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Effects of Temperature and Time of Harvest on the Growth and Yield of Aubergine (*Solanum melongena* L.)

Ahmet KÜRKLÜ

Akdeniz Üniversitesi, Ziraat Fakültesi, Tarım Makinaları Bölümü, Antalya-TÜRKİYE

Paul HADLEY, Anne WHELDON

University of Reading, Departments of Horticulture, and Engineering, Whiteknights, Reading RG6 2AY, U.K.

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Abstract: An experimental study was conducted to define the response of aubergine to different temperatures in controlled greenhouses. Set temperatures of the greenhouses were 14, 18, 22, 26 and 30°C. In terms of vegetative growth, the plant response was the highest to the highest temperature then gradually decreasing for the lower temperatures. This was in contrast with the fruit development since as the temperature decreased from 30°C, mean fruit weight and size increased, and the total fruit yield was highest in 22°C which indicated an optimum temperature. However, there was no optimum for vegetative growth. This was found, by using a growth model, about 32 to 34°C for almost all plant components. The results are useful for production planning.

Sıcaklığın ve Hasat Zamanının Patlıcanın (*Solanum melongena* L.) Büyümesi ve Meyve Verimi Üzerine Etkisi

Özet: Bu çalışmada, Patlıcanın sıcaklığa olan tepkisi, sıcaklığı kontrol edilen 4 adet serada belirlenmiştir. Seraların kurulan sıcaklıkları 14, 18, 22 ve 30°C idi. Ölçülen verilerden, sıcaklık arttıkça bitki büyümesinin arttığı görülmüştür. Ancak, bunun tersi olarak, sıcaklık arttıkça ortalama meyve boyutları ve ağırlığı dolayısı ile toplam meyve verimi azalmıştır. Meyve verimi açısından en uygun sıcaklığın 22°C olduğu görülmüştür. Bununla birlikte, ölçümlerden bitki büyümesi açısından herhangi bir en uygun sıcaklığa rastlanmamasına rağmen, bir bitki büyüme modelini kullanarak bunun yaklaşık 32 ile 34°C arasında olduğu bulunmuştur. Sonuçlar üretim planlaması açısından faydalıdır.

Introduction

The aubergine (*solanum melongena* L.) is one of the most important commercial vegetables in the Mediterranean region and Turkey in particular. Turkey has about 8533ha greenhouse area of which more than half is in the Antalya region on the Mediterranean coast and 17% of the total area is used in aubergine production (1). However, the U.K. has a total greenhouse area of about 3292ha and most of this area is dedicated to tomato and cucumber production and the aubergine is mostly imported (2). Its high temperature requirement is the main factor limiting its growth in Western and Northern Europe (3). Heating costs are the main input associated with the production of the crop. Thus energy management or energy saving techniques aimed at reducing heat costs will increase the efficiency of crop production.

In general, young crop plants are cultivated at a

day temperature somewhat higher than the night temperature. Thermoperiodicity term is a term first introduced by Went in 1944 who defined it as "all effects of a temperature differential between light and dark periods of the plant, whether they be flowering, fruiting or growth" (4). If a plant shows increased growth under alternating day and night temperature conditions compared with constant temperature conditions, that plant is said to show thermoperiodicity. However, it is indicated that the literature on the growth responses to temperature is confused and sometimes contradictory (5); for example, a close reexamination of the original data of Went (1944) shows little evidence for thermoperiodicity. Although (6) showed that there was evidence for optimal thermoperiodicity in stem elongation, flower initiation, and other developmental aspects of growth, there has been little experimental support for the existence of optimal thermoperiodicity in terms of total plant weight. It was found by (7) that dry matter accumulation of young tomato plants was also

greater at the optimal constant temperature of 25°C than under an alternating day and night temperature of 30/20 or 20/30 °C, which supported the view of (5). Experiments were also carried out by (4) to investigate whether there was any, evidence for the existence of the optimal thermoperiodicity in terms of total plant weight. In their study a wide range of crop plants (spring wheat, spring oats, tropical cereal corn, pea, bean, cucumber, and tomato) were grown under different temperature conditions in growth rooms. They found that the optimal temperatures for the temperate crops (pea, oats, and wheat) was 20-30 °C and for the tropical crops (corn, bean, cucumber, and tomato) 30-35 °C. They also found that there was no evidence for optimal thermoperiodicity in weight accumulation in any of the seven crop plants investigated and optimal growth occurred under constant temperature conditions. It was suggested by (8) that as the average day temperature increased, leaf number in tomato (*Lycopersicon esculentum* Mill.) increased. However, it was found by (9) that, for cucumber (*Cucumis sativus* cultivar 'Farbiola'), plant dry weight increased as average day temperature increased and plant fresh and dry weight, root development and plant height were significantly higher when day temperature was higher than night temperature compared with constant temperature or day temperature lower than night temperature. Low night temperature was found to have an inhibitory effect on the growth of young tomato plants but this might stimulate flower, yield of tomato was found to be affected mainly by the temperature integral not by the diurnal temperature regime (11, 12). For example, (13) used three different day/night temperature regimes with daily averages of about 17.7 and 18.7°C in two experiments on tomato at different times. Results showed that plant development (increase in number of trusses) was not affected by the temperature regime and lower day temperatures reduced the growth in stem length. Final yield and average fruit weight were higher at the higher night temperature. It was indicated by (14) that for sweet pepper (*Capsicum annuum* L.) grown under uncontrolled greenhouse conditions where high day temperatures prevailed, fast growth rates, a high percentage of flower abortion and a progressive reduction in fruit weight and seed yield occurred. They stated that the reason for smaller fruit sizes might have been due to increasing level of light intensity. The fruit setting ability of aubergine is affected by pollination and fertilization, previous fruiting and climatic conditions (15). It was indicated by (16) that, for to-

mato plants grown at 10°C night temperature, fruit setting was influenced by day temperature in a way that there was less fruit setting below and above and optimum temperature and 22°C gave the best fruit setting results when compared to 17 and 27°C. However, in a study by (17), yields of tomato grown at night temperatures from 14 to 18°C and at a constant night temperature of 16°C were compared and no significant difference in yield was found. Three day temperatures of 15, 20 and 25°C and three night temperatures of 10, 15 and 20°C were used by (18) to define the effect of day and night temperature on the growth, development and yield of cucumbers. Comparisons were also made between two temperature regimes (21/19°C and 24/17°C) applied during the pre-planting stage (late January to late February). In the pre-planting stage the 24/17°C temperature combination produced taller, heavier and leafier plants than those grown at 21/19°C. This resulted in higher fruit yield in the first 12 weeks of harvesting. In the early post-planting period (planting to fourth week after first harvest, 46 days) increases in total leaf area and stem length were closely correlated with 24 h mean temperature.

This study was carried out as part of a PhD research programme applying phase change materials (PCMs) for energy management in greenhouses. Thus aubergine was chosen since there has been little detailed and informative research on the effect of the temperature on the growth and yield of aubergine crop and this information was necessary for further research on energy management in greenhouses using PCMs.

Materials and Methods

This experiment was conducted between May and October in 1991 in the glasshouse facilities of the School of Plant Sciences at the University of Reading. Seeds of aubergine were sown on 19 March 1992 in seed trays containing Fisons peat based compost. The seed trays were maintained in germination bed in a greenhouse. After germination, the trays were removed from the germination bed and placed on benches in the same greenhouse. Sixteen days after sowing the seeds, on 4 April 1991, plants were transplanted into 15cm pots containing a plant each and 105 pots were moved into each of six controlled temperature greenhouse compartments (size 4*8m) with a spacing of 5cm. The minimum set temperatures for the greenhouses were 10, 14, 18, 22, 26 and 30°C. The

vents were operated to increase ventilation when temperature rose more than 4°C above the set temperature. Mean temperature was recorded in every compartment of daily solar radiation integrals were obtained from the Department of Meteorology which was located 300m from the experimental ground and mean temperature and solar radiation for each harvest time was calculated by taking the average of the daily temperature and radiation values from the day the plants were moved into the greenhouse to the actual harvest day.

Plant leaf area was measured by a leaf area meter (Delta-T Dvices Ltd.). Dry weight was measured after drying to constant weight at 80°C in a fan assisted drying oven. Plant height and fruit length were measured to an accuracy of 1mm. The first destructive harvest was carried out 6 days after moving the plants into the greenhouse compartments, on 10 April 1991. At the sametime 75 plants were transplanted into grow bags containing a peat based compost (Fisons) in each compartment. Each compartment contained 15 growbags and each growbag contained 5 plants, giving approximately 8 plants/m². Crop measurements in the coolest compartment (10°C) were abandoned since plant growth was not satisfactory in this compartment. Harvests took place every 10 days. At each harvest, 6 plants from each compartment were taken and their fresh and dry weights, leaf areas, heights and leaf numbers were measured. The leaves which were longer than 1cm were included in the calculation of the leaf number. These destructive harvests were carried out on 7 occasions. Twenty plants in each compartment were allowed to grow to maturity. Yields of fruit were measured in weight and length every 10 days. Fruits were picked when ripe and their lengths and weights were measured.

Results

Figure 1 shows the variation of the daily integrals of outside solar radiation and air temperatures in the greenhouses over the experimental period, respectively. As will be seen from the figure, the minimum temperatures in the 14 and 18°C compartments were not at their set values but slightly higher.

Vegative Growth

Figure 2 shows the variation of the fresh and dry weights, leaf area, and height with time and daily mean temperature. Total fresh or dry weight increased progressively with temperature, approaching

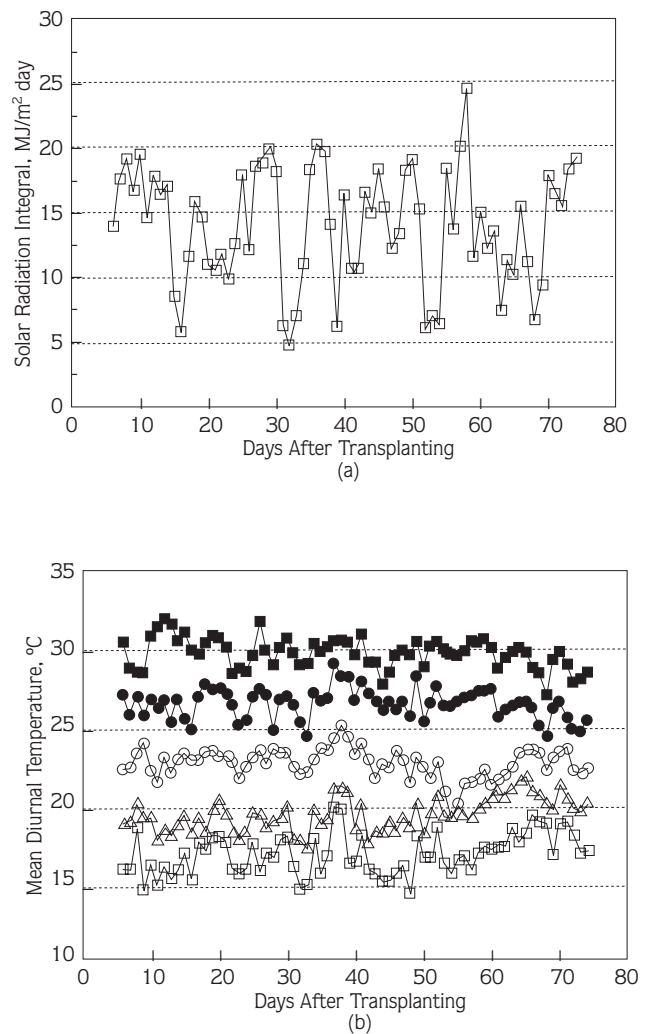


Figure 1. Variation of daily temperature (a), and solar radiation integrals (b) over the experimental period.

an asymptote of about 700 grams for fresh weight and about 80 grams for dry weight (a, b, c and d). The asymptotes of leaf area and height were approximately 700 cm² and 180 cm, respectively (e, f, g and h). After about 46 days, the difference in plant growth between the different temperature compartments became smaller. This meant that the plant growth in higher temperature compartments were relatively quicker than the lower temperature compartments and approached their asymptotic values faster. However, as the time progressed further, the difference in terms of plant growth between the compartments declined.

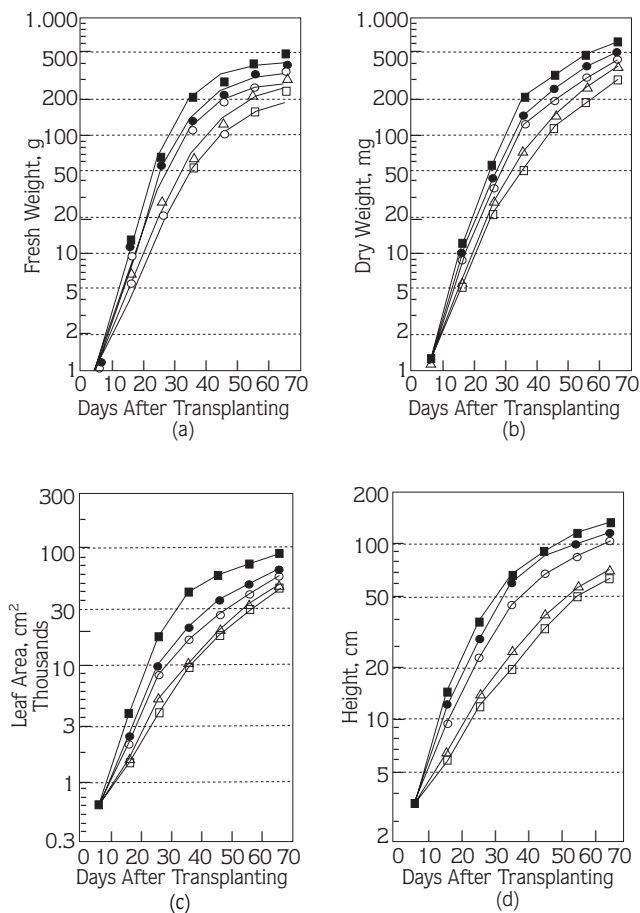


Figure 2. Variation of fresh and dry weight (a and b), leaf area (c) and height (d) with time.

A Curve Fitting Study

There are several advantages of fitting mathematical functions to plant growth data as stated by (20). These advantages are:

1. The function fitted provides a convenient summary of the data,
2. A series of predictions of the growth characteristics may be calculated at as many times as required, and these predictions are less disturbed by biological variability,
3. The function fitted to the transformed data (logarithmic function) may be differentiated to obtain a relative growth rate function,
4. If the function fitted is based on some biologically meaningful model, then the parameters (con-

stants) of the function may provide useful information, either by themselves, or in various combinations.

There are basically two types of functions which could be used to fit a curve to plant growth data (21). These are polynomial and asymptotic functions. The order of the polynomial may change from first to any higher order. The polynomial exponentials, for example, are usually used for their mathematical convenience for data smoothing purposes but they are not based on a biological model and usually parameters cannot supply any significant information. Unlike the polynomial functions, asymptotic functions are non-linear, that is, the parameters are not additive in a linear fashion but they may be divided, multiplied or exponentiated with one another. Of the types of asymptotic functions available (i.e. monomolecular, logistic, Gompertz and Richards functions), the Richards function (also known as the generalized logistic) is considered here since it includes all of the other main asymptotic functions as special cases of the Richards function (20) for a detailed information on the properties and use of the Richards function).

The Richards function is a four-parameter function having the general structure below (20, 21, 22):

$$\ln W = a (1 + e^{(b-kt)})^{-1/n} \tag{1}$$

Where $\ln W$ represents the natural logarithm of dry weight, fresh weight, height or leaf area, and a , b , k and n are parameters. n defines the point of inflection of the function. The constant a is the maximum value of growth (asymptote); the constant b is a measure of the starting size of the growth, in other words it merely positions the curve correctly with respect to time axis and it has no biological significance. The rate constant, k , has no significance by itself but can be usefully considered in combination with n . When $n = -1$, the curve is monomolecular in form (there is no point of inflection); when $n = 1$, the curve is in the form of logistic function. The Richards function cannot assume the Gompertz function exactly, since the relationships break down when $n = 0$; but as n approaches zero the resulting curve approaches the form of the Gompertz function. All statistical analysis and nonlinear curve fittings were accomplished by the Statgraphics computer software, Version 2.1 (23).

Having entered the initial estimates of the parameters a , b , k and n of the function in equation 1 in the computer software, the program calculated the residual sum of squares of the fitted curve from the actual data by an iterative technique. When the stop-

ping condition of the iteration, which was the calculation step where the least residual sum of squares of the fit was obtained, was reached, the calculated parameters of the equation 1 and ANOVA table for the fitted curve were displayed.

Part of the results of the curve fitting study only for leaf area is summarised in Table 1. As can be seen from the table, the asymptotes (a values) for all temperatures follow a similar pattern. Values of k of the components with time were, in general, highest for the highest mean temperature. Generally, there was little difference in k value between mean temperatures between 16 and 19°C and between 22 and 26°C. The point of inflection occurred at approximately the same values for each of the response components of each temperature.

Table 1. Results of the curve fitting study**

response comp.	fitted curve	min.temp.	parameters					R	p.i.*
			a	b	k	n			
		16	12.64	-2.81	0.024	0.073	0.99	0.38	
	Richards	19	12.20	-3.44	0.028	0.040	0.99	0.37	
leaf area	function	22	11.37	-3.46	0.043	0.042	0.99	0.37	
		26	11.54	-3.34	0.045	0.045	0.99	0.37	
		30	11.55	-2.76	0.060	0.074	0.99	0.38	

* : point of inflection

** : all of the coefficients were significantly different from zero (p<0.01).

Fruit Yield

Figure 3 shows the total harvested yield for aubergines grown at different temperatures. Plants grown at 22°C gave the highest fruit yield, followed by 19 and 16°C (approximately 33, 32 and 28 kg, respectively). Plants grown at 26 and 30°C yielded much less than plants grown at lower temperatures (18 and 15.5 kg, respectively). It is clear therefore that the optimum temperature for fruit production is approximately 22°C.

Mean fruit length (Figure 4 (a)) had the highest value initially for 19°C compartment and the lowest value for the highest temperature compartment all the

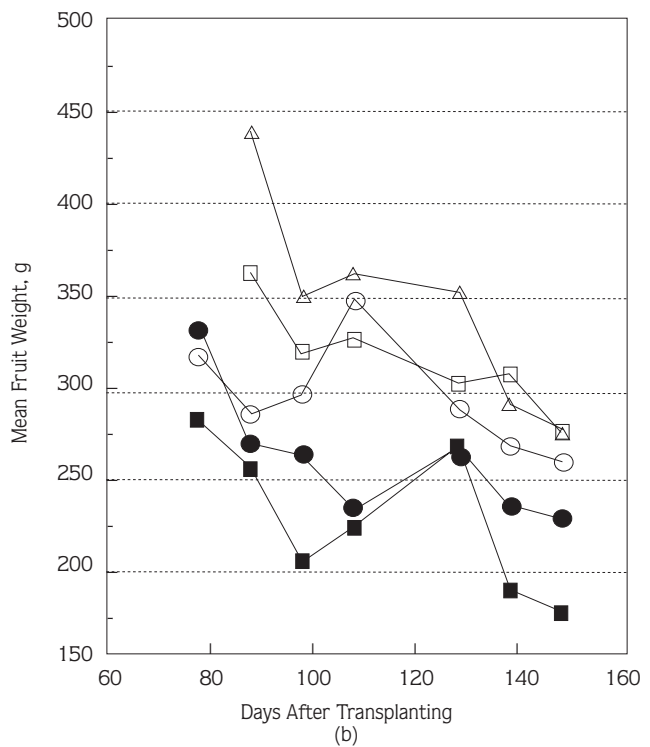
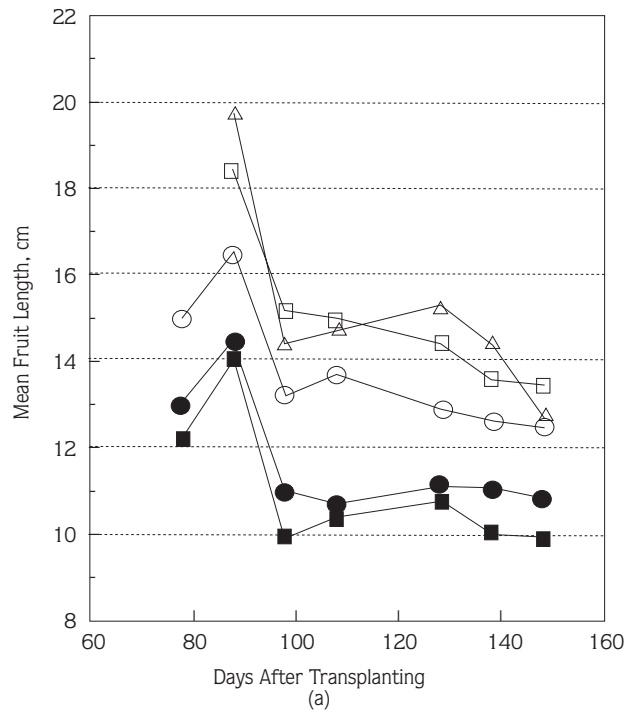


Figure 3. Total fruit yield.

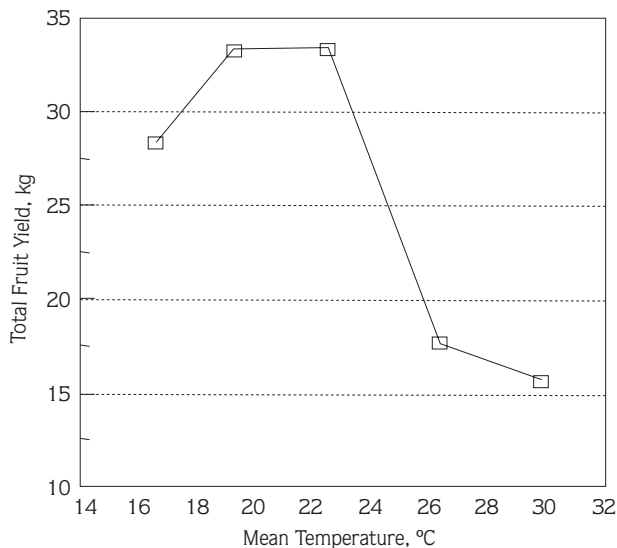


Figure 4. Variation of the mean fruit length (a) and weight (b) with temperature and time.

way through. There was little difference in fruit length between 16 and 19°C or between 26 and 30°C. However, there was a large difference between 22 and 19 or 16°C and between 22 and 26 or 30°C. Mean fruit weights (figure 4 (b)) showed similar responses to mean fruit length. Thus, the highest temperature compartment had the lowest mean fruit weight. Fruits from this compartment were of orange-like shapes for nearly the whole experimental period. As the temperature dropped to 16°C, the fruit length and its mean weight increased. Both fruit length in general and weight declined with time for all temperatures, though the decline in the fruit length was smaller.

A Plant Growth Model

The growth rates of many plant parts, such as root, stem, leaf and fruits are positive linear function of temperature between a base temperature (T_b) and an optimum temperature (T_o), and negative linear function above this optimum until a maximum temperature (24, 25). The values of optimum temperature for fruit yield are often different from that of optimum for vegetative growth since high temperatures effect the flower set of the plants in a negative way. Models of plant growth given an insight to how the plants response to different environmental conditions and how these conditions effect final yield. The overall growth efficiency of a plant is measured by its relative growth rate (RGR), and it can be calculated over a time interval as:

$$RGR = \frac{\ln W_2 - \ln W_1}{(t_2 - t_1)} \quad (2)$$

Where, RGR is the mean relative growth rate (g/gd) and W_1 and W_2 are, for example, the plant dry weights (g) at time t_1 and t_2 , respectively.

Here, a model of RGR proposed by (24) from their study on soyabean (*Glycine max* L. Merrill) grown in controlled environments is used. In this model, potential relative growth rate (RGR_0) decreases with accumulated thermal time and can be expressed as:

$$RGR_p = RGR_0 \left(1 - \sum_{i=1}^{i=n} (Ta - Tb) / \theta_f \right) \quad (3)$$

In which RGR_0 denotes the maximum potential relative growth rate, Ta is daily temperature (°C), Tb is the base temperature (°C) for the rate of development and θ_f is the thermal time (°Cd) at which RGR_p is zero. The value of instantaneous relative growth rate, (RGR_i), is also effected by daily temperature and can be represented as:

$$RGR_i = RGR_0 (1 - a|Ta - T_o|) \quad (4)$$

Where T_o is the optimum temperature for RGR and a is a constant. If a solar radiation integral term is added to this model in a simple fashion which is acceptable, (see for example (26)), the final relationship becomes:

$$RGR_i = RGR_p (1 - a|Ta - T_o| + bI) \quad (5)$$

In which b is a constant and I is the solar radiation integral (MJ/m²d). From this estimate of RGR_i the progress of increase in dry and fresh weight accumulation at different temperatures can be estimated for the successive time steps, such that:

$$W_2 = W_1 \exp \left(\int_{t_1}^{t_2} RGR_i dt \right) \quad (6)$$

This plant growth model was optimised in a worksheet environment using Lotus 1-2-3, version 2.2. To do this, the equations were incorporated in this worksheet environment and cells were fixed for each of RGR_0 , T_b , θ_f , a , b and regression coefficient, R^2 . Values of the parameters were assumed to be optimised when the residuals between the data and the predictions were minimised.

The relationships between the data and plant growth model predictions are shown in figure 5 for different plant parts. The solid lines in the graph represent the line of identity. The parameters optimised for the model are shown in table 2. As can be seen clearly from figure 5 the agreement between the data and the model prediction was good. As can be seen from the table 2, optimum temperature for the vegetative growth was around 32 to 34°C.

Table 2. Optimised parameters of the plant growth model

Parameters	Fresh Weight (gr)	Dry Weight (gr)	Leaf Area (cm ²)	Height (cm)
RGR ₀	0.2	0.25	0.23	0.17
max.θ _f	930	930	930	930
T _b	10	10	10	10
T _o	33	33.5	32.8	33.6
a	0.052	0.029	0.044	0.039
b	0.022	0.003	0.003	0.0002
R ²	0.86	0.86	0.85	0.87

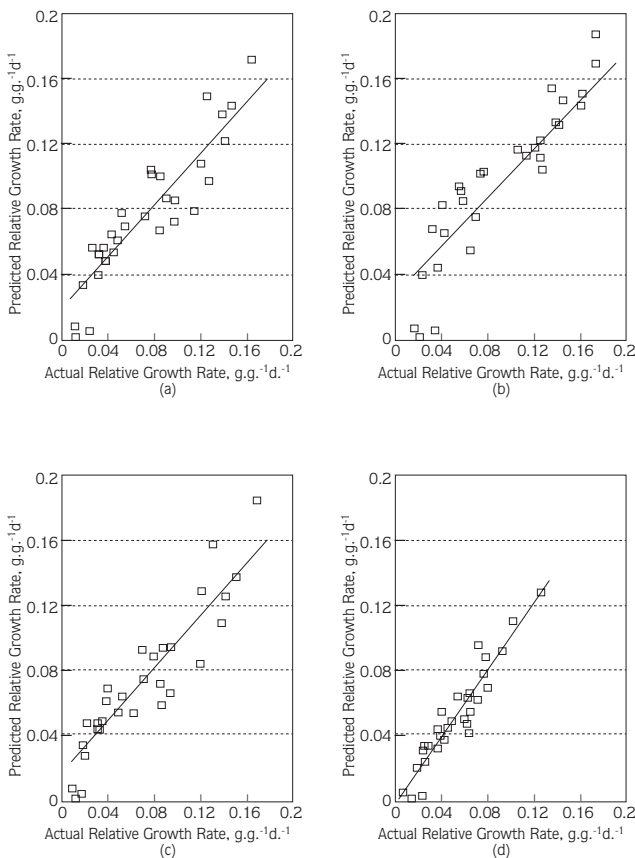


Figure 5. Relationship between actual and predicted data for fresh weight (a) and dry weight (b), leaf area (c) and height (d). Solid line is the line of identity.

Discussion

After nearly 46 days from the first harvest, the difference between the plants grown at different temperatures became smaller on both fresh and dry weight gain. Thus plants grown at higher temperature approached an asymptote faster than those grown at a lower temperature so that growth responses to temperature also declined.

When table 1 is investigated, it will be seen that the slopes of the all fitted curves for response variables at each harvest interval were different from the previous harvest. This indicated that the plant growth was always different in different time and temperature. The slopes of the curves were, in general, increasing till the fourth harvest, then gradually descending for all harvests. The decrease of the slope after the fourth harvest means that whilst the plant growth in higher temperature compartments was approaching its growing limit, that is the parameter a in Richards function, the lower temperature compartments showed relatively faster plant growth in comparison to the previous difference in the plant growth between different temperatures. It may also be noted that nearly all the n-values for all the plant components fitted with Richards function lay near to zero except dry weight, although most were significantly different from zero. This implies that a good approximation to the plant growth curves is provided by the Gompertz function.

It was indicated by (4) that maximum rate of dry matter production in greenhouse cucumber was achieved at a constant air temperature of 430 to 35°C. But it was found by (9) that an average day temperature optimum for growth of young cucumber plants (based on dry weight) was about 28 to 29°C. They indicated that the disagreement could be possibly explained by different light levels during temperature of different parts of aubergine plant using basic model of RGR of (26) revealed a temperature of about 32 to 34°C. Thus, this study is in accordance with the study of (4) on the definition of optimum growing temperature of some similar plants.

It was found by (27) that, for sweet pepper, plant height and number of flowers increased as average day temperature increased. He also found that average fruit weight was higher when the plant was young and when there was lower average day temperature which gave softer fruits. It was shown by (14) that, for sweet pepper, overall fruit weight declined throughout the life of the plant. Fruit size also reduced in this

study as the plant aged and temperature increased after an optimum for fruit growth, which was around 22°C. The fruits harvested from 26 and 30°C compartments were of orange-like shape and hard whereas fruit from lower temperature compartments were much softer. Why the total fruit yield was lesser in cooler greenhouses could be because of the low level

of relative humidity, especially at noon, within these two high temperature compartments. This situation might have caused a high percentage of natural flower abortion and smaller fruit sizes and weights via its effect on pollen germination in the compartments as indicated by (14).

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