individual organ were fitted using Evolutionary Algorithms (EAs) and the improvement of parameters was defined through an innovative EA. So, by estimating the (near) optimal model of the growth of each individual organ, the proposed method manages to simulate the plant growth and how the two levels of EC in two different nutrient solutions affects it, as demonstrated by experimental results.

The leaves were longer in the lower electrical conductivity. The length of the leaves and the growth rate of the older leaf were higher than those of the newer leaf in both nutrient solutions. The total soluble solids of fruits were more at the higher EC level.

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1. Introduction

The cultivation method of the plants without soil or soil mix is called hydroponics [18]. The soil is replaced by a sub-layer, which can be any solid inert material or water. The principle of the method is the solution of all necessary nutrients in water for the growth of the plant and their administration through an irrigating system, without using soil. The better control of the environmental factors (e.g. fertilization, irrigation, and root temperature), the higher automation rate and higher yield render hydroponics economically attractive for producers around the world. Hydroponics consists of the production and feeding tank for the nutrient solution, where it is necessary to control the functional parameters of the nutrient solution, the pH, the dissolved oxygen, the temperature, the osmotic pressure and the electrical conductivity as well as the installation and growing area of the plants. The measurement of the electrical conductivity aims to control the concentration of nutrients. By regulating the electrical conductivity of the nutrient solution, producers can change the water availability and improve the quality of their production, and also alleviate the risk of possible reduction to the marketable yield that increases in salinity could cause. Under high ECs, the size of the fruits is negatively correlated to the EC. The reduction rate of the production varies and depends on the species, the environmental factors, the composition of the nutrient solution and the management of each production [8]. Hydroponics is a method that allows good control of the elongation and growth of plants and is currently at an experimental stage around the world [21,6]. The cultivation method without soil allows the achievement of high production without risking the quality of the product [5].
Zucchinis (*Cucurbita pepo* L.) are commercially cultivated using conventional methods in fields and greenhouses in the Mediterranean countries [9] in order to meet the high demand for fresh products in the national and international markets. During the past 20 years, the hydroponic zucchini has become popular among the commercial producers [16]. Shaw and Cantliffe [20], and Cantliffe et al. [17] mention zucchini species that could be cultivated using hydroponic methods and supply the market.

The increased use of computers in managing the plant growth has led producers to request software that will be based on mathematical models, in order to foresee or simulate the performance of their production. The models, apart from the description of the final performance, provide information so that the course of the production can be dynamically depicted and controlled. The models are simplification of reality that can be used for quantitative description of the plants’ elongation [12–14]. The Richards function is a sigmoid mathematical function that has been widely used in model applications.

Evolutionary Algorithms (EAs) are search and optimization algorithms developed by imitation of the mechanisms of natural selection and evolution. For quite some time, over the past few years, they have become quite popular, mainly due to the evolution of the hardware and software that has rendered their implementation very easy and efficient [1–4]. EAs do not solve the problem in an analytical/mathematical way but in a biological way, and are considered to be the most appropriate tool for the optimization of functions with discrete variables or variables that cannot be numerically described, such as rational expressions.

The purpose of this paper was to use the Richards function as a model in order to study the elongation of the leaves and fruits of zucchini (*C. pepo* L. cv. Abodanza) under the influence of two ECs of 2.2 dS/m and 4.4 dS/m in two nutrient solutions of hydroponic cultivation. The Richards function was adapted with innovative EAs in experimental data of the individual values being measured for each part of the plant. EAs were used, instead of using an analytical/mathematical method, because it is widely known that EAs perform better when the space, which will be searched, has a large number of elements [2,3], as it is in our case for all four unknown parameters of the Richards function. So, when the unknown parameters of a problem belong to a space with large cardinality or belong to an infinite space or follow a probability distribution it is better to use EAs instead of using an analytical/mathematical method [2,3]. Except for that, using EAs enables the proposed method to easily follow and describe any unexpected or sudden changes that may occur in the plants’ elongation. Therefore, by estimating the (near) optimal model of the plant’s elongation, the proposed method manages to simulate the plant growth and the effects of the two levels of EC in two different nutrient solutions.

2. Methods and materials

2.1. Hydroponic cultivation of zucchini

At the heated glasshouse located at the Institute of Plant Protection in Patras a hydroponic cultivation experiment for zucchini of the species (*C. pepo* L. cv. Abodanza) was carried out under the influence of two electrical conductivity levels (EC).

The seeds of the zucchini were first sowed on turf in special trays sized 32.5 × 43.5 cm at an air-conditioned chamber for growing plants (temperature 23 ± 1°C, relative humidity: 70 ± 5%, light: 12 Klx and duration of day/night: 12 h respectively). The seedlings remained for 10 days in the chamber for plant growing and then were transferred to the heated glasshouse and were transplanted in plates (100 × 12 × 7 cm) (Grodan, Grodania SA) of the hydroponic system. The experimental premises consisted of 8 double sloping benches (10 × 0.4 × 0.6 m), which were by two equipped for the collection of the runoff with a calibrated 100 L tank. The system of the water fertilization (AMI 5000, DGT Volmatic Denmark) was fully automated and the hydroponic system was renewed every 1 hour daily.

In order to study the impact of the EC over the hydroponic cultivation of zucchini, two interventions were conducted with a fully randomized design of 14 replicates. The two levels of EC during the experiment varied in the witness nutrient solution 2.2 dS/m and the nutrient solution of increased salinity 4.4 dS/m. The environmental parameters controlled with sensors during the hydroponic cultivation had the following values: Temperature: (08:00) 19.6 °C, (14:00 h) 27 °C.

The assessment of the impact of the EC in the growth of zucchini in hydroponic cultivation was conducted every second day from the 15th day after the zucchinis were transplanted into the hydroponic system and until week 14. Every time the leaf blade and petiole of leaves No. 9 and No. 29 were measured, as well as the dimensions and weights of the plant’s fruits. Moreover, the number of male and female flowers, the lengths and widths of the fruit stalks, the dry and fresh weight of the fruits and the total soluble solids of the fruits were measured every time.

2.2. Assessment of biological parameters and data analysis

In order to biologically interpret the elongation of leaves and internodes regarding the observation time of each experiment, the well known Richards function was used [15].

The Richards function is defined by the following differential equation:

$$\frac{dl}{dt} = \frac{k L}{n A} (A^n - L^n),$$

where, \( L \) is the value of a growth attribute at time \( t \) and describes the length of the regarded individual organ and \( t \) is the number of days after transplant until the abscission of each individual organ. \( A \) and \( k \) are positive constants while constant \( n \) can lie in the range of \(-1 \leq n < \infty, n \neq 0\).
In order to better fit the experimental data, the following logarithmic form of Eq. (1) has been used:

\[ \ln L = \ln A - \frac{1}{n} \ln (1 + e^{b \cdot t_k}) , \]

where, \( A \) is the asymptote (maximum size of the individual leaf) and \( n \) describes the shape of the curve. The constant \( b \) has no biological significance. It is purely correlated with the positioning of the curve in relation to the \( t \)-axis. Finally, \( k \) is a rate constant that depends upon the value of \( n \) and has also significant biological importance. Richards [15] proposed three different combinations of parameters all of which have great biological significance:

- The first parameter \( K = \frac{k}{e^{b \cdot t_k}} \) is the weighted mean relative growth rate over the whole period.
- The second parameter \( G = \frac{D}{e^{b \cdot t_k}} \) is the corresponding weighted mean relative growth rate.
- The third parameter \( D = \frac{2 \cdot A}{\ln 1 + C0/C1} \) represents the time required for the major portion of the growth to occur and is usually described as the duration of elongation. However, this can only be approximated from an asymptotic function.

The determination of the primary parameter \( A \) and the three second parameters are of great importance because this information can be very helpful to researchers in order to better study and understand the growth of the plants.

The Richards function which has been constructed for each individual plant organ was fitted to the successive growth values of the organs of each plant and their respective experiments observation time by using the method of EAs. The development of the program for the growth models and the evaluation of the experimental data with the help of this program was carried out in the Department of Business Administration of Food and Agricultural Enterprises, University of Western Greece, Agrinio, Greece and was implemented in Matlab 7.0.1. The maximum length \( A \) of each part of the plan was used as the initial value for the length of the plants' parts. The initial values of the rest of the parameters were estimated empirically. Based on the values of the parameters that have been calculated by the application of the EA method on Richards function, the values of the parameters which have great biological significance have been estimated; that is the maximum length \( A \), the weighted mean relative growth rate over the whole period \( K \), the corresponding weighted mean relative growth rate \( G \) and the duration of elongation \( D \). These estimations have been completed not only for the leaves but also for the internodes of all individual organs for all four out of the 14 plants used in each experiment.

2.3. Evolutionary Algorithms

Evolutionary Algorithms (EAs) are search and optimization algorithms that were developed while attempting to imitate the mechanisms of natural selection and natural genetics. They have been used for quite some time, but have recently gained popularity due to the advances in computing equipment, which make their implementation feasible and efficient. EAs operate on string structures, relative to biological significance, which are evolving in time according to the rule of survival of the fittest by using a randomized, yet structured information exchange scheme. Thus, in every generation, a new set of strings is created, using parts of the fittest members of the old set [1–4].

EAs process a coding of the parameter space and work on it. This coding (which is an essential part of the EA design procedure) results in formation of strings composed of characters belonging to a finite alphabet. Having decided on the coding to be used, an initial set of strings (a population) is created at random. Next, a set of operators is applied to this initial population to generate successive generations that hopefully will improve over time. An objective function (usually referred to as fitness function in EA terminology) serves as a measure of goodness of a string, and is a functional of the function that we are trying to optimize. Several operators have been proposed at times; however, three simple operators perform well in a variety of problems. These are the Selection operator, the Crossover operator and the Mutation operator.

Selection is a process by virtue of which individual strings are tentatively selected as candidate parents for the next generation, according to their objective function values. The selection is performed by a randomized technique ensuring survival of the fittest; its details may vary according to the specific problem that the EA is designed for, but a biased roulette wheel selection scheme usually suffices. Once a string is selected, an exact replica of itself is made and entered into a mating pool to be tentatively used as a parent of the next generation.

Crossover is the process by virtue of which the actual mating is performed. Again, several methods of crossing over have been proposed at times, each one having its relative merits. The common feature of all crossover operators is that they select (randomly) pairs of mates out of the tentative population generated by the reproduction operator and they create new individuals (strings) with hopefully improved fitness. Combining elements of both randomly selected parents usually achieves improves fitness.

Mutation is the occasional (with small probability though) random alteration of the value of a string position. By itself, mutation is a random walk through the coded parameter space. It is usually used sparingly, together with the two previously mentioned operators, in order to ensure that important information contained within strings may not be lost prematurely.

It should be noted that several other (more advanced) operators, as well as different reproductive schemes have been proposed at times. However, the three operators examined previously have been proved [1–4] to be both computationally simple and effective in attacking a number of important optimization problems.

An important aspect of the design of an EA is the incorporation of constraints. Indeed, the above discussion pertains only to the unconstrained optimization problem. Constraints are usually classified as equality or inequality relations. Equality constraints can usually be incorporated within the function to be optimized. Inequality constraints may be handled in
two ways: a very simple way is to simply evaluate the objective function and then check if any constraints are violated. If not, the parameter set is assigned the fitness function value corresponding to the objective function evaluation. If some constraints are violated, the solution is deemed unacceptable and the corresponding string(s) is (are) assigned no fitness. The second way is to utilize a penalty method, decreasing the fitness value of strings that violate constraints by an amount proportional to the cost of violating the constraint. Thus, the constrained problem is actually transformed into an unconstrained one with a different (penalized) objective function.

The EA used in this contribution is the simple EA. The structure and operation of the simple EA is presented in Fig. 1. The genome used to represent each parameter of the algorithm consists of a binary string with length 31. The experimental results presented in Section 3 show that such a string length is not necessary for this specific application. However, we decided to use such a string length in order to demonstrate that the proposed method can also be applied in other or similar application cases where a bigger precision is needed. That is, the proposed method is robust enough in order to be applied to more complex problems where a bigger precision is necessary. So, the total length of the genome for all the unknown parameters is $4 \times 31 = 123$ (for four unknown parameters), as shown in Fig. 2.

The size of the population for all experiments is set to 100. The binary digits of each genome are set initially, randomly and independently with probability 1/2, to 1. The bounds of the unknown parameters to be optimized are the following:

- for the $A$ parameter: [7, 80].
- for the $b$ parameter: [0, 3].
- for the $k$ parameter: [0, 2].
- for the $n$ parameter: [0, 10].

The objective function used was Eq. (2) which comprises the function that the EA are trying to optimize by finding the best values for the four unknown parameters $A$, $n$, $b$ and $k$. The selection operator that was decided to use is the classic biased roulette wheel selection according to the fitness function value of each possible solution (binary string which represents the four unknown parameters to be optimized). As far as the crossover is concerned, the uniform crossover operator with crossover probability equal to 0.9 was used [2]. Regarding mutation, the flip mutation operator with mutation probability equal to 0.01 [2] was used. Every new generation of possible solutions (genomes) iterates the same process as the old ones and the whole process may be repeated for as many generations as is desired or until a termination criterion is satisfied. In this case

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![Fig. 1. The structure and operation of the EA used in the experiments.](image1.png)

![Fig. 2. The structure of a random genome of the EA's population.](image2.png)
the termination criterion used is the number of generations. The EA will end its execution when the number of generations equals 10.

3. Results

The maximum lengths of the leaf blades and of the petioles of the leaves No. 9 and No. 29 of the zucchini plants in the nutrient solution with the conductivity (EC) of 2.2 dS/m were statistically significantly larger than the corresponding ones in the nutrient solution with increased salinity and conductivity 4.4 dS/m. The longest lengths of the leaf blades and petioles of the leaf No. 9 in both conductivity levels were statistically significantly larger than the corresponding ones in leaf No. 29 of the zucchini (Figs. 3 and 4).

Fig. 3. Effect of EC of the nutrient solution (2.2 dS/m and 4.4 dS/m) in hydroponic culture on maximum leaf-blade length during the elongation period, of zucchini leaves (Cucurbita pepo var. Abbodanza) (No. 9 and 29). The parameter maximum leaf-blade length (A) was calculated on the Richards function, fitted to individual leaf blade of zucchini leaves (Cucurbita pepo var. Abbodanza) (No. 9 and 29) of the experimental data taken from a 11-week long observation. Estimated values of Richards function’s parameters and their standard errors. ■ EC 2.2 dS/m, □ EC 4.4 dS/m. Each column represents the mean of fourteen values.

Fig. 4. Effect of EC of the nutrient solution (2.2 dS/m and 4.4 dS/m) in hydroponic culture on maximum petiole length during the elongation period, of zucchini leaves (Cucurbita pepo var. Abbodanza) (No. 9 and 29). The parameter maximum petiole length (A) was calculated on the Richards function, fitted to individual petiole of zucchini leaves (Cucurbita pepo var. Abbodanza) (No. 9 and 29) of the experimental data taken from a 11-week long observation. Estimated values of Richards function’s parameters and their standard errors. ■ EC 2.2 dS/m, □ EC 4.4 dS/m. Each column represents the mean of fourteen values.
Table 1
Effect of EC of the nutrient solution (2.2 dS/m and 4.4 dS/m) in hydroponic culture on the secondary parameter mean relative growth rate (R), mean absolute growth rate (A), and duration of elongation period (D), during the elongation period, of zucchini leaves (Curcubita pepo var. Abbodanza) (No. 9 and 29). Estimated values of Richards function’s parameters and their standard errors. ■ EC 2.2 dS/m, □ EC 4.4 dS/m. Each column represents the mean of fourteen values.

<table>
<thead>
<tr>
<th>Leaf No.</th>
<th>EC (dS/m)</th>
<th>Leaf blade</th>
<th>Petiole</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R (d⁻¹)</td>
<td>A (mm⁻¹ d⁻¹)</td>
<td>D (d)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>2.2</td>
<td>0.303 ± 0.05</td>
<td>28.290 ± 6.40</td>
</tr>
<tr>
<td></td>
<td>4.4</td>
<td>0.301 ± 0.06</td>
<td>21.690 ± 6.40</td>
</tr>
<tr>
<td>29</td>
<td>2.2</td>
<td>0.275 ± 0.05</td>
<td>22.183 ± 6.40</td>
</tr>
<tr>
<td></td>
<td>4.4</td>
<td>0.188 ± 0.06</td>
<td>24.899 ± 6.40</td>
</tr>
</tbody>
</table>

The values that are followed by the same letter are not statistically different at a significance level of 5% (P < 0.05).

Table 2
Effect of EC of the nutrient solution (2.2 dS/m and 4.4 dS/m) in hydroponic culture on the parameter maximum fruit length (A), mean relative growth rate (R), mean absolute growth rate (A), and duration of elongation period (D), during the elongation period, of zucchini fruits (Curcubita pepo var. Abbodanza) (No. 9 and 29). Estimated values of Richards function’s parameters and their standard errors. ■ EC 2.2 dS/m, □ EC 4.4 dS/m. Each column represents the mean of fourteen values.

<table>
<thead>
<tr>
<th>Fruit</th>
<th>EC (dS/m)</th>
<th>A (mm)</th>
<th>R (d⁻¹)</th>
<th>A (mm⁻¹ d⁻¹)</th>
<th>D (d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>2.2</td>
<td>56.765 ± 2.30</td>
<td>0.441 ± 0.06</td>
<td>6.459 ± 0.91</td>
<td>13.757 ± 1.28</td>
</tr>
<tr>
<td></td>
<td>4.4</td>
<td>56.259 ± 1.70</td>
<td>0.440 ± 0.05</td>
<td>6.747 ± 0.67</td>
<td>12.944 ± 0.95</td>
</tr>
<tr>
<td>Width</td>
<td>2.2</td>
<td>14.549 ± 0.50</td>
<td>0.429 ± 0.05</td>
<td>1.632 ± 0.22</td>
<td>13.547 ± 0.98</td>
</tr>
<tr>
<td></td>
<td>4.4</td>
<td>14.265 ± 0.36</td>
<td>0.426 ± 0.04</td>
<td>1.653 ± 0.15</td>
<td>13.407 ± 0.70</td>
</tr>
<tr>
<td>Length/width ratio</td>
<td>2.2</td>
<td>3.90</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.4</td>
<td>3.94</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The mean relative growth rate (R) of the blades’ length of leaf No. 9 was statistically significantly higher and the elongation period (D) was statistically significantly smaller than the equivalent one of the younger leaf No. 29 in both nutrient solutions. The mean absolute growth rate (A) of the length of the leaves’ blades (No. 9 and 29) of the zucchini did not present statistic differences in any treatment (Table 1).

At conductivity (EC) 2.2 dS/m the mean relative growth rate (R) and the mean absolute growth rate (A) of the length of the leaf blades of leaf No. 9 was statistically significantly higher than the corresponding in leaf No. 29, while in the nutrient solution with EC 4.4 dS/m the mean relative growth rate (R) did not differ among them in the corresponding leaf blades. The elongation period (D) of the leaf blades’ length for all leaves did not differ statistically among them in all treatments (Table 2).

The measured parameters – maximum length (A), mean relative growth rate (R), mean absolute growth rate (A) and elongation period (D) – regarding the diameters of the zucchini fruits during the growing period in two conductivity levels, did not present significant statistical difference. The length/width ratio of the witness was 3.90, and in the increased salinity 3.94 (Table 2).

The male/ female flowers ratio of the zucchini in both conductivity levels showed no statistic difference between them and was 8.86 in 2.2 dS/m and 9.02 in 4.4 dS/m EC. The weight of the fresh and dry fruit of the fruit’s stalk as well as the diameters of the stalks did not statistically differ in the hydroponic sub-layer in all treatments.

The mean value of the total soluble solid components of the fruits is significantly different in the two conductivity levels, whereas in the conductivity of 2.2 dS/m it was 5.19 °Brix and in 4.4 dS/m it was 5.48 °Brix (Table 3).

Table 3
Effect of EC of the nutrient solution (2.2 dS/m and 4.4 dS/m) in hydroponic culture on fresh and dry fruit weight, total soluble solids, length and width of fruit stalk, number of female and male flowers during the elongation period, of zucchini fruits (Curcubita pepo var. Abbodanza).

<table>
<thead>
<tr>
<th></th>
<th>EC 2.2 (dS/m)</th>
<th>EC 4.4 (dS/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flower</td>
<td>Male flowers number</td>
<td>12 ± 1.80</td>
</tr>
<tr>
<td></td>
<td>Female flowers number</td>
<td>1.44 ± 0.80</td>
</tr>
<tr>
<td>Fruit</td>
<td>Dry weight (g)</td>
<td>3.47 ± 0.36</td>
</tr>
<tr>
<td></td>
<td>Fresh weight (g)</td>
<td>47.24 ± 2.67</td>
</tr>
<tr>
<td></td>
<td>Total soluble solids (°Brix)</td>
<td>5.19 ± 0.11</td>
</tr>
<tr>
<td></td>
<td>Stalk Weight (g)</td>
<td>60.33 ± 5.6</td>
</tr>
<tr>
<td></td>
<td>Stalk length (mm)</td>
<td>26.24 ± 0.73</td>
</tr>
<tr>
<td></td>
<td>Stalk width (mm)</td>
<td>17.74 ± 0.44</td>
</tr>
</tbody>
</table>

The values that are followed by the same letter are not statistically different at a significance level of 5% (P < 0.05).
4. Discussion and conclusions

The maximum length ($A$), the mean relative ($R$) and absolute ($\overline{A}$) growth rate, and the duration of elongation period ($D$) of leaf blade and petiole of the 9th and 29th leaf, and in the fruits, were calculated using the Richards function. The equations for each individual organ were fitted using innovative EAs. EAs were used, instead of using an analytical/mathematical method, because it is widely known that EAs perform better when the space, which will be searched, has a large number of elements. Except for that, using EAs enables the proposed method to easily follow and describe any unexpected or sudden changes that may occur in the plants' growth. Therefore by estimating the (near) optimal model of the plant's growth, the proposed method manages to simulate the growth of the plant and how the two levels of electrical conductivity in two different nutrient solutions affects it, as demonstrated by experimental results.

To our knowledge, the only conventional method that has been applied so far to this simulation/modelling problem is the application of the Richards function by trial-and-error. That is, researchers until now have selected arbitrarily the values of the unknown parameters of the model and tried in this way to simulate the plant elongation. It is obvious that the proposed method is superior to that conventional method since it does not select arbitrarily the values of the four unknown parameters, but instead it uses an EA in order to estimate their optimal values. Except for that, as stated before, using an EA enables the proposed method to easily follow and describe any unexpected or sudden changes that may occur in the plants' growth, which is almost impossible for any known simulation/modelling conventional method.

The concentration of the nutrient solution in the hydroponic sub-layer is the cultivating factor that can be controlled and which has impacts on the plant growth and fruit quality. In zucchini plants, the conductivity (EC) of 2.2 dS/m resulted in further elongation of the leaf blades and petiole lengths of both leaves than the corresponding ones in the nutrient solution with increased salinity, with a conductivity of 4.4 dS/m.

In our study, the lengths of the blades and the lengths of the petioles in both leaves were reduced in the high conductivity of 4.4 dS/m, suggesting that the high conductivity suppressed the elongation of the leaves. The suppression of the elongation in the high conductivity (EC) of 4.4 dS/m is linked to the water status of the leaves and has also been mentioned by other researchers [7,10].

The higher relative growth rate of the length of blades and petioles of the older leaf of the zucchini plants in both nutrient solutions compared to the corresponding ones in the younger No. 29 leaf of the zucchini is possibly caused by the increased cell turgor. In increased osmotic ability, the water absorption rate of the leaves is easily performed and subsequently the leaf elongation increases.

The conductivity (EC) of 4.4 dS/m caused an increase of the total soluble solid components of the fruits, a parameter that defines the preference of the zucchini. Similar results are also mentioned for tomatoes [11].

EAs were used since they perform better where there are a large number of elements in the space which will be searched. The use of EAs for the description of zucchini growth in hydroponic culture using the Richards function calculated the values of the four parameters having biological significance. The leaves were longer in the lower electrical conductivity. The length of the leaves and the growth rate of the older leaf were higher than those of the newer leaf in both nutrient solutions. The maximum length ($A$) and absolute ($\overline{A}$) growth rate, and the duration of elongation period ($D$) of leaf blade and petiole of the 9th and 29th leaf, and in the fruits, were calculated using the Richards function. The equations for each individual organ were fitted using innovative EAs. EAs were used, instead of using an analytical/mathematical method, because it is widely known that EAs perform better when the space, which will be searched, has a large number of elements. Except for that, using EAs enables the proposed method to easily follow and describe any unexpected or sudden changes that may occur in the plants' growth. Therefore by estimating the (near) optimal model of the plant's growth, the proposed method manages to simulate the growth of the plant and how the two levels of electrical conductivity in two different nutrient solutions affects it, as demonstrated by experimental results.

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In our study, the lengths of the blades and the lengths of the petioles in both leaves were reduced in the high conductivity of 4.4 dS/m, suggesting that the high conductivity suppressed the elongation of the leaves. The suppression of the elongation in the high conductivity (EC) of 4.4 dS/m is linked to the water status of the leaves and has also been mentioned by other researchers [7,10].

The higher relative growth rate of the length of blades and petioles of the older leaf of the zucchini plants in both nutrient solutions compared to the corresponding ones in the younger No. 29 leaf of the zucchini is possibly caused by the increased cell turgor. In increased osmotic ability, the water absorption rate of the leaves is easily performed and subsequently the leaf elongation increases.

The conductivity (EC) of 4.4 dS/m caused an increase of the total soluble solid components of the fruits, a parameter that defines the preference of the zucchini. Similar results are also mentioned for tomatoes [11].

The male/female flower ratio was around nine in zucchini plants in both nutrient solutions. The male and female flower ratio in zucchini is influenced by the environmental conditions [19].

EAs were used since they perform better where there are a large number of elements in the space which will be searched. The use of EAs for the description of zucchini growth in hydroponic culture using the Richards function calculated the values of the four parameters having biological significance. The leaves were longer in the lower electrical conductivity. The length of the leaves and the growth rate of the older leaf were higher than those of the newer leaf in both nutrient solutions. The total soluble solids of fruits were more at the higher EC level.

References


