Agric Res (October–December 2012) 1(4):362–369
DOI 10.1007/s40003-012-0035-5

FULL-LENGTH RESEARCH ARTICLE

Modeling of Tomato Seedling Growth in Greenhouse

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Received: 10 March 2012 / Accepted: 21 August 2012 / Published online: 19 September 2012

Abstract This study was undertaken to model the growth of tomato seedlings under greenhouse conditions. The micro-environment of the seedlings (temperature and solar radiation) was correlated with the seedling growth factors. Seed emergence was studied for five different temperatures, and a mathematical model was developed to fit the data to determine relationship between seed germination and soilless medium temperature. In post-emergence phase, a model was developed to estimate the dry weight attained by the seedlings as a function of cumulative heat units (CHU) and cumulative solar radiation (CSR). It was observed that the number of days required for seedling emergence was a function of average root medium temperature. Tomato seedlings emerged in 12 days at average root medium temperature of 20 and 35 °C, while the minimum duration was observed to be 7 days at 30 °C. The power model represented the seedling emergence behavior with correlation coefficient of 0.96. The growth of tomato seedlings after emergence was affected by both CHU and CSR. Modified Gompertz model explained the post emergence tomato seedling growth under different climatic variations with correlation coefficient from 0.96 to 0.97.

Keywords Greenhouse · Tomato · Seedling growth · Temperature · Solar radiation · Modeling

Introduction

A greenhouse is an enclosed structure covered with transparent or translucent material that provides partial or total controlled environment for crop cultivation. This technology enables food production at a given location without any constraint of agro-climatic conditions. Environment control for optimum plant growth has a significant role in crop production and accounts for 90 % of the yield [1].

Modeling is a promising technique for decision support system for greenhouse production system. Planning models offer help logistically in the planning of a crop to aid in crop timing, maximizing production, or evaluating an alternative system. Regression models [3], based on predictive equations, could be reasonably accurate over a defined range.

Production using transplanted seedlings of vegetables crops is an important method for vegetable growers. Healthy seedlings ensure the successful development of the plants and ultimately result into more profits for the farmer. Moreover, in a climate-controlled greenhouse, healthy seedlings can be produced in advance as compared to those produced in open field conditions. As the seedling for transplanting would be available early, a better price for the

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farmer could be ensured, as during peak season, prices of seedling would be higher, and this would be helpful in augmenting the farmer's income. In the near future, growers would prefer to buy seedlings from nurseries because it is often difficult for farmers to produce quality seedlings under open field conditions. A greenhouse with controlled environment permits efficient seedlings production with desired attributes.

Many researchers have worked on crop growth modeling such as Boonen et al. [2], who conducted studies to explore the possibility of modeling the fast dynamic response of net photosynthesis of leaves on a tomato plant to sudden step changes in light intensity, using a dynamic simple transfer function model. Olesen and Grevsen [6] described a model of cauliflower growth and development under conditions where water and nutrients were not limiting. Giniger et al. [4] developed a computer simulation model for greenhouse tomato crop management. The management models, based on a crop production model, are available to determine a production schedule designed to provide a continuous yield, optimize greenhouse space utilization, and predict production rates throughout the year, but very few such models are available for seedling production. The present study was undertaken to establish mathematical relations for greenhouse tomato seedling production under controlled conditions. The models were further used to develop a decision support system for greenhouse tomato seedling production [5].

Materials and Methods

Greenhouse Facility, Growing Medium, and Instrumentation

The seedling production was analyzed for two phases, i.e., tomato seedling emergence and post emergence. The experiments were conducted under controlled temperature and actual greenhouse conditions.

Nursery facility at the Centre for Protected Cultivation & Technology, IARI, New Delhi was used to conduct the experiments for tomato seedling production. The physical dimensions of the nursery are presented in Fig. 1a. The greenhouse was covered with a 200-µm UV-stabilized polyethylene cover, and it was closed on all sides having two doors: one for entrance, and the other one for exit purpose. Two exhaust fans, a heating chamber, boom irrigation supported on rails on the top of the greenhouse, tray holding benches, two high-pressure pumps for irrigation through booms, and a turbo pump for fertigation through booms were the main facilities installed in the nursery. Some artificial lighting arrangement with the help of sodium lamps was also there for critical periods of lower solar radiation availability. As shown in Fig. 1b, plug trays were used to grow tomato seedlings. A tray had 187 plugs, and it was supported by a thermocole covering, having 187 round holes matching with the lower opening of the plugs of tray. Soilless medium was used as root medium. Soilless medium was the mixture of coco peat, vermiculite, and perlite in the ratio of 3:1:1, respectively.

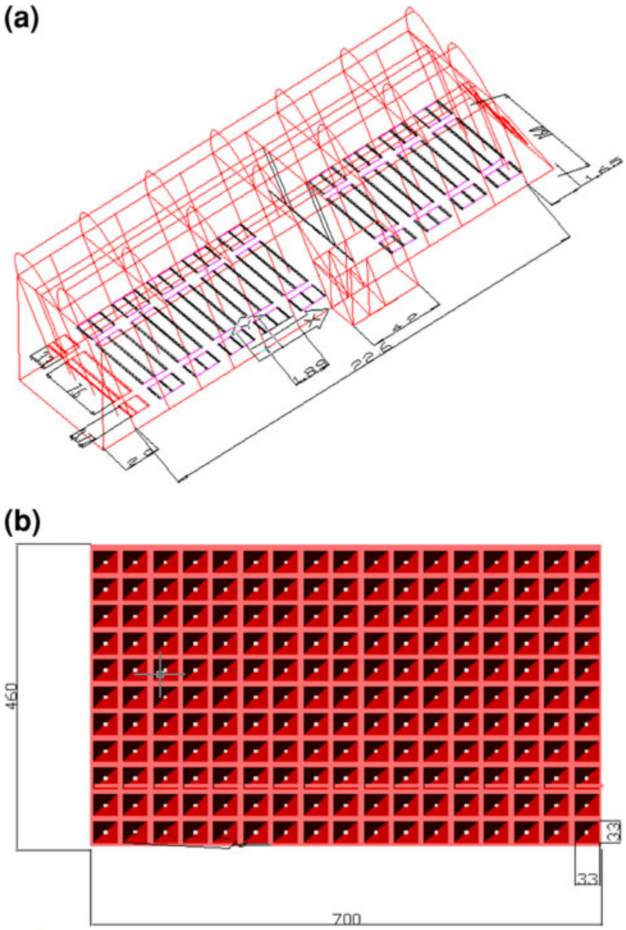

Fig. 1 Physical dimensions of nursery and plug trays; the dimensions given in (**a**) are in 'm' and in (**b**) in 'mm'

All temperatures were recorded with help of copper constantan thermocouples. Relative humidity was also recorded with the help of wet bulb and dry bulb thermometer concept using thermocouples. Li-cor pyranometers were used to measure the solar radiation at respective places. All these sensors were connected to 10× micro data logger for data logging. The data logger was programmed to measure and store temperature, relative humidity, and solar radiation at 60 s interval.

The trials were undertaken on tomato seedling production. Seeds of tomato cv. Pusa hybrid 2 were procured from the National Seed Corporation. Germination test for these seeds were conducted to find out the germination percentage before placing them into the actual trials. For this purpose, 25 seeds in triplicate were kept on water-soaked filter papers in petri dishes. These petri dishes were then kept in a germinator at 25 °C, at the Division of Seed science and Technology, IARI, New Delhi, and observations were taken on number of seeds germinated at the end of seventh day.

Tomato Seedling Production

The whole cycle of seedling production was studied in the following two stages for analysis:

1. Emergence of seedling from soilless medium
   This was the stage when shoot of the seedling just emerged out from the soilless medium surface, and the length of shoot was at least 1 cm above the root medium surface.
2. Post Emergence
   The stage started just after the emergence of the seedling from root medium surface.

Tomato seedling emergence was observed at five different root medium temperatures (20, 25, 30, 35, and 40 °C) to establish the relationship among the number of days required for emergence, and root medium temperature. For this purpose, soilless medium was prepared as mentioned and sufficient moisture was added to the mix. It was filled in the plugs of the trays. Fourteen plugs, in triplicate, having seeds of tomato seeds were placed in seed germination chambers at the selected temperatures. Similar trays were also placed in actual greenhouse conditions to compare the results. In accordance with the practices followed at the Centre for Protected Cultivation & Technology, these trays were covered with a polyethylene sheet of 200 μm before placing them into germination chambers and in greenhouse to prevent moisture loss from the soilless medium. No water application was given until tomato seedling emerged from the root medium.

For post-emergence growth analysis, the same Pusa hybrid 2 tomato seeds were sown in the plugs, filled with soilless medium, of three trays having 3 × 187 plugs. Sufficient moisture was added to the soilless medium, and then the trays were placed on the benches in the nursery. These trays were covered with a thermocole covering to prevent moisture loss. No irrigation was applied before emergence of the seeds. Three sets of experiments were conducted to evaluate the effect of temperature and solar radiation on vegetative growth of the newly emerged seedlings. Three different temperature regimes were observed by growing tomato seedlings in different ambient temperature conditions. The temperature, outside greenhouse, during the experiments varied from 10.8 to 41 °C. Three different shade levels (0, 40, and 60 %) were employed in the nursery to provide three different light levels to investigate the impact of light on seedlings growth, after emergence. The daily ambient cumulative solar radiation (CSR) during the experiments varied from 25.04 to 26.07 MJ/m^2. Two benches in the greenhouse were covered with 40, and 60 % shading net. Six trays, three in each level of shading, with tomato seeds were placed to ascertain the impact on incoming solar radiation in the vicinity of the young seedlings. Three trays (as control), without any shade, were placed on a bench so that the seedlings had 100 % access to the incoming solar radiation. After seed emergence, irrigation was scheduled on daily basis and fertilizer application was scheduled on alternate days. Nutrients were given in the liquid form, and it was applied simultaneously with irrigation. Water-soluble fertilizer, Nitrophoska–Foliar, was used for fertigation purpose. The Nitrophoska–Foliar contained 19 % N, 19 % P_2O_5, and 19 % K_2O. The concentration of the nutrient solution coming directly to the seedlings with water through the irrigating booms was 140 ppm. At two false leaves stage of the seedling, growth regulator, GLC, was applied in concentration of 25 ppm to regulate the growth of the tomato seedlings.

Observations

Climatic Parameters

Soilless medium temperature, ambient air temperature and relative humidity, and nursery temperature and relative humidity were observed with the help of copper constantan thermocouples connected to the data logger. Solar radiation values, in the nursery at different shade levels and in ambient conditions, were observed with the help of pyranometer, connected to the data logger.

Seedling Parameters

As discussed, the seedling growth was analyzed in two parts. For seedling emergence observations, the number of seeds emerging from the soilless medium was counted on daily basis until more than 75 % of the seeds emerged.

Dry weight of the seedlings was considered as the post-emergence growth parameter. Observations were taken after 7 days of emergence and then recorded on every third day. Ten seedlings were taken out from each tray at random, and then total dry mass of the seedling was determined by standard oven method. Dry weight of seedling's bio mass was determined by keeping the fresh biomass in a convective hot air oven at 65 °C. The weight was observed until it became constant (Hand book of Agriculture, ICAR, 2003), Besides, the final constant weight was the weight of the dry bio mass of tomato seedlings.

Development of Mathematical Relations

Black box or empirical modeling was used to establish mathematical relations between seedling growth and prevailing environment (temperature and solar radiation). Tomato plant has the ability to integrate temperature and light in the long run and respond accordingly. Temperature and solar radiation sum concept [8] was employed to find out the relationship between tomato seedling growth and its surrounding environmental conditions. Cumulative heat units (CHU) and CSR were calculated and used to correlate tomato seedling growth with prevailing environment.

CHU was defined as the sum of average daily greenhouse air temperature obtained during the specified period starting from the seed sowing.

$$\mathrm{CHU}_i = \sum_{i=1}^{n=\mathrm{DAS}} T_i \qquad (1)$$

where CHU_i is the cumulative heat units on ith day; °C days, DAS is the days after sowing; and T_i = Temperature on ith day, °C

Cumulative solar radiation (CSR) was defined as the sum of daily solar radiation incoming in greenhouse obtained during the specified period starting from the seed sowing.

$$\mathrm{CSR}_i = \sum_{i=1}^{n=\mathrm{DAS}} \sum_{h=1}^{24} S_i \qquad (2)$$

where CSR_i is the cumulative solar radiation on ith day, MJ-day/m^2; h is the hour of the day; and Si is the CSR on ith day, MJ

Non-linear least square method was used for modeling of seedling growth with respect to CHU and CSR by employing the SAS statistical software.

Results and Discussion

Tomato Seed Emergence

Tomato seeds sown in soilless medium were kept in controlled temperature germination chamber and actual green house conditions to ascertain seedling emergence responses with respect to growing medium temperature. Figure 2 shows the variation of temperature in soilless medium during germination of tomato seeds in actual greenhouse conditions. The root medium temperature was almost the same in different shade levels. Table 1 clearly depicts that the number of days required for seedling emergence was a function of average root medium temperature. Maximum duration of 12 days was recorded for required percentage of seedling emergence at average root medium temperature of 20 and 35 °C, while the minimum duration was observed to be 7 days at 30 °C. Therefore, it appeared that the number of days required for emergence depended on root medium temperature. At all temperatures, seed emergence was found to be more than 75 %, but in case of 35 °C, the emergence percentage was lower than 70 %, and the quality of the newly established seedling was poor in terms of its physical appearance and stability. Sakthivel and Thamuraj [7] also reported that tomato seed germination was completely inhibited at low temperatures (2–5 °C) and also at high temperature of 40 °C, whereas germination was the highest at 25 and 30 °C with high quality seedlings. On the basis of seedling emergence data, a power model was best fitted to establish a relation between the number of days required for emergence and daily average temperature. The model represented the observed data with 0.96, correlation coefficient.

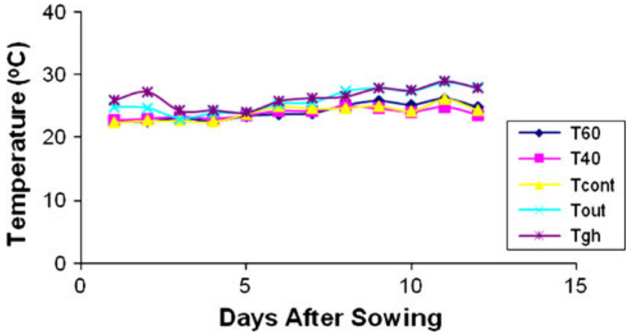

Fig. 2 Root medium temperature during Emergence under different shade conditions

The best fitted model was as follows:

$$\mathrm{DEF} = a \times T^{b \times T} \qquad (3)$$

where a and b are the constants; DEF is the number of days required for emergence; and T is the daily average temperature of the soilless medium (°C); $a = 24.2$, the value of initialization for the model; and $b = -0.12$, inherent rate of decrement

Figure 3 represents the variation of time required for emergence with daily average temperature of the growing medium. The equation was further used to make a decision support system [5] for greenhouse tomato seedling production.

Table 1 Emergence of tomato seedlings at different temperatures

Temperature (°C)	Days for emergence
20	12
22	10
25	9
30	7
35	12

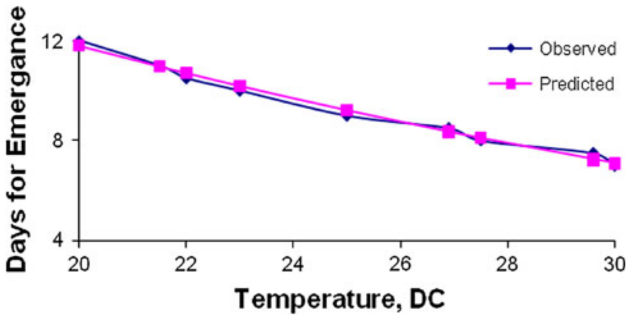

Fig. 3 Effect of temperature variation on the number of days required for emergence

Post-Emergence Growth of Tomato Seedlings

Three different production cycles of tomato seedlings (E1, E2, and E3) were completed in the months of March, April, and May to avail different prevailing climatic conditions. Table 2 presents seedling production time in terms of the number of days required for emergence and number of days, including emergence period, required for tomato seedlings ready for transplanting. The seedlings produced under third experiment with 0 % shade level took only 27 days to get transplanted, while seedlings under first experiment with 60 % shade level took 37 days to attain the stage of transplanting. The temperature and solar radiation level increase from March to May creating favorable conditions for the seedling production. Therefore, the seedlings under E3 took minimum days to emerge and were ready for transplanting earlier as compared to those produced under E1 and E2 environmental conditions.

Table 3 elaborates the results in terms of vegetative growth from all the three experiments. The table describes tomato seedlings' growth parameters with respect to greenhouse air temperature and incoming solar radiation. Depending on the different prevailing greenhouse environmental conditions and shade levels, seedlings were exposed to different degree of cumulative heat and solar radiation units. For post-emergence growth, greenhouse air temperature was considered to be appropriate, while root medium temperature was more appropriate for the emergence stage. The response of tomato seedling to each condition was different as depicted in the Table 3. It was observed, Table 3, that the samples, which received less CSR required more CHU to compensate for the resultant effect of CSR. Root length, fresh root weight, shoot weight, and total dry biomass were higher for the samples under 0 % shade because of higher solar radiation. All the three experiments indicated that maximum root length, fresh root, and shoot weight, and total dry biomass were found in case of 0 % shade. Moreover, the samples within these conditions were ready for transplant 1 day earlier and 6 days earlier than those under 40 and 60 % shade levels, respectively. Similar results were obtained in E2 and E3. With the help of Table 3, it was concluded that the number of days required for the seedlings to be ready for transplant reduced as the CSR and heat units increased for tomato seedlings ready for transplanting.

Plant growth of tomato seedling after emergence was affected by both CHU and CSR. Greenhouse air temperature was the basis for CHU calculations for post-emergence phase and it was found to be the same under different shade's level. Under these circumstances, CSR was the only variable factor for a set of experiment. CSR was more during experiment E3 in comparison to the experiment E1 and E2, because solar radiation intensity and photoperiod during this month (April) of the year was more. With the help of Fig. 4 it was concluded that the tomato seedlings under 60 % shade required more CHU compared to those under 0 and 40 % shade to achieve the required growth for transplanting, because of lower level of solar radiation accumulation. It was observed that more heat units, resulting from more days for accumulation of heat, are required to compensate the lower level of CSR to achieve the targeted growth of tomato seedling for transplanting.

Fresh root, shoot and total seedling dry weight variation with days after sowing were recorded. All these growth parameters had an incremental trend with respect to time. Initially weight gain was at slower rate, but after two true leaves stage, the rate of weight gain was higher. The tomato seedling exposed to 0 % shade under experiment E3 conditions gained weight at higher rate than those under experiments E1 and E2 with 40 and 60 % shade conditions. Figure 5 presents the variation in CSR under different shades for a set of experiment.

This difference in weight gains at different rates of increase was due to different levels of CSR, available for

Table 2 Tomato seedling production schedule at different incoming solar radiation levels in greenhouse

Experiment	Days required for seedling emergence			Total number of days required for the seedlings, ready for transplanting		
	Shade level			Shade level		
	0 %	40 %	60 %	0 %	40 %	60 %
E1	8.5	9.0	9.0	31.0	32.0	37.0
E2	8.0	8.0	8.0	28.0	29.0	31.0
E3	7.6	7.6	7.6	27.0	28.0	28.0

Table 3 Tomato seedling growth parameters under all the three different experimental conditions

Experiment	Observations	Shade Level		
		0 %	40 %	60 %
E1	CHU (DD)	827.08	858.02	975.65
	CSR (MJ/m^2)	187.19	100.61	94.41
	Root length (cm)	11.23	10.74	8.67
	Fresh root weight (mg)	205	152	140
	Shoot length (cm)	7.37	9.03	10.66
	Fresh shoot weight (mg)	621	566	507
	Total dry weight of seedling (mg)	210	176	175
	No. of leaves	7	7	6.5
	Shoot diameter (mm)	2.5	2.4	1.7
E2	CHU (DD)	896.05	908.1	937
	CSR (MJ/m^2)	186.11	106.54	96.04
	Root length (cm)	11.0	10.75	10.90
	Fresh root weight (mg)	264	247	235
	Shoot length (cm)	6.2	7.41	8.7
	Fresh shoot weight (mg)	610	500	457
	Total dry weight of seedling (mg)	230	180	172
	No. of leaves	6	5.5	5.5
	Shoot diameter (mm)	2.6	2.5	2.2
E3	CHU (DD)	820	853.57	858.99
	CSR (MJ/m^2)	180.12	96.98	80.61
	Root length (cm)	9.16	10.14	8.75
	Fresh root weight (mg)	217	180	162
	Shoot length (cm)	5.2	5.4	6.21
	Fresh shoot weight (mg)	460	410	370
	Total dry weight of seedling (mg)	179	159	135
	No. of leaves	6.5	6	6
	Shoot diameter (mm)	2.15	1.97	1.56

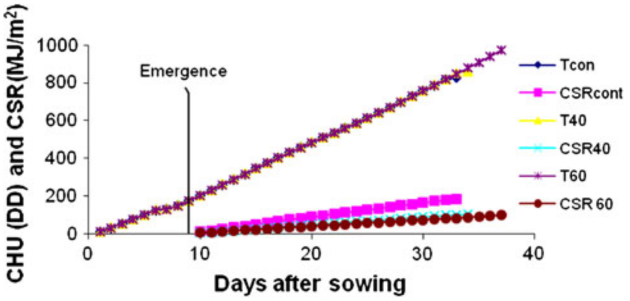

Fig. 4 Accumulated CHU and CSR

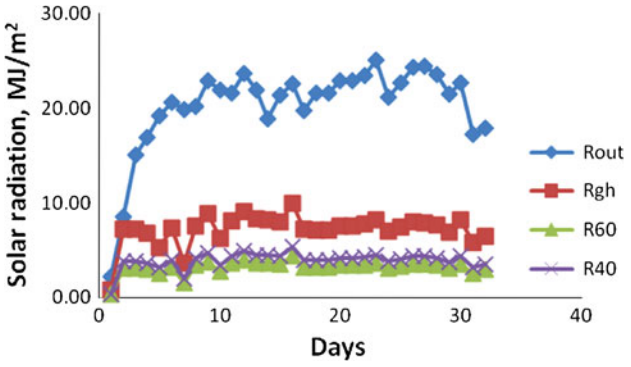

Fig. 5 Solar radiation variation during seedling production under no shade, gh, 40 and 60 % shade

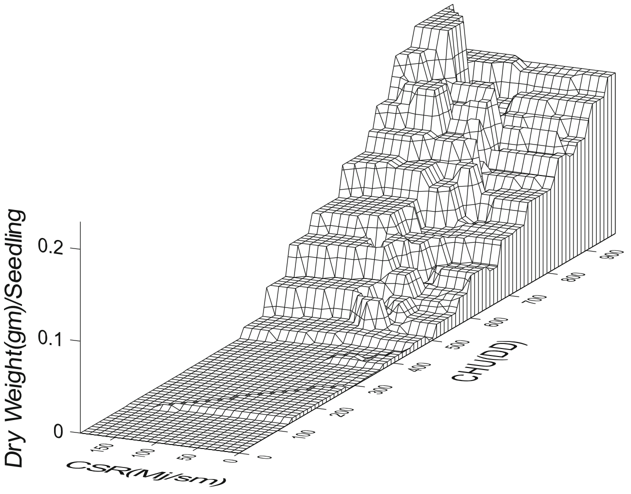

Fig. 6 Tomato seedling growth with respect to CHU and CSR

the seedlings. Tomato seedlings under E3 experiments with 0 % shade were ready for transplant within minimum days because under E3 conditions the solar radiation intensity was higher than that of E1 and E2. The weight gain was directly correlated with solar radiation accumulation during seedling production for a particular prevailing temperature conditions. With the help of recorded observations as shown in the Fig. 6, it was concluded that the samples, which got higher level of solar radiation, developed rapidly and took less days in comparison to those under 40 and 60 % shade. Biomass gain rate was maximum for the seedling which received complete solar radiation incoming in the greenhouse and it got slower with respect to the shade percentage applied over seedlings. So, the biomass accumulation rate or rate of gain in dry weight of seedlings was higher for the seedlings under 40 % shades than those under 60 % shade conditions, respectively.

Mathematical Modeling of Post Emergence Growth of Tomato Seedlings

Mathematical relationship was developed to correlate tomato seedling growth with its microenvironment. Cumulative heat and CSR parameters were employed to express the growth behavior of tomato seedling. Daily average of relevant temperature from the day of seed sowing to the required maturity of tomato seedlings for transplanting was summed up to obtain cumulative temperature integral. Cumulative solar light integral was obtained by summing up the daily integral from the day after emergence to the day of tomato seedlings' maturity. Total dry weight of seedling represented the seedling growth.

The data on total dry mass accumulation from all the three experiments were pooled and plotted to study the dry mass accumulation, as shown in Fig. 6, with respect to CHU and solar radiation accumulation. Dry mass accumulation during the initial period was similar for all the different shade levels: 0, 40 and 60 %. After about 400 degree days of heat accumulation, the effect of solar radiation variation became more visible. The rate of dry mass accumulation was maximum in case of 0 % shade and it was minimum under 60 % shade. Similar trend was observed in the experiments E2 and E3, but the rate of dry matter accumulation was different as per prevailing environmental conditions in the greenhouse. The rate of dry matter accumulation was highest for the seedlings grown under experimental conditions E3 with 0 % shade and it was minimum for the seedling grown under experiment E1 conditions with 60 % shade. The similar trends were observed for the other two experiments E2 and E3. For a certain level of CSR, if CHU increase, the dry mass accumulation also increases. Similarly, for a certain level of CHU, the dry mass increases if the CSR units increase. If both, CSR and CHU are increased, then the dry mass accumulation increases at the higher rate.

The modified Gompertz model was the best fit to the observed data to represent the tomato seedling growth under different climatic conditions.

$$\mathrm{DW} = A * e^{-e(B - C_1 * CHU_i - C_2 * CSR_i)} \tag{4}$$

where A, B, C_1, and C_2 are the constants; $A = 0.326084$, $B = 2.97864$, $C_1 = 0.00313$, and $C_2 = 0.005737$.

A in the above equation represents the initialization value, and B is the limiting value; C_1 and C_2 are the inherent rates of dry mass accumulation, which depend on both CSR and CHU.

Comparison between the predicted and observed values is presented in Fig. 7. These graphs represent degree of fit in different sets of observation under all three experimental conditions with varied CHU and solar radiation profiles. Correlation coefficient among all the different sets of observations and the prediction was in the range from 0.96 to 0.97. It was concluded that post-emergence model of tomato seedling growth represented the total dry mass accumulation under different climatic variations well.

The behavior of the growth was modeled to find out the balancing factor to maintain the required growth of tomato seedling. The following relation was developed

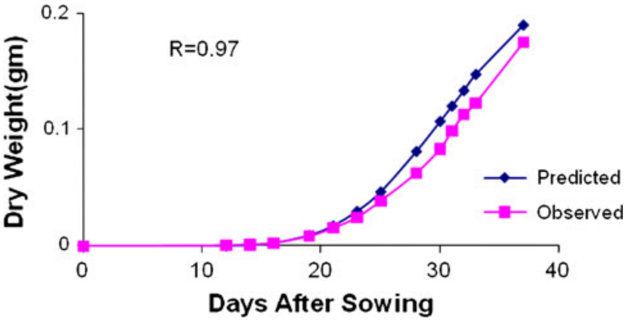

Fig. 7 Correlation between predicted and observed weight (E1, 60 %)

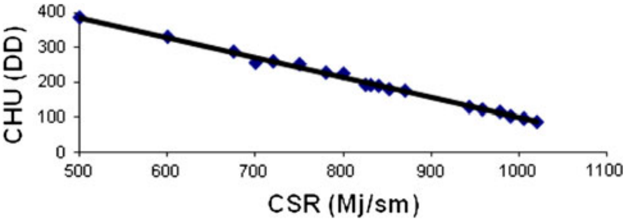

Fig. 8 Relation between CHU and CSR

$$\mathrm{CSR}_i = 0.5713 * \mathrm{CHU}_i + 670.92 \tag{5}$$

The correlation coefficient between observed and model's prediction was 0.99 (Fig. 8).

Conclusions

Tomato seed emergence was better between 20 and 30 °C temperatures in terms of percentage germination and quality seedlings. Tomato seedling emergence was a function of the root medium temperature for the set of experiments, and power model described clearly the relation between the number of days required for the seed emergence and average temperature of soilless medium during seed emergence. Post-emergence growth of tomato seedling depended on greenhouse temperature and solar radiation. CHU and CSR concept were employed to represent tomato seedling growth. Modified Gompertz model described post-emergence growth of tomato seedling well. The models obtained from the study were further employed to develop a decision support system to regulate environmental factors, temperature, and solar radiation, to achieve targeted growth of tomato seedlings with respect to specified time deadlines.

Acknowledgments The authors thank the Heads of Division of Seed Science, and the Centre for Protected Cultivation & Technology and Phytotron facility, the Indian Agricultural Research Institute, New Delhi for supporting the presented study.

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