Asian Journal of Crop Science

ISSN 1994-7879

science alert
http://www.scialert.net

ANSInet
an open access publisher
http://ansinet.com

OPEN ACCESS Asian Journal of Crop Science

ISSN 1994-7879
DOI: 10.3923/ajcs.2021.24.35

Research Article
Effect of Polybag Size on Growth, Root Morphology and Yield of Chilli (*Capsicum annuum* L.) Grown in Soilless Culture

[1]Nurul-Idayu Zakaria, [1,2]Mohd Razi Ismail, [2]Yahya Awang and [2]Puteri Edaroyati Megat Wahab

[1]Laboratory of Climate-Smart Food Crop Production, Institute of Tropical Agriculture and Food Security, Universiti Putra Malaysia, 43400, Serdang, Selangor, Malaysia
[2]Department of Crop Science, Faculty of Agriculture, Universiti Putra Malaysia, 43400, Serdang, Selangor, Malaysia

Abstract

Background and Objective: In soilless culture, the dimension of polybag affects plant growth and a higher volume of the substrate is related to high production cost. This study was conducted to determine the optimum polybag size for chilli grown in soilless culture. **Materials and Methods:** The effect of 6 treatments combination consist of two polybag arrangements (horizontal and upright) and three lengths of polybag (17, 19 and 27 cm) were evaluated on growth, dry matter production, root morphology and yield of chilli. This study was performed in a Randomized Complete Block Design (RCBD) with three replications. All the data were analyzed using the two-way analysis of variance (ANOVA) and Least Significant Different (LSD) was used for mean comparison at $p \leq 0.05$. **Results:** Chilli plants grown in a horizontal polybag of 17 cm in length showed a reduction of growth, dry matter production, root length and yield. With a similar volume of substrate, chilli grown in a horizontal polybag of 27 cm in length produced higher leaf, root dry matter and yield compared to control treatment. Chilli grown in a horizontal polybag of 17 cm in length and horizontal polybag of 27 cm in length had 32% reduction and 32% increment in fruit fresh weight, respectively compared to control. Chilli grew in an upright polybag of 27 cm in length with a higher volume of substrate produced a similar yield with control. **Conclusion:** Among the six different polybag sizes, a horizontal polybag of 27 cm in length had shown better growth and yield for chilli grown in soilless culture.

Key words: *Capsicum annuum*, polybag size, soilless culture, growth, root morphology, yield

Citation: Zakaria, N.I., M.R. Ismail, Y. Awang and P.E.M. Wahab, 2021. Effect of polybag size on growth, root morphology and yield of chilli (*Capsicum annuum* L.) grown in soilless culture. Asian J. Crop Sci., 13: 24-35.

Corresponding Author: Mohd Razi Ismail, Laboratory of Climate-Smart Food Crop Production, Institute of Tropical Agriculture and Food Security, Universiti Putra Malaysia, 43400, Serdang, Selangor, Malaysia

Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Chilli (*Capsicum annuum* L.) is an economically important vegetable crop grown worldwide due to its pungency. It contains a high level of pro-vitamin A, vitamin C and E and carotenoids[1,2]. In Malaysia, the chilli production area increased from about 2.8 thousand hectares while annual production reached about 32.8 thousand tons[3]. However, the domestic production of chilli in Malaysia is still below 70% of demand[4]. The adoption of a soilless culture system for growing chilli is more cost-effective due to efficient and accurate control of water and nutrients which can enhance growth and yield quality[5-7].

Container specifications such as length, height, volume and shape affect the size and depth of the root system and also distribution, availability and absorption of water and nutrient in the substrate[8]. Root growth usually occupies the space of its container and optimal root growth and distribution depends on the physical rooting environment which is the container size[9]. It has been proved that a larger container size increased root mass in plant[10,11]. The inadequate container size usually causes root restriction and decrease both shoot and root dry matter and total leaf area[12,13]. Under ample supply of water and nutrient, root growth is the major factor that controls the shoot growth[14].

The optimum container size varies according to many different factors such as plant species, growing density, environmental conditions and duration of growing period[15]. To select optimum container size for each specific crop, studies have been conducted on different plant types such as fruit vegetables[16,17], fruit trees[18], ornamental[19,20] and forest tree[21]. Yield response to different container sizes has been reported for sweet pepper[22] and cotton[23]. In general, the yield was enhanced in the larger container compared to the small container. However, Byers *et al.*[24] found that apple trees grown in small containers showed an increase in the number of flowering and fruit set while Ayarna *et al.*[25] showed improvement of dry matter allocation to the fruit of tomato grown in a partial root restriction in Coco wool compared to complete root restriction.

Although container size can affect the growth and development of soilless culture plants such as tomato[26], lettuce[27], strawberry[28] and muskmelon[29], yet there was little research have been conducted on the chilli pepper.

Soilless culture depends largely on the use of polybags filled with coconut coir dust as the substrate. Inefficient use of substrate causes wastage of this resource and in the future, it may become a limited resource and expensive due to higher demand and consumption. Therefore, it is important to maximize efficient use of substrate possibly by using less substrate. Therefore, the present study was conducted to determine the effect of polybag size on growth of shoot, root morphology and yield of chilli under soilless culture.

MATERIALS AND METHODS

Experiment site, plant material and cultural conditions: The study was conducted from September-December, 2009 under rain shelter at Field 10, Universiti Putra Malaysia (UPM), Serdang, Selangor. Seeds of chilli pepper (*Capsicum annuum* var. Kulai) were germinated in peat moss. Four weeks after germination, seedlings that consisted of 4 true leaves were transplanted into a plastic polythene bag containing Coconut Coir Dust (CCD) and Empty Fruit Bunch (EFB) compost (70:30 v/v). The nutrient concentration of 2.5 dS m^{-1} based on Cooper formulation as stated by Berahim *et al.*[30] was supplied to the plants twice daily via by drip irrigation system. The substrate was flushed with tap water once a week to avoid excessive salt accumulation in the substrate.

Treatments combination and experiment design: The experiment was conducted as a factorial experiment design with 2 different arrangements of polybag (horizontal and upright)×3 lengths of polybag (17, 19 and 27 cm) as presented in Table 1. The experiment was organized in Randomized Complete Block Design (RCBD) with three replications. This experiment was performed with a blocking effect due to the different water pressure along the drip irrigation line. The schematic diagram of seedlings of chilli planted in different polybag sizes is presented in Fig. 1.

Plant growth, total leaf area and plant biomass determination: Plant height was measured from the ground level to the shoot tip using a measuring tape, stem diameter was measured using callipers and total leaf area was obtained using leaf area meter (Li-3000, Li-cor Inc., Lincoln, NE, USA). Measurement was taken from three plants from each treatment during the peak fruiting stage at 84 days after transplant. Plants were harvested and partitioned into leaves, stems and roots before oven-dried at 65°C for 72 hrs for determination of dry weight. The root: shoot ratio was calculated based on dry weights of shoot and root parts as described by Razak *et al.*[31] using the following Eq.:

$$\text{Root: shoot ratio} = \frac{\text{Total root dry weight}}{\text{Total leaf and stem dry weight}}$$

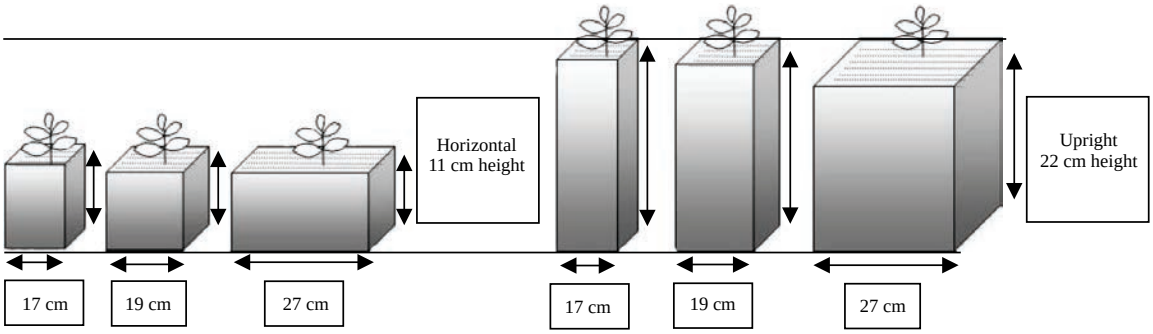

Fig. 1: Schematic diagram showing seedlings of chilli planted in polybags

Table 1: Treatments combination with the specification of the polybag and quantity of media used in the experiment

		Specification of polybag			
Polybag arrangement	Polybag length (cm)	Polybag dimension (long×wide×height cm)	Polybag size	Quantity of growing media mixture (kg)	Ratio of CCD: EFB (kg: kg)
Horizontal	17	17×15×11	12×12	0.5	0.35: 0.15
	19	19×17×11	16×16	1.0	0.70: 0.30
	27	27×23×11	20×20	2.0	1.40: 0.60
Upright	17	17×15×22	12×12	1.0	0.70: 0.30
	19	19×17×22	16×16	2.0	1.40: 0.60
	27	27×23×22	20×20	4.0	2.80: 1.20

CCD: Coconut coir dust and EFB: Empty fruit bunch

Determination of root morphology: At the 84th Day After Transplantation (DAT), the roots of three plants from each treatment were thoroughly cleaned and were put into acrylic trays of root image analyzer (WinRhizo STD 1600$^+$ Scanner, Regent Instruments Inc., Quebec, Canada) to measured root length and root surface area.

Yield: Mature fruits were harvested from three plants from each treatment at 84th DAT. Total numbers of fruits were calculated and the total fresh weight of fruit was weighed using an electronic balance immediately after harvest. Fruit length was measured from the base to the apex of the fruit without considering the peduncle by using a 30 cm ruler meanwhile fruit diameter was determined at the widest part of the fruit by using a calliper.

Statistical analysis: All the data were analyzed using the two-way analysis of variance (ANOVA) procedure in the statistical analysis system[32]. The Least Significant Different (LSD) was used to compare differences between the treatments at $p \leq 0.05$.

RESULTS

Plant growth

Plant height: The effect of polybag arrangement was highly significant ($p \leq 0.01$) on the height of the chilli plant. Similarly, the length of polybag likewise the interaction effects were highly significant ($p \leq 0.01$) on the plant height in Fig. 2. The plant height of chilli grown on horizontal polybags showed no significant differences among the three polybags length. However, when grown on an upright polybag, plant on polybag of 19 and 27 cm in length grew taller than polybag of 17 cm.

Stem diameter: The stem diameter of the chilli plant was significantly ($p \leq 0.05$) affected by polybag arrangement. Moreover, the effect of length of polybag and interaction effect of polybag arrangement and length of polybag was highly ($p \leq 0.01$) significant for this trait in Fig. 3. The stem diameter of chilli grown on horizontal polybags of 27 cm in length was significantly greater than those grown on 17 and 19 cm. In upright polybags, polybags of length 19 and 27 cm showed greater stem diameter compared to those of length 17 cm.

Total leaf area: The total leaf area of chilli on the 84th day of growing is presented in Table 2. The total leaf area of plants grown in upright polybag was greater (5643.1 cm^2) than in horizontal polybag (5089.4 cm^2) although the difference was not significant. Chilli plant grown in a polybag of 27 cm in length had the highest total leaf area with the value of 6327.6 cm^2 which was about 19% greater than the polybag of 19 cm in length with the value of 5316.6 cm^2. Meanwhile, a polybag of 17 cm in length showed a reduction in total leaf area with a value of 4454.6 cm^2. F-test analysis showed that

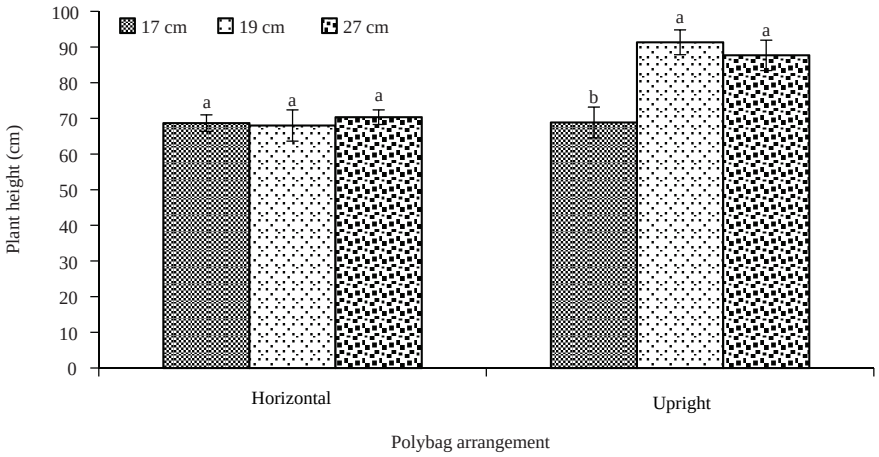

Fig. 2: Interaction effect of polybag arrangement and polybag length on plant height of chilli after 84 days of transplanting
Mean values followed by the same letters for each polybag arrangement were not significantly different at p = 0.05 level by the LSD test

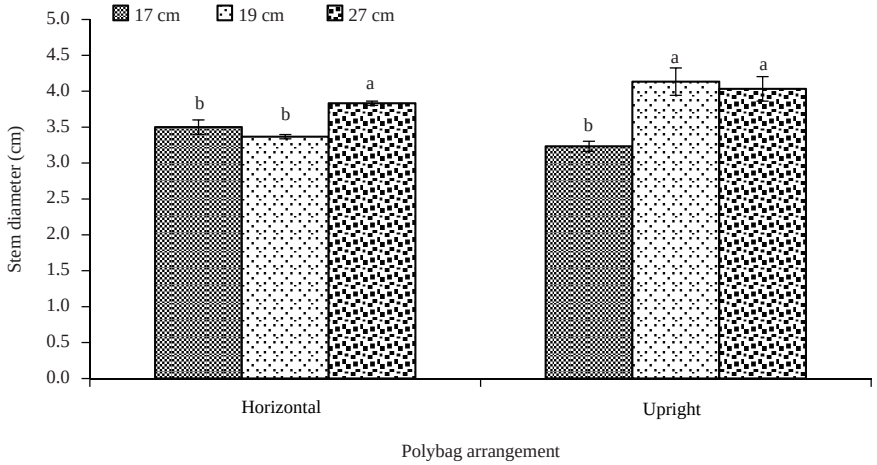

Fig. 3: Interaction effect of polybag arrangement and polybag length on stem diameter of chilli after 84 days of transplanting
Mean values followed by the same letters for each polybag arrangement were not significantly different at p = 0.05 level by the LSD test

the total leaf area was not significantly ($p \geq 0.05$) affected by polybag arrangement. However, polybag length had a significant ($p \leq 0.05$) effect on the total leaf area of the chilli plant whilst their interaction effects were not significantly different ($p \geq 0.05$).

Biomass partitioning

Total leaf dry weight: Chilli plants grown on horizontal polybags of 27 cm in length have greater total leaf dry weight with the value of 24.84 g plant^{-1}, compared to 17 and 19 cm with the value of 18.32 and 12.09 g plant^{-1}, respectively. However, while grown on an upright polybag, lengths of polybags had no significant effect on total leaf dry weight. F-test analysis showed that the total leaf dry weight was not significantly affected by polybag arrangement ($p>0.05$). On the other hand, the effect of polybag length was significant ($p \leq 0.05$) and the interaction effect was highly significant ($p \leq 0.01$) for the total leaf dry weight of chilli at 84 days after transplant in Table 3.

Total stem dry weight: The total stem dry weight of chilli is presented in Table 4. Polybag arrangement showed no significant effect on total stem dry weight however plants grown in upright polybag have greater (31.6 g plant^{-1}) stem dry weight. The total stem dry weight of chilli was 31.4% greater in polybag of 27 cm in length (37.64 g plant^{-1}) than plant those grown in a polybag of 19 cm in length (28.65 g plant^{-1}). Polybag of 17 cm in length showed a 23.2% reduction in total stem dry weight (21.99 g plant^{-1}) compared to polybag of 19 cm in length (28.65 g plant^{-1}). This indicated

Table 2: Mean total leaf area (cm^2 $plant^{-1}$) of chilli plant as affected by the arrangement of polybag and length of polybag with their interactions after 84 days of transplanting

Treatment	Total leaf area (cm^2 $plant^{-1}$)
Polybag arrangement	
Horizontal	5089.4[a]
Upright	5643.1[a]
LSD (p = 0.05)	913.8
Polybag length (cm)	
17	4454.6[b]
19	5316.6[ab]
27	6327.6[a]
LSD (p = 0.05)	1119.2
F-test	
Arrangement	NS
Length	**
Arrangement × length	NS
CV	16.21

Mean values followed by the same letters within a column are not significantly different at p≤0.05 by LSD test, *: p≤0.05, **: p≤0.01,***: p≤0.001, NS: Non-significant and CV: Coefficient of variation

Table 3: Mean total leaf dry weight (g $plant^{-1}$) of chilli plant affected by the arrangement and length of polybag with their interactions after 84 days of transplanting

	Polybag arrangement	
Polybag length (cm)	Horizontal	Upright
17	18.32[b]	16.50[a]
19	12.09[b]	19.69[a]
27	24.84[a]	16.17[a]
LSD (p = 0.05)	6.33	5.26
CV	15.17	13.29
F-test		
Arrangement	NS	
Length	*	
Arrangement × length	***	

Mean values followed by the same letters within a column are not significantly different at p≤0.05 by the LSD test, *: p≤0.05, **: p≤0.01,***: p≤0.001, NS: Non-significant and CV: Coefficient of variation

Table 4: Mean total stem dry weight (g $plant^{-1}$) of chilli plant as affected by the arrangement and length of polybag with their interactions after 84 days of transplanting

Treatment	Total stem dry weight (g $plant^{-1}$)
Polybag arrangement	
Horizontal	27.26[a]
Upright	31.60[a]
LSD (p = 0.05)	5.99
Polybag length (cm)	
17	21.99[b]
19	28.65[b]
27	37.64[a]
LSD (p = 0.05)	7.34
F-test	
Arrangement	NS
Length	**
Arrangement × length	NS
CV	19.39

Mean values followed by the same letters within a column are not significantly different at p≤0.05 by the LSD test, *: p≤0.05, **: p≤0.01, ***: p≤0.001, NS: Non-significant and CV: Coefficient of variation

Table 5: Mean total root dry weight (g $plant^{-1}$) of chilli plant as affected by the arrangement and length of polybag with their interactions after 84 days of transplanting

	Polybag arrangement	
Polybag length (cm)	Horizontal	Upright
17	8.49[a]	7.43[a]
19	5.37[b]	8.17[a]
27	9.37[a]	7.51[a]
LSD (p = 0.05)	2.39	1.36
CV	13.62	7.79
F-test		
Arrangement	NS	
Length	**	
Arrangement × length	***	

Mean values followed by the same letters within a column are not significantly different at p≤0.05 by the LSD test, *: p≤0.05, **: p≤0.01,***: p≤0.001, NS: Non-significant and CV: Coefficient of variation

that the more room for the root to grow the higher will be the stem dry weight. Total stem dry weight showed no significant difference (p>0.05) in terms of polybag arrangement. However, the length of the polybag was highly significant (p≤0.01) whilst their interaction effects were not significantly different (p>0.05).

Total root dry weight: Chilli plants grown in a horizontal polybag of 17 and 27 cm in length had higher total root dry weight with the value of 8.49 and 9.37 g $plant^{-1}$, respectively than those grown in 19 cm polybag length (5.37 g $plant^{-1}$). On the other hand, total root dry weight did not show any differences when grown in upright polybags for the root did not fully occupy the space available since water availability was lower at the upper part than the lower part of the substrate. F-test analysis showed that the total root dry weight was not significantly (p>0.05) affected by polybag arrangement. Nevertheless, polybag length and the interaction effects were highly significant (p≤0.01) showed in Table 5.

Total plant dry weight: The total plant dry weight showed no significant (p>0.05) effect due to polybag arrangement. However, it was a highly significant (p≤0.01) effect due to polybag length and interaction effect. The total plant dry weight of chilli grown on horizontal and upright polybags was greater in the treatment of longer polybags (27 cm) than those grown on 17 cm in Fig. 4.

Root to shoot ratio: Polybags of 17 cm in length had the highest root to shoot ratio among the three lengths, showing a significant increase by 33.3% higher than those grown in polybags of 19 and 27 cm in Table 6.

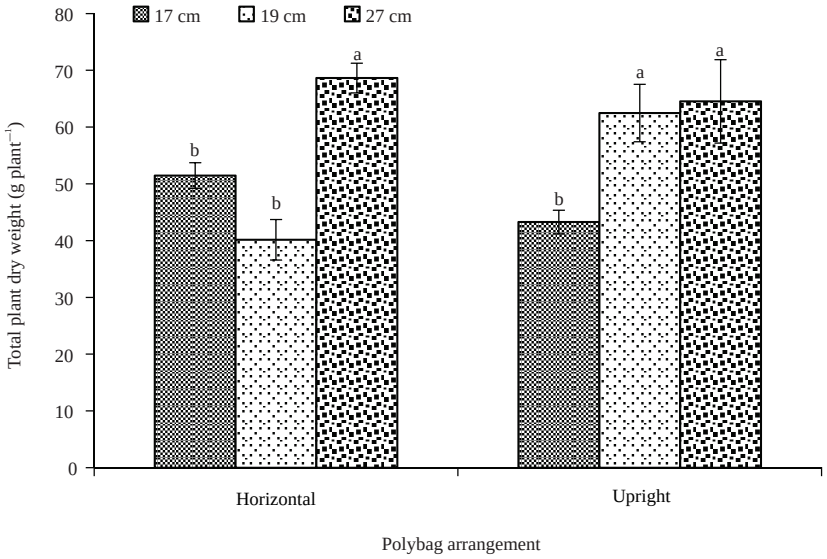

Fig. 4: Interaction effect of polybag arrangement and polybag length on total plant dry weight of chilli after 84 days of transplanting

Mean values followed by the same letters for each polybag arrangement were not significantly different at p = 0.05 level by the LSD test

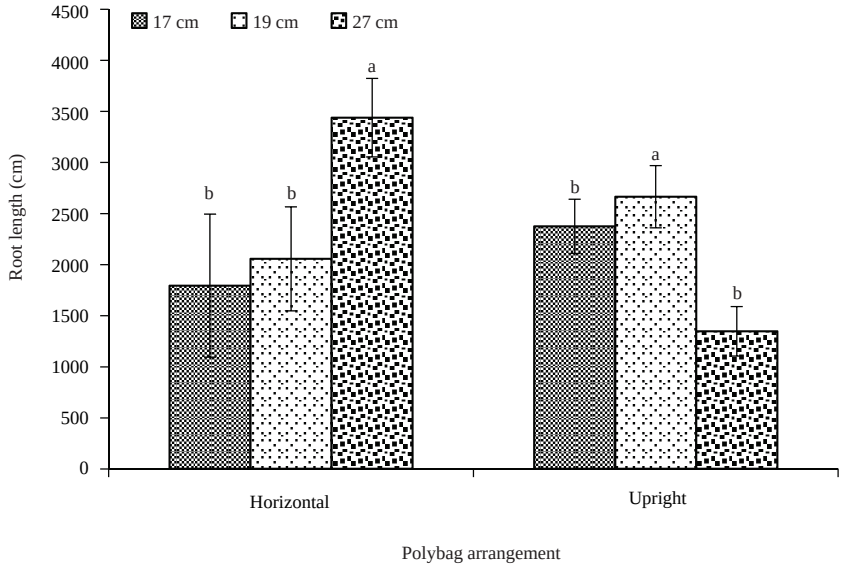

Fig. 5: Interaction effect of polybag arrangement and polybag length on total root length of chilli after 84 days of transplanting

Mean values followed by the same letters for each polybag arrangement were not significantly different at p = 0.05 level by the LSD test

F-test analysis showed that the root to shoot ratio showed no significant effect ($p>0.05$) due to polybag arrangement and interaction between the two factors. However, it was highly significant ($p\leq0.01$) due to polybag length. Root to shoot ratio was not affected by the arrangement of the polybag.

Root morphological parameters

Root length: The root length of chilli was not significantly affected ($p>0.05$) by polybag arrangement or polybag length. However, the interaction effect of polybag arrangement and polybag length was highly significant ($p\leq0.01$) in Fig. 5. The root length of chilli grown on horizontal polybags of 27 cm in length was significantly higher than those grown on 17 and 19 cm. In upright polybags, polybags of 19 cm in length showed the greatest root length compared to those of 27 cm.

Root surface area: The root surface area of chilli plants was not significantly affected ($p>0.05$) by polybag arrangement. However, polybag length and the interaction effect were highly significant ($p\leq0.01$) in Fig. 6. Chilli plants grown on

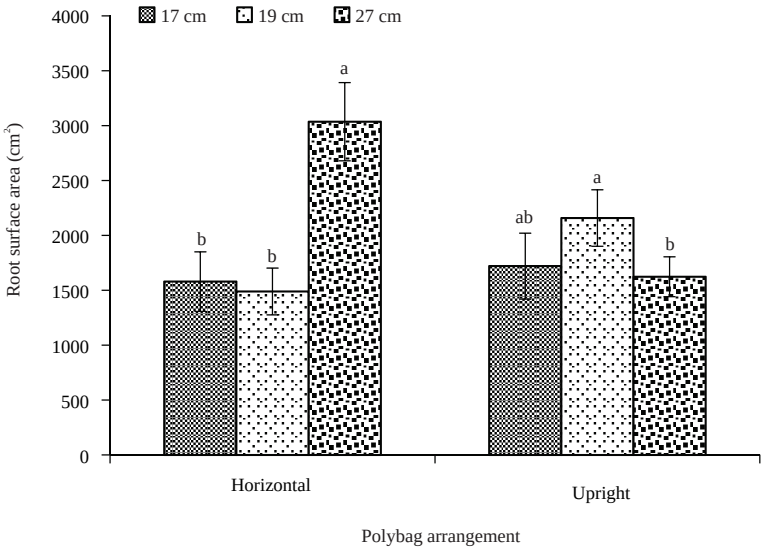

Fig. 6: Interaction effect of polybag arrangement and polybag length on total root surface area of chilli after 84 days of transplanting

Mean values followed by the same letters for each polybag arrangement were not significantly different at p = 0.05 level by the LSD test

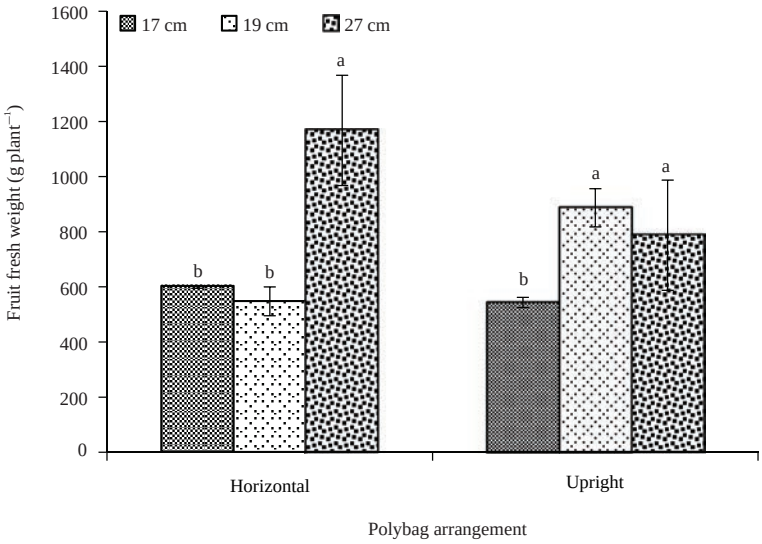

Fig. 7: Interaction effect of polybag arrangement and polybag length on fruit fresh weight of chilli after 84 days of transplanting

Mean values followed by the same letters for each polybag arrangement were not significantly different at p = 0.05 level by the LSD test

horizontal polybags of 27 cm in length have higher root surface area compared to 17 and 19 cm. However, upright polybag of 19 cm in length had the highest root surface area than plant those grown on 17 and 27 cm.

Yield production and fruit characteristics: Total fruit fresh weights of chilli were not significantly ($p>0.05$) influenced by the polybag arrangement. Meanwhile, the effect of polybag length and their interaction were highly significant ($p\leq0.01$) for the total fruit fresh weight in Fig. 7. The plant grown on horizontal polybags of 27 cm in length produced the highest total fruit fresh weight compared to 17 and 19 cm. However, the greatest total fruit fresh weight was obtained on upright polybags of 19 cm in length followed by 27 and 17 cm.

The total fruit number per plant of chilli was similar between horizontal (66) and upright (59) polybag. A polybag of 17 cm in length showed the lowest total fruit number per plant (44) which was 33.3% lower compared to a 19 cm polybag (66). Fruit length of chilli was highly significant ($p\leq0.01$) affected by polybag arrangement. Similarly, polybag

Table 6: Root to shoot ratio of chilli plant as affected by the arrangement and length of polybag with their interactions after 84 days of transplanting

Treatment	Root: shoot ratio
Polybag arrangement	
Horizontal	0.17[a]
Upright	0.16[a]
LSD (p = 0.05)	0.03
Polybag length (cm)	
17	0.20[a]
19	0.15[b]
27	0.15[b]
LSD (p = 0.05)	0.03
F-test	
Arrangement	NS
Length	**
Arrangement × length	NS
CV	14.72

Mean values followed by the same letters within a column are not significantly different at p≤0.05 by LSD test,*: p≤0.05, **: p≤0.01,***: p≤0.001, NS: Non-significant and CV: Coefficient of variation

Table 7: Mean fruit number and fruit characteristics of chilli plant as affected by the arrangement and length of polybag with their interactions after 84 days of transplanting

Treatment	Total fruit number per plant	Fruit length per plant (cm)	Fruit width per plant (cm)
Polybag arrangement			
Horizontal	66[a]	12.8[b]	1.65[a]
Upright	59[a]	15.1[a]	1.48[b]
LSD (p = 0.05)	10.59	0.79	0.15
Polybag length (cm)			
17	44[b]	13.6[b]	1.63[a]
19	66[a]	13.7[b]	1.53[a]
27	78[a]	14.7[a]	1.53[a]
LSD (p = 0.05)	12.97	0.98	0.18
F-test			
Arrangement	NS	***	*
Length	***	*	NS
Arrangement × length	NS	NS	NS
CV	16.10	5.45	8.97

Mean values followed by the same letters within a column are not significantly different at p≤0.05 by LSD test, *: p≤0.05, **: p≤0.01,***: p≤0.001, NS: Non-significant and CV: Coefficient of variation.

length showed a significant (p≤0.05) effect on the fruit length. However, there were no significant interaction effects in Table 7. Fruit of plant grown in horizontal polybag was shorter (12.8 cm) than in upright polybag (15.1 cm). The fruit length of chilli is greater in polybag length of 27 cm (14.7 cm) than those grown in 19 cm polybag length (13.7 cm). Polybag arrangement significantly affected (p≤0.05) the fruit width of chilli. But, there was no significant (p>0.05) effect of polybag length and their interaction on fruit width of chilli plants (Table 7). The plant grown in a horizontal polybag had greater fruit width (1.65 cm) than those in an upright polybag (1.48 cm). The fruit width per plant was ranged from 1.53-1.63 cm among the different polybag lengths. F-test analysis showed that the total fruit number of chilli was not significantly (p>0.05) affected by polybag arrangement and interaction of arrangement and polybag length. However, there was a highly significant (p≤0.01) effect between polybag lengths (Table 7).

DISCUSSION

Polybag arrangement and length influenced the growth and development of chilli plants grown in soilless culture. Chilli plants grown in restricted root space in a horizontal and upright polybag of 17 cm in length showed similar changes of plant growth and development as observed in other studies which are related to small container volume[13,33]. The morphological changes in this study include decreased plant height, stem diameter, total leaf area, leaves and root dry matter production. Besides, reducing container size in a horizontal and upright polybag of 17 cm in length affected root length and root surface area of chilli which may lead to limited nutrient availability. Luo *et al.*[34] and Hess and Kroon[35] found that varying container sizes affected the root architecture and nutrient acquisition. A small polybag implies a small quantity of substrate thereby reduced the availability of water and nutrients to the plants[36].

In this study, it was found that there was an accumulation of root mass at the bottom of the container that may cause by the gravitropism effect. High root density in small container size increased the overlapping zone and barriers to diffusion causing low nutrient acquisition and nutrient deficiency even though nitrogen supply was available in the soil or hydroponic solution[37]. A partial solution to the restricted supply of water and nutrient in small container sizes is through frequent supply through fertigation[38]. Accumulation of roots in small container size exposed the plant to oxygen deficiency due to the respiration of dense root mass and existence of a water layer at the bottom of the container[39]. Oxygen deficiency may partly cause inhibition of root and shoot growth of the plant in small container size[40,41].

With increasing container size in horizontal polybags of 27 cm in length, those measured parameters including stem diameter, leaves and root dry matter production were proportionally greater. Similarly, Graham and Wheeler[17] and Salisu *et al*.[10] found that growth and dry matter production increased proportionally with container size. Besides, plants grown in this polybag size developed greater root length and root surface area. The shallow root zone about 11 cm depth in the horizontal polybags of 27 cm in length probably allowed water and nutrient to be directly available within the root. A well-developed root system is important because it provides better uptake of water and nutrient followed by increased protein, hormones and other organic substances formation[42]. Tian *et al*.[43] has reported a similar result that larger containers produced greater root lengths of *Cyclocarya paliurus*. However, increasing the 22 cm depth of the container in the upright polybag of 27 cm in length with more volume of substrate did not translate into greater dry matter production. This was probably due to irrigation water did not directly available to the plant root since water moves laterally and deeply within the greater depth of this upright polybag. More energy is required by the roots for water uptake in greater substrate volume[44]. This showed that the shallow root zone of about 11 cm in depth is the suitable rooting size for better growth and development of chilli in soilless culture.

Container size was found to markedly affect the yield of chilli. Fruit fresh weight of the chilli plant was reduced when grown in a horizontal and upright polybag of 17 cm in length. Fruit fresh weight was found to be reduced by 32% when grown in a horizontal polybag of 17 cm in length as compared to the upright polybag of 19 cm in length as the control treatment. Similarly, Bouzo and Favaro[45] found a yield reduction of tomato grown in small containers due to the limited water and nutrient absorption by the roots[46]. Lower dry matter production and yield in small polybag size could be due to lower photosynthesis rate although the limited study has measured photosynthesis rate in plants subjected to varying container size[16].

Horizontal polybag of 27 cm in length had 32% greater fruit fresh weight of chilli was in line with the study conducted by Saito *et al*.[47] on the tomato of different pot sizes. Greater fruit fresh weight was more dependent on the increased number of fruit rather than the size of the fruit. The balanced growth of the roots, combined with the readily available water, air and nutrients contribute to the vigorous yield. Large container size allows root to be spread into the new area and developed larger nutrient pool and available water substrate can retained[48]. Besides, coconut coir dust and EFB compost mixture also had a higher ability to retain water and nutrient[46,49]. However, greater substrate use in an upright polybag of 27 cm in length showed no increment of yield compared with a horizontal polybag of 27 cm in length. In container culture, an equilibrium point was reached after irrigation and drainage that developed a water table[50] and to be absorbed in meaningful quantities, water must be in contact with the roots[27]. The water table in an upright polybag of 27 cm in length was at the bottom of the container and far from the active developing root zone which restricts water availability to the plant. Therefore, it was not a suitable container size for optimum substrate use in soilless culture.

Several studies to determine suitable container sizes for vegetable crops have been conducted. It is recommended to use a 5-7.5 L volume of substrate for high yield production of tomato[38,47]. Pot size of 52 L may not be enough for eggplant growth however 36 L was enough for okra[51]. Larger container size of 33 dm^3 produced a high fruit yield of sweet pepper when grown and fruits set for a long period[22]. However, for the past decade, very few studies had been conducted to determine suitable container dimensions for chilli with similar substrate volume. Hence, this study revealed that a horizontal polybag of 27 cm in length was suitable and optimum than an upright polybag of 19 cm in length for chilli in soilless culture.

The selection of polybag size is critically important to saving the cost of production in soilless culture and for efficient use of the substrate. The use of 17 cm polybag length with less substrate resulted in hampered yield because of root restriction while the highest substrate usage in an upright polybag of 27 cm in length did not produce greater yield compared to horizontal polybag of 27 cm in length. Therefore, it is recommended to use the horizontal polybag of 27 cm

in length which could be a possible alternative polybag dimension and size for the current commercial chilli cultivation in soilless culture. Since a small polybag can reduce the high cost of substrate and manpower, optimize water and fertilizer use and reduce the problem of substrate disposal, study on the yield improvement of plant in a horizontal polybag of 17 cm in length merit further investigation.

CONCLUSION

Plants grown in horizontal polybags of 17 cm in length had dense and compacted root systems and showed a reduction of growth, root length, dry matter production and fruit fresh weight which was associated with root restriction. Horizontal polybags of 27 cm in length are suitable for chilli in a soilless culture based on greater plant growth, root length and fruit fresh weight. The minimum substrate in a horizontal polybag of 17 cm in length with optimum fertilizer and water use can reduce the high cost of substrate, manpower and problem of substrate disposal however required more explanation on the aspect of plant physiological response.

SIGNIFICANCE STATEMENTS

This study discovers the suitable polybag dimension and size for efficient use of substrate without hampering the growth and yield of chilli in soilless culture. This study reveals the combined effects of polybag dimension and polybag length on plant growth and yield that can be beneficial for researchers in the area of horticulture, crop production and agronomy as well as farmers in managing the substrate volume for vegetable crops production in soilless culture. This study will help the researcher to uncover the critical areas of growth and yield reduction affected in small polybag sizes that many researchers were not able to explore. Thus, a new theory on the selection of polybag dimension and size for chilli in soilless culture for promoting economically feasible and practical soilless substrate management may be arrived at.

ACKNOWLEDGMENT

The authors acknowledge the support of the Ministry of Higher Education, Malaysia under the Malaysia Research University Network (MRUN) Grant (Vot Number: 5539120), entitled "Elucidating Human Exposure to Chemical through Food Chain" and Universiti Putra Malaysia for Graduate Research Fellowship for financial support of this project.

REFERENCES

1. Perucka, I. and M. Materska, 2007. Antioxidant vitamin contents of *Capsicum annuum* fruit extracts as affected by processing and varietal factors. Acta Sci. Pol. Technol. Aliment., 6: 67-74.
2. Olatunji, T.L. and A.J. Afolayan, 2018. The suitability of chili pepper (*Capsicum annuum* L.) for alleviating human micronutrient dietary deficiencies: A review. Food Sci. Nutr., 6: 2239-2251.
3. Awang, N.A., M.R. Ismail, D. Omar and M.R. Islam, 2015. Comparative study of the application of jasmonic acid and pesticide in chilli: Effects on physiological activities, yield and viruses control. Biosci. J., 31: 672-681.
4. Usman, M.G., M.Y. Rafii, M.R. Ismail, M.A. Malek and M.B. Latif, 2014. Heritability and genetic advance among chili pepper genotypes for heat tolerance and morphophysiological characteristics. Sci. World J., Vol. 2014. 10.1155/2014/308042.
5. Grafiadellis, I., K. Mattas, E. Maloupa, I. Tzouramani and K. Galanopoulos, 2000. An economic analysis of soilless culture in gerbera production. HortScience, 35: 300-303.
6. Nicola, S., J. Hoeberechts and E. Fontana, 2005. Comparison between traditional and soilless culture systems to produce rocket (*Eruca sativa*) with low nitrate content. Acta Hortic., 697: 549-555.
7. Nejad, A.R. and A. Ismaili, 2014. Changes in growth, essential oil yield and composition of geranium (*Pelargonium graveolens* L.) as affected by growing media. J. Sci. Food Agric., 94: 905-910.
8. Gallegos, J., J.E. Álvaro and M. Urrestarazu, 2020. Container design affects shoot and root growth of vegetable plant. HortScience, 55: 787-794.
9. Judd, L.A., B.E. Jackson and W.C. Fonteno, 2015. Advancements in root growth measurement technologies and observation capabilities for container-grown plants. Plants, 4: 369-392.
10. Salisu, M.A., Z. Sulaiman, M.Y. A. Samad and O.K. Kolapo, 2018. Effect of various types and size of container on growth and root morphology of rubber (*Hevea brasiliensis* Mull. Arg.). Int. J. Sci. Technol. Res., 7: 21-27.
11. Haldankar, P.M., Y.R. Parulekar, M.M. Kulkarni and K.E. Lawande, 2014. Effect of size of polybag on survival and growth of mango grafts. J. Plant Stud., Vol. 3. 10.5539/jps.v3n1p91.
12. Zakaria, N.I., M.R. Ismail, Y. Awang, P.E.M. Wahab and Z. Berahim, 2020. Effects of container sizes and nutrient solution concentrations on growth and yield of chilli. Asian J. Crop Sci., 12: 130-140.
13. Zakaria N.I., M.R. Ismail, Y. Awang, P.E.M. Wahab and Z. Berahim, 2020. Effect of root restriction on the growth, photosynthesis rate and source and sink relationship of chilli (C*apsicum annuum* L.) grown in soilless culture. Biomed Res. Int., 2020: 1-14.

14. Dodd, I.C., 2005. Root-to-shoot signalling: Assessing the roles of 'up' in the up and down world of long-distance signalling *In planta*. Plant Soil, 274: 251-270.
15. Tsakaldimi, M., T. Zagas, T. Tsitsoni and P. Ganatsas, 2005. Root morphology, stem growth and field performance of seedlings of two mediterranean evergreen oak species raised in different container types. Plant Soil, 278: 85-93.
16. Al-Debei, H.S. and S. Mugnai, 2011. Starch accumulation in the leaves of root-restricted pepper affects plant growth by a feedback-inhibition of the photosynthesis. Adv. Hortic. Sci., 25: 253-259.
17. Graham, T. and R. Wheeler, 2016. Root restriction: A tool for improving volume utilization efficiency in bioregenerative life-support systems. Life Sci. Space Res., 9: 62-68.
18. Boland, A.M., P.H. Jerie, P.D. Mitchell, I. Goodwin and D.J. Connor, 2000. Long-term effects of restricted root volume and regulated deficit irrigation on peach: I. Growth and mineral nutrition. J. Am. Soc. Hortic. Sci., 125: 135-142.
19. Yeh, D.M. and H.H. Chiang, 2001. Growth and flower initiation in hydrangea as affected by root restriction and defoliation. Sci. Hortic., 91: 123-132.
20. Taweesak, V., T.L. Abdullah, S.A. Hassan, N.H. Kamarulzaman and W.A.W. Yusoff, 2014. Growth and flowering responses of cut chrysanthemum grown under restricted root volume to irrigation frequency. Sci. World J., Vol. 2014. 10.1155/2014/254867.
21. Chirino, E., A. Vilagrosa, E.I. Hernández, A. Matos and V.R. Vallejo, 2008. Effects of a deep container on morpho-functional characteristics and root colonization in Q*uercus suber* L. seedlings for reforestation in mediterranean climate. For. Ecol. Manage., 256: 779-785.
22. Xu, G., S. Wolf and U. Kafkafi, 2001. Interactive effect of nutrient concentration and container volume on flowering, fruiting and nutrient uptake of sweet pepper. J. Plant Nutr., 24: 479-501.
23. Yong, J.W.H., D.S. Letham, S.C. Wong and G.D. Farquhar, 2010. Effects of root restriction on growth and associated cytokinin levels in cotton (*Gossypium hirsutum*). Funct. Plant Biol., 37: 974-984.
24. Byers, R.E., D.H. Carbaugh and L.D. Combs, 2004. Root restriction, an alternative to rootstocks, for control of flowering, fruiting, tree growth, yield efficiency and fruit quality of apple. J. Tree Fruit Prod., 3: 11-31.
25. Ayarna, A.W., S. Tsukagoshi and G.O. Nkansah, 2021. Effect of root restriction on the performance of three-truss cultivated tomato in the low-node pinching order at high-density cultivation system. Horticulture, Vol. 7. 10.3390/horticulturae7030060.
26. Oagile, O., P. Gabolemogwe, C. Matsuane and T. Mathowa, 2016. Effect of container size on the growth and development of tomato seedlings. Int. J. Curr. Microbiol. Appl. Sci., 5: 890-896.
27. Heller, H., A. Bar-Tal, S. Assouline, K. Narkis and S. Suryano *et al*., 2014. The effects of container geometry on water and heat regimes in soilless culture: Lettuce as a case study. Irrig. Sci., 33: 53-65.
28. Sharma, V.K. and A.K. Godara, 2017. Response in strawberry (Fragaria × ananassa duch. 'sweet charlie') growth to different substrates and containers under greenhouse. Int. J. Curr. Microbiol. Appl. Sci., 6: 2556-2568.
29. Walters, S.A., H.A. Riddle and M.E. Schmidt, 2005. Container cell volume and transplant age influences muskmelon development and yield. J. Veg. Sci., 11: 47-55.
30. Berahim, Z., S.S. Salamat, N.A. Razak, P.E.M. Wahab and M.R. Ismail, 2016. Efficiency of fertilizer formulation, stock solution volume and media on chili (*Capsicum annum* kulai F1). J. Plant Nutr., 39: 1570-1577.
31. Razak, A.A., M.R. Ismail, M.F. Karim, P.E.M. Wahab, S.N. Abdullah and H. Kausar, 2013. Changes in leaf gas exchange, biochemical properties, growth and yield of chilli grown under soilless culture subjected to deficit fertigation. Aust. J. Crop Sci., 7: 1582-1589.
32. SAS., 2004. SAS/INSIGHT 9.1 User`s Guide. Version 9.1. SAS Institute Inc., United States, ISBN-13: 978-1580256971, Pages: 824.
33. Ronchi, C.P., F.M. DaMatta, K.D. Batista, G.A.B.K. Moraes, M.E. Loureiro and C. Ducatti, 2006. Growth and photosynthetic down-regulation in *Coffea arabica* in response to restricted root volume. Funct. Plant Biol., 33: 1013-1023.
34. Luo, H.H., X.P. Tao, Y.Y. Hu, Y.L. Zhang and W.F. Zhang, 2015. Response of cotton root growth and yield to root restriction under various water and nitrogen regimes. J. Plant Nutr. Soil Sci., 178: 384-392.
35. Hess, L. and H. de Kroon, 2007. Effects of rooting volume and nutrient availability as an alternative explanation for root self/non-self discrimination. J. Ecol., 95: 241-251.
36. Poorter, H., J. Buhler, D. van Dusschoten, J. Climent and J.A. Postma, 2012. Pot size matters: A meta-analysis of the effects of rooting volume on plant growth. Funct. Plant Biol., 39: 839-850.
37. Tanyaradzwa, Z.L., M. Tuarira, M. Moses and T. Jefta, 2015. Effects of planting depth and variety on container produced potatoes. J. Global Innovations Agric. Social Sci., 3: 1-7.
38. de Matos Pires, R.C., P.R. Furlani, R.V. Ribeiro, D.B. Junior, E. Sakai, A.L. Lourenção and A.T. Neto, 2011. Irrigation frequency and substrate volume effects in the growth and yield of tomato plants under greenhouse conditions. Sci. Agri., 68: 400-405.
39. Raviv, M., J.H. Lieth, A. Bar-Tal and A. Silber, 2008. Growing Plants in Soilless Culture: Operational Conclusions. In: Growing Plants in Soilless Culture: Operational Conclusions, Raviv, M. and J.H. Lieth (Eds.)., Elsevier B.V., London, UK, pp: 545-571.

40. Yafuso, E.J. and P.R. Fisher, 2017. Oxygenation of irrigation water during propagation and container production of bedding plants. HortScience, 52: 1608-1614.
41. Shi, K., W.H. Hu, D.K. Dong, Y.H. Zhou and J.Q. Yu, 2007. Low O_2 supply is involved in the poor growth in root-restricted plants of tomato (*Lycopersicon esculentum* Mill.). Environ. Exp. Bot., 61: 181-189.
42. Wang, Y., K. Thorup-Kristensen, L.S. Jensen and J. Magid, 2016. Vigorous root growth is a better indicator of early nutrient uptake than root hair traits in spring wheat grown under low fertility. Front. Plant Sci., Vol. 7. 10.3389/fpls.2016.00865.
43. Tian, N., S. Fang, W. Yang, X. Shang and X. Fu, 2017. Influence of container type and growth medium on seedling growth and root morphology of *Cyclocarya paliurus* during nursery culture. Forests, Vol. 8. 10.3390/f8100387.
44. Ertek, A. and S. Bolat, 2016. Growth and yield of pepper (*Capsicum annuum* L.) under root zone restriction. Agric. Res. Technol.: Open Access J., Vol. 2. 10.19080/artoaj.2016.02.555599.
45. Bouzo, C.A. and J.C. Favaro, 2015. Container size effect on the plant production and precocity in tomato (*Solanum lycopersicum* L.). Bulg. J. Agric. Sci., 21: 325-332.
46. Xiong, J., Y. Tian, J. Wang, W. Liu and Q. Chen, 2017. Comparison of coconut coir, rockwool and peat cultivations for tomato production: Nutrient balance, plant growth and fruit quality. Front. Plant Sci., Vol. 8. 10.3389/fpls.2017.01327.
47. Saito, T., N. Fukuda, T. Iikubo, S. Inai, T. Fujii, C. Konishi and H. Ezura, 2008. Effects of root-volume restriction and salinity on the fruit yield and quality of processing tomato. J. Jpn. Soc. Hortic. Sci., 77: 165-172.
48. Chong, C.W. and L.M. Chu, 2007. Growth of vetivergrass for cutslope landscaping: Effects of container size and watering rate. Urban For. Urban Greening, 6: 135-141.
49. Barrett, G.E., P.D. Alexander, J.S. Robinson and N.C. Bragg, 2016. Achieving environmentally sustainable growing media for soilless plant cultivation systems-A review. Sci. Hortic., 212: 220-234.
50. Navindra, B., D. Gianjeet and G.S. Joyce, 2011. Influence of soilless growing media, pot size and sieved media on the production of *Hibiscus sabdariffa* L. seedlings. Aust. J. Agric. Eng., 2: 147-154.
51. Kurunç, A. and A. Ünlükara, 2009. Growth, yield and water use of okra (*Abelmoschus esculentus*) and eggplant (*Solanum melongena*) as influenced by rooting volume. N. Z. J. Crop Hortic. Sci., 37: 201-210.