Research article

Crop Growth Model for Hydroponic Cultivation of *Solanum lycopersicum* (Tomato) in a Semi-automated System

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Abstract Hydroponics can be integrated into Controlled Environment Agriculture (CEA), in combination with greenhouses. They can successfully optimize the use of fertilizers and water for arid zones. Elevated costs of this type of agriculture lead farmers to implement semiautomated systems and use recyclable materials to stabilize plant productivity. This paper discusses the different growth ratios of tomato plants estimated with logistic curves when tap water with fertilizer (T1), Oxidixed Water-OW [reclaimed water] (T2), and Disinfected Tertiary Recycled Water- DTRW [renewable water] (T3) are used; additionally, a new module is presented to avoid underestimation of plant height when fertilization is carried out at the flowering stage. This model was adapted only for treatment 1. Logistic curves were created with low RMSE values using the least-square method. Despite presenting better mass volume and fruit quantity in OW [reclaimed water] treatment at the final stage of the plant, a t-test revealed that there is not a significant difference among treatments of OW and DTRW [renewable and reclaimed water] for the height of plants. The adjustment of a logistic equation with the inclusion of a linear module allowed to decrease in the RMSE from 73 to 21 mm.

Keywords logistic models, tomato, hydroponics, wastewater, semi-automated systems

INTRODUCTION

Hydroponics and Wastewater

Controlled Environment Agriculture (CEA) is getting attention due to high productivity and adaptation to environmental changes. Saving resources is the main advantage of the direct application of nutrients to the plant's roots (Benke and Tomkins, 2018). To ensure this, automatic systems are installed to monitor water, air, CO_2, and other parameters; the higher the technology, elevation of the costs are inevitable. In automated systems, the balance of nutrients is usually pumped to the system considering optimum values of EC and pH values in the water; in others, the amount of nutrients is applied manually depending on the stage of the crop.

Most hydroponic nutrient solutions are based on non-renewable sources, which eventually will cause depletion and/or inaccessibility by some farmers (Mikkelsen, 2019). The inclusion of wastewater in hydroponic systems offers an alternative use for wastes and has been analyzed from different perspectives, such as nutrient absorption or as a purifying system (Carvalho, 2018; Ottoson, 2005). However, it has been found that the use of wastewater in hydroponics is not enough to complete a crop cycle but can be achieved with the addition of fertilizers (Magwaza et al., 2020; Cifuentes-Torres et al., 2021; Da silva et al., 2018).

Meselmani (2022) recognizes the importance of a balanced amount of nutrients, pH, and oxygen, and appoints that excessive use of fertilizer is not required to secure crop productivity. Solis et al., (2020) attempted to establish recommendations for nutrient amounts but failed due to the interaction of several parameters engaged in plant growth, nevertheless, they found that the solution replacement periodically provides better results than those systems with single applications.

Tomato plants are known for having an undetermined growth, the ripening of fruits is not uniform, and farmers tend to harvest up to 3 times per season, being able to extend the life cycle of these plants inside greenhouses. In semiautomated systems, the late application of fertilizers combined with a large difference in day and night temperatures may cause the elongation of stems of plants, consequently, it can interfere with harvesting works and spacing inside a greenhouse (Myster and Moe, 1995). Although many authors are investigating the role of wastewater in hydroponics, there has not been integration of logistic models on plant growth. Furthermore, since the difference between OW and DTRW [reclaimed and recycled water] relies on the number of microorganisms keeping it alive, therefore oxygenation and contents of N and P vary.

Crop Growth Models

Growth models also called mathematical models are useful equations to represent physical phenomena of real life. Simulations and predictions can successfully be modeled with the right parameters. Since the growth ratio of the crops is directly related to the nutrient content in the water, sigmoid models have a high accuracy in estimating the growth of crops due to their similar tendency to plant phenology (Di Crescenzo et al., 2021). Within these models, a logistic curve is characterized by a “s” shape; crop growth can be well represented with this type of graph due to slow growth in the early stage, fast vegetative development, and cessation of activities for the end-of-life cycle.

OBJECTIVE

Using a hydroponic system, the purpose of this study is 1) to compare the growth of tomato plants using logistic curves when OW and DTRW [reclaimed and renewable water] is applied and 2) to adjust a logistic equation when additional fertilizer is introduced.

Table 1 Chemical properties of water in every treatment (ppm)

	T-N	T-P	Cations				Anions				
			Na^+	K^+	Mg^+	Ca^+	Cl^-	NO_2^-	NO_3^-	PO_4^-	SO_4^-
T1	1.71	0.47	8.11	2.02	4.81	19.30	6.74	0.19	2.72	0.01	18.80
T2	8.75	1.83	126.50	18.10	10.40	31.40	173.00	0.00	31.10	0.07	92.50
T3	7.46	1.86	115.00	17.10	10.90	31.60	160.50	0.82	21.70	0.17	86.50

Source: Own analysis at the Laboratory of Hydro-structure Engineering, Tokyo University of Agriculture.

METHODOLOGY

The experiment was carried out inside a semiautomated greenhouse located in the facilities of the Hokubu-Daini Wastewater Treatment Plant in Yokohama City, Kanagawa Prefecture, Japan. Tomato seeds were transplanted after 7 days of sown on a portion of a hydroponic plot of 10 m x 1 m. Three treatments were set: T1) tap water and fertilizers, T2) Oxidized Water [reclaimed water (with secondary treatment)], and T3) Disinfected Tertiary Recycled Water [renewable water (with tertiary treatment)] (Table 1); the composition of the fertilizer applied to T1 is shown in Table 2. Fertilizer applications were made on the 1st and 49th days after transplanting (d). Daily temperature and relative humidity were registered using a Hobo datalogger.

Table 2 Nutrient content in soluble fertilizer OAT House No.1 & No.2 (ppm)

	TN	AN	NN	P_2O_5	K_2O	MgO	MnO	B_2O_3	CaO	Fe	Cu	Zn	Mo	EC (dS/m)
OAT House No.1 & No.2	260	23	233	120	405	60	1.5	1.5	230	3	0.03	0.1	0.03	2.6

TN=Total Nitrogen, AN= Ammonia Nitrogen, NN=Nitrate Nitrogen, Source: oat-agri.co.jp

The creation of logistic curves was following Eq. 1 (Bacaër, 2011).

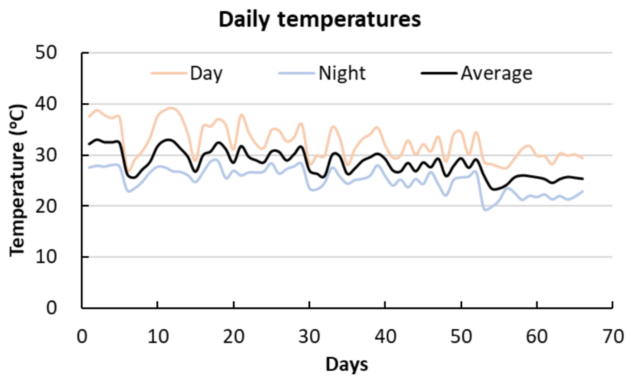
$$y = \frac{k}{1+be^{-cx}} \quad (1)$$

Where y is the dependent variable, k is the upper limit of plant height, x is the independent variable, and b and c are coefficients. Recently Fang et al. (2022) compared Gompertz curves and logistic curves, and even when GDD (growing degree-days) models provide a slightly better performance than those when using DAT (days after transplanting) as independent variables, there is no great difference to be considered as a discriminant for DAT.

RESULTS AND DISCUSSION

Temperature

Daily temperature data in Fig. 3 shows that higher temperatures were recorded at the beginning of the experiment, having peaks of 39℃; on the other hand, the lower temperatures were registered at night by the end of the experiment due to winter proximity. Regimes of CO_2 were kept below 500 ppm during the experiment.



Note: day and night averages were estimated from 6:00 to 18:00 and from 18:00 to 6:00, respectively.

Fig. 1 Temperature recorded with Hobo datalogger

Growing Logistic Models

For height estimation, parameter K in Eq. 1 was substituted by the maximum height measured in every treatment. Coefficient *b* stands for crop growth in the middle of the period, a low value of *b* represents high crop growth, while a high value indicates small growth. The growth ratio of tomato is denoted with a *c* letter in the equation. To find optimal values of *b* and *c*, the Solver function in

Excel was selected to calculate them by the least squares method. Height "y" is the dependent variable of "x" which represents the change in days after transplant (d).

When comparing the evolution of crop growth among the two types of wastewaters, it was observed that there are similar values for maximum plant height on T2 and T3 (T2=1,141 mm, T3=1,052 mm), the T-test shows that there was not a significant difference on plant height among T2 and T3 of the data collected weekly. On the other hand, b values represent the amount of crop growth during the middle of the period in observation (35 days), pointing out that the development of crops on T2 was almost two times that of those on T3 (T2: *b*=284, T3: *b*=489) (Table 3). However, regarding crop growth ratio, it is observed that plants under both treatments had a relatively similar *c* coefficient value, showing that there is no significant difference among them.

Table 3 Parameters of logistic equations with single logistic curves for each treatment

	T1	T2	T3
K (mm)	1,506	1,141	1,051
b (adim)	39.7	283.9	489
c (adim)	0.0874	0.1191	0.134
RMSE	73	28	23

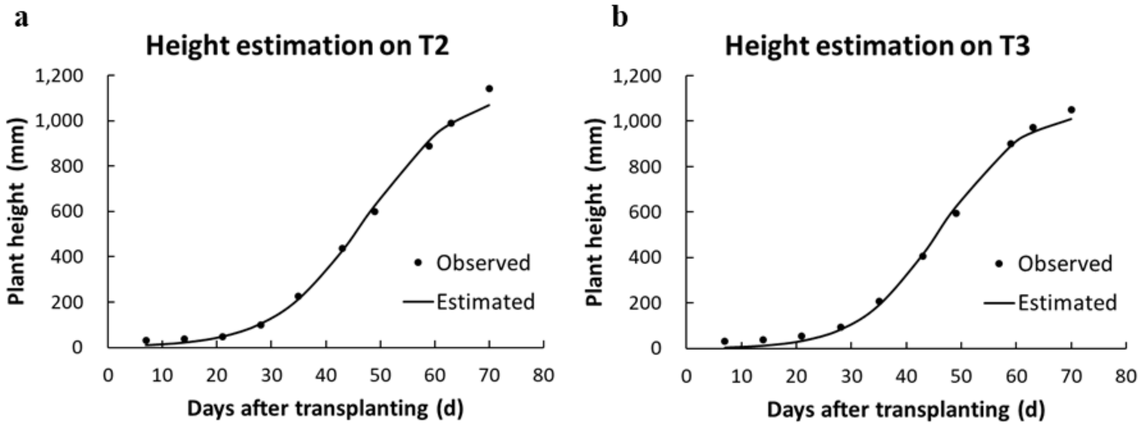


Fig. 2 a) Estimated height for treatment with OW [reclaimed water] (T2) and b) Estimated height for treatment with DTRW [renewable water] (T3)

The amount of crop (*b*) and growth ratio (*c*) had much better performance on T1, though a high RMSE was obtained. It was noted that the reason for the high RMSE was derived from the second application of fertilizer in this treatment, therefore a new module was adapted to the equation to be able to simulate this event. The new module was integrated with the difference between the last measure previous the application of fertilizer and the estimated height with a logistic curve. For the new logistic curve, K, which represents the maximum plant growth, was taken as the maximum height before the application of fertilizer. The module resulted in a linear equation after the second fertilization. The parameters of the equations are shown in Table 4.

Table 4 Adjustment parameters for the combined model

	Original Logistic curve	Adjusted logistic curve	Linear module	Combined equations
K (mm)	1506	898.8	-	898.8
b (adim)	39.7	212	-	212
c (adim)	0.0874	0.1785	-	0.1785
d (adim)	-	-	27.76	27.76
e (adim)	-	-	159.87	159.87
	RMSE=73	RMSE=18	R^2=0.98	RMSE=21

To estimate the plant height after transplant (y) and the height after second fertilization (y_1) in T1, it is necessary to introduce the values of days after transplant (x) and days after second fertilization (x_1). Eq. 2 can be used to estimate plant height before fertilization while Eq. 3 includes Eq. 2 to obtain estimations after fertilization.

$$y = \frac{898.8}{1+212^{-0.1785x}} \tag{2}$$

$$y_1 = y + 27.76x_1 + 159.87 \tag{3}$$

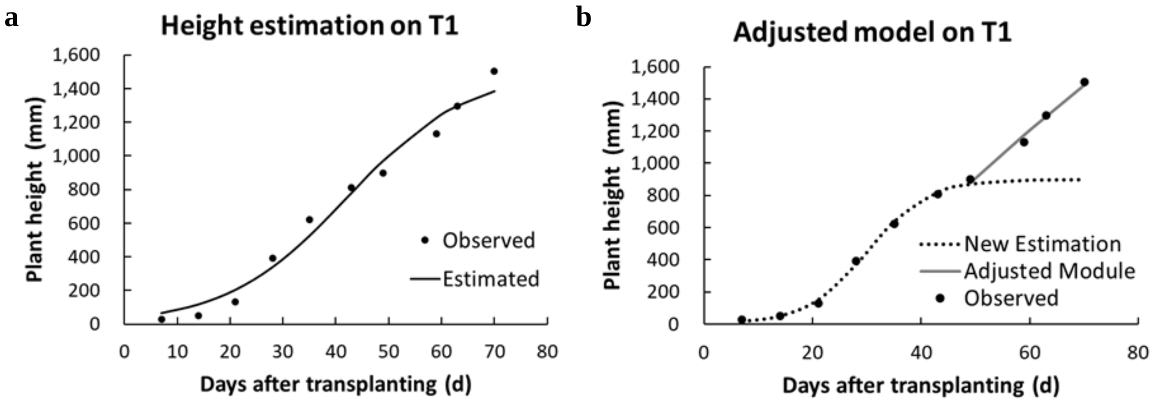


Fig. 3 a) Height estimation with a single logistic curve and b) Adjustment of estimation model after fertilization

With the modified equations, RMSE was improved from 73 to 21 mm (Table 4), therefore the inclusion of the new module significantly improved the estimation of plant height when sudden fertilization is considered.

Despite the constant decrease of temperature from the beginning until the end of the season (Fig. 1), the estimation of plant height when being irrigated either by OW or DTRW [renewable water or reclaimed water] can be predicted with a single logistic curve (Figs. 2a, 2b). The growth of plants with wastewater is a great opportunity for the reuse of Nitrogen and Phosphorus, the correct implementation of the nutrient is necessary to avoid the overgrowth of stems, moreover, fertilizer application should be selected based on the nutrient content to enhance fruit development and considering the proper stage of the crop.

CONCLUSION

In principle, the use of logistic curves can highly estimate the growth of tomato plants in semiautomated systems when being irrigated either by OW or DTRW [renewable or reclaimed water] and when their natural phenology is not perturbed; despite having notable differences in the amount of growth by the middle of the period there were no significant differences in the growth ratio among these two treatments. When sudden fertilization occurs, a logistic curve can be expanded with a new module that estimates the plant height according to the days after fertilization. This model can improve height estimation for these plants under greenhouses and can be used to avoid the overgrowth of plants inside these facilities. Since the “x” variable on the modified logistic curve depends directly on the daily phenology performance in each crop, this module can be studied and adopted in similar crops such as shrubs, herbs, and other vegetables.

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