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Short title: Plant growth response to greenhouse microclimate

Differential response of plant species to greenhouse microclimate created by design technology and ambient conditions

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LIST OF SYMBOLS

HTG, high technology greenhouse

LTG, low technology greenhouse

MTG, medium technology greenhouse

PAR, photosynthetic active radiation

w/w, weight by weight

ABSTRACT

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Food insecurity amongst First Nation populations living on reserves across Canada is purported to be about 27% of the national average. However, crop production is limited by factors such as climate and soil conditions. A two-year study was carried out to assess production of collard (*Brassica oleracea* L. var. acephala 'Champion'), carrot (*Daucus carota* L. 'Adelaide') and tomato (*Lycopersicon esculenta* L. 'Beefsteak') in three separate greenhouses with contrasting design technology. The greenhouses were categorized as: i. high technology (HTG); ii. medium technology (MTG); and iii. low technology (LTG) greenhouses. The MTG and the LTG were basic facilities but the MTG had in-floor heating. The HTG was fully equipped with climate control systems. Mean monthly air temperature was stable at 23±1^{o}C in the HTG but fluctuated in the MTG and the LTG. Air temperature and water loss were highest in the MTG. Vapor pressure deficit and daily light integral followed the trends, LTG>MTG>HTG>ambient; and ambient>MTG>HTG>LTG, respectively. Growth rate of collard plants was equally high in the MTG and the LTG as compared to the HTG. Comparatively, growth and yield of carrot plants were highest in the HTG. Conditions in the HTG and the MTG favored growth and yield of the tomato plants. Thus, the different greenhouse design technology created different microclimates, which differentially affected growth and yield performances of the different vegetable species. Future work should consider economic benefits of greenhouse technology and production management for northern and remote communities.

Keywords: greenhouse design, greenhouse microclimate, controlled-environment production

INTRODUCTION

Food and nutrition insecurity is a serious public health problem worldwide. This can negatively impact health and wellbeing (i.e. physical, psychological and social) of people, and put considerable budgetary constraint on healthcare systems. Canada is not immune from these constraints especially, certain socioeconomic subgroups within urban areas and in northern and remote regions. More than 12% of Canadians are faced with various forms of food insecurity related problems (CCA 2014). Food insecurity is a serious problem in northern and remote First Nation communities. For instance, it was reported that food insecurity experienced by First Nation populations living on reserves across Canada is twice the national average, which stands at 27%. This has led to an increase in food-related health issues (Butler Walter, 2009), which was confirmed in a study on traditional and market food accessibility in Canadian Arctic regions by Lambden et al. (2006). The cost of food is also generally high compared to communities outside northern communities and First Nation reserves in Canada. About 12.5% of the global population do not have enough food for an active and healthy life as expected and therefore, the Food and Agriculture Organization of the United Nations estimated that food production must increase by 60% by 2050 to meet this challenge. The pursuit for sustainable food and nutrition security solutions are constrained by factors such as "limited access to clean water, finite land for agriculture production, climate change, and evolving diets that demand more high-value food products" (APLU 2017).

The effect of food and nutrition insecurity on chronic and specific health conditions such as obesity, abnormal development in children, diabetes and cardiovascular diseases in these regions are universally known and well documented. It is therefore suggested that indigenous food and nutrition security can be improved through the understanding of traditions around food, and the adoption of suitable food production systems such as the use of an appropriately designed and cost-effective greenhouse technology for controlled-environment production. Worldwide, the greenhouse vegetable industry is fast growing with an estimated 489 214 ha of production area (Hickman, 2017). As such, it is acknowledged that greenhouse technology can be used to the benefit of remote and northern communities through the establishment of a secure food supply chain.

The potential growth and yield of plants are determined by genotype, climate, edaphic factors, cultural practices and technological input (Katsoulas and Kittas 2008; Pregitzer et al. 2013; Li and Yang 2015). As such, the appropriateness of technology and stability of controlled-environment conditions are critical to greenhouse crop production. The extent of technological input is dependent on prevailing climatic conditions, the purpose and use of the facility and the socioeconomic environment (Kittas et al. 2013). Greenhouse technological input can vary from basic technology to a more expensive and sophisticated technology depending on scale of production, choice of structure, and climate control and monitoring systems. These can affect the climate i.e. temperature, relative humidity and light and energy-use efficiency by plants (Katsoulas and Kittas 2008; Li and Yang 2015), generally termed as microclimate inside the greenhouse. Natural light transmission and radiant energy inflow into a greenhouse can be influenced by structural design and greenhouse glazing material (Hemming et al. 2007). For instance, polyvinyl fluoride glazing diffuses incoming light, which then becomes more available to plants as compared to direct light penetration through a clear polyethylene glazing material (Mercado et al. 2009; Li et al. 2014). This suggested that light distribution throughout a plant canopy under a polyvinyl fluoride glazed greenhouse can be higher than that under clear glass or polyethylene glazed greenhouse.

The responses of plants to the environmental parameters that vary, in concert or independently, to establish microclimates within a greenhouse, such as air temperature, light energy and relative humidity are well researched (Challa and Schapendonk 1984; Tian et al. 2014). These climatic factors can vary widely across seasons and ambient conditions. To minimize external influence, control systems such as automatic regulation of greenhouse environment (Jiaqiang et al. 2013), robust control of temperature and humidity (Bennis et al. 2008), predictive models (Blasco et al. 2007) or fuzzy logic (Hahn 2011) can be employed. However, the acquisition and operation of such technologies are expensive. As such, researchers and industry are currently seeking more sustainable design technologies and suitable plant genotypes to reduce energy dependence without compromising potential yield and quality.

The quest for low input sustainable greenhouse technology, as recommended by Katsoulas and Kittas (2008), particularly for remote and northern communities in Canada is timely. It was therefore, hypothesized that greenhouse design technology will interact with ambient conditions to create microclimates that will significantly affect plant growth and yield. The key goal was to evaluate potential greenhouse designs for remote and northern communities in Canada. The objective of the present study was to assess the differential effects of variations in greenhouse design technology on microclimate, plant growth and yield of three different vegetable plant species, namely; leafy (collard), root (carrot) and fruit (tomato) vegetable plants.

MATERIALS AND METHODS

LOCATION

A 2-year greenhouse study was performed at Assiniboine Community College, Brandon, Manitoba (49^{o}52’7” north, 99^{o}56’14” west) in 2013 and 2014. The 10-year average climate normals for Brandon as follows: mean temperature varies from -22^{o}C to 25^{o}C; frost-free days is between 105 and 115; growing degree days is 1539; daylight hours went up from 11 hrs 52 mins in March, 14hrs 24 mins in April, 15 hrs 25 mins in May, 16 hrs 20 mins in June, and 14 hrs 26 mins in July and August; and growing season precipitation is 373 mm (source: Environmental Canada Weather Station, Brandon Airport).

GREENHOUSE DESIGN TECHNOLOGY

The present study evaluated potential greenhouse design technological systems for remote and northern communities in Canada. The growth performances of three different vegetable species (i.e. collard, carrot and tomato) were compared in three physically attached but separate greenhouse sections with different design technologies. Each of the three crop species was used in a single-factor independent experiment. The treatments were: i. high technology greenhouse (HTG) – standard A-frame greenhouse features (triangular, cross-rafters with a peak) and better control of climate due to supplemental heating and lighting (mix of 400 W metal halide lamps and 400 W high sodium pressure lamps in alternate rows); ii. medium technology greenhouse (MTG) – half-dome structure with passive solar system in addition to in-floor heating, and consisted of basic features but warmer due to better heat sinks; and iii. low technology greenhouse (LTG) – half-dome structure with passive solar system, polyvinyl fluoride glazing material with basic features and lowest mean daily temperatures. The passive solar greenhouses, MTG and LTG, were designed to collect, store and distribute solar energy in the form of heat in the winter and dissipate heat in the summer. The classification of the greenhouse design technology was based on existing greenhouse infrastructure and the level of technology in remote and northern communities in Canada. Details of the design features of each of the greenhouse are described in Table 1. A sketch is also provided in Fig. 1 to show the structural differences and the arrangement of the different greenhouses.

The gravel and concrete slab floor, the south-facing black metal-wall and the water-filled polyvinyl chloride tubes attached to the black wall in the LTG served as passive heat sinks that enabled storage and exchange of excessive heat energy with the air inside the greenhouse. The MTG was an improvement on the LTG with the replacement of the gravel and concrete slab floor with heating tubes embedded in a concrete floor for in-floor heating (Table 1 and Fig. 1). Solar tubes supplied the heat for the in-floor heating through active circulation of heated glycol:water mix of 30%:70% by volume. The LTG and the MTG each had small backup propane powered unit heater and a small window for natural ventilation. The HTG on the other hand, was designed to meet industry standard with relatively high technological input and glazed with double-layer semi-rigid polycarbonate (Table 1). Unlike the LTG and MTG, the environmental variables in the HTG was fully controlled.

GREENHOUSE TEMPERATURE SETTING

The greenhouse environment was controlled by an Argus Titan system version 718 (Argus Control Systems Limited, Surrey, British Columbia, Canada). The temperature profile for all the greenhouses was set at 25^{o}C (day) and 20^{o}C (night) from March to April and 22^{o}C (day) and 18^{o}C (night) from May to August in accordance with the ambient conditions and requirement for crop growth.

SUPPLIES

Seeds of collard (*Brassica oleracea* L. var. acephala 'Champion') and carrot (*Daucus carota* L. 'Adelaide') were obtained from Bejo Zaden b.v., The Netherlands. Seeds of tomato (*Lycopersicon esculenta* L. 'Beefsteak'), two different soluble fertilizers of nitrogen (N), phosphorus (P) and potassium (K) i.e. N_{20}-P_{20}-K_{20} and N_{10}-P_{52}-K_{10} (Master Plant-Prod Inc., Brampton ON., Canada) and organic garden lime (The Espoma Company, Millville, NJ, USA) were purchased from a local retailer. Pro-mix BX™ soilless potting medium (Premier Horticulture Inc., Quakertown, PA) was purchased from a local retailer. A commercial vermicompost producer (Arnold Gourmet Food Farm, Garson, Manitoba) donated 60 kg of vermicompost for the study.

SEEDING AND TRANSPLANTING

Seeds of collard 'Champion' and tomato 'Beefsteak' were sown separately in a 72-cell tray filled with Pro-mix BX™ soilless potting medium in March of each year. After germination, the tomato and the collard seedlings were allowed to grow for five and three more weeks respectively, before transplanting. Seedlings were watered as required without the application of fertilizer. All plants were treated similarly in both years. Seedlings of the collard and the tomato were transplanted into 15.2-cm and 30.4-cm diameter plastic pots filled with approximately 450 g and 1 kg of moistened Pro-mix BX™ soilless medium, respectively. Each pot was planted with two seedlings, and then thinned to one after two weeks of plant establishment.

Seeds of carrot 'Adelaide' (baby type) were directly sown into 15.2-cm diameter pots filled with approximately 700 g of the moistened Pro-mix BX™ soilless medium in March 2013 and April 2014. Initially, each pot had 10 seedlings which was later thinned to seven plants at approximately 3-cm spacing after two weeks of germination. All the plants (tomato, collard and carrots) received vermicompost, which was incorporated into the growing medium at a ratio of 5:1 Pro-mix BX™:vermicompost by weight prior to transplanting of seedlings or sowing of seeds. Plants were watered as required. The N_{20}-P_{20}-K_{20} fertilizer was supplied to plants every three weeks at a rate of 1.16 g pot^{-1} to the collard and carrots plants, and 2.32 g pot^{-1} to the tomato plants. The tomato plants received an additional 1.16 g N_{10}-P_{52}-K_{10} pot^{-1} at six weeks after transplanting to boost fruit production. There was a wide spread of blossom-end rot on the tomato fruits at 12 weeks after transplanting in all the greenhouses in both years, which was remedied by the application of 20 g calcium oxide (organic garden lime) plant^{-1}. Final harvests were done at 10 weeks after transplanting of collard ‘Champion’, 12 weeks after sowing of carrot ‘Adelaide’ and 16 weeks after transplanting of tomato ‘Beefsteak’.

WATER LOSS

Water loss by evaporation and evapotranspiration in a 10-day period was determined in each greenhouse. Five extra pots of diameter 15.2 cm were filled with mixture of moistened Pro-mix BX™ soilless medium and vermicompost as previously described. These pots were randomly placed on the benches among the planted-pots in the HTG, the MTG and the LTG. All the planted- and unplanted-pots were treated similarly. Water loss by evaporation was estimated by the difference in unplanted pot weight. Water loss by evapotranspiration was estimated by recording the daily changes in weight of the potted collard plants before and after watering. Total plant fresh weight in each greenhouse was determined by destructive sampling of three plants per treatment every four days and subtracted from the total pot weight during the estimation of water loss to account for the increase in pot weight as the collard plant grew.

PLANT GROWTH

Growth rates for collard and carrot plants were estimated by leaf elongation rates. The youngest leaves were tagged on each potted plant and the elongation of the leaves were measured at 4-day interval for 36 days. At final harvest, the number of edible collard leaves were recorded. The width of the collard leaf was measured from the middle section across the leaf blade; and the leaf length was measured from the tip of the leaf blade to the end of the petiole. At final harvest, fresh weight yield per pot of the collard greens, carrot roots and tomato fruits were recorded using a Scout-Pro balance (model: SPE 123; Ohaus Corp., Parsippany, NJ, USA). The size of the carrot roots and the tomato fruits were classified into three categories based on marketable size as: <10 mm, 10 to 15 mm and >15 mm for the carrot roots; and <35 mm, 35 to 65 mm and >65 mm for the tomato fruits using a pair of electronic caliper (model 58-6800-4; Mastercraft Tools, Johannesburg, South Africa). Size measurements were made from the crown and mid-section of the carrot root and tomato fruit, respectively. Samples of the harvested produce of each crop species for each treatment (greenhouse technology) were chopped into pieces of approximately 5-mm thick prior to drying in a preheated (70^{o}C) Garland static-bed oven-dryer (model: NSF D042302; Garland Canada, Mississauga, ON, Canada) to constant weights to determine percentage dry-matter content: [= (dry weight/fresh weight)*100]. Samples of the carrot roots (50 g) and the tomato fruits (100 g) were blended in deionized water (1:3 w/w) and the slurries were strained in cheese cloth, and the total soluble solids contents were recorded using Atago digital refractometer (model: PAL-1; Atago Co. Ltd., Bellevue, WA, USA).

EXPERIMENTAL DESIGN AND DATA ANALYSES

Replication of greenhouse structural treatments is impractical due to expense. Experimental design, data analysis and data interpretation techniques to deal with realities of controlled environment research were described by Hurlbert (1984), Schank and Kohnle (2009) and Millar and Anderson (2004). These authors recommended techniques for minimizing lack of independence, analyzing data and identifying limitations of using pseudoreplications. Pseudoreplication, a term coined by (Hurlbert 1984), refers to “the use of inferential statistics to test for treatment effects with data from experiments where either treatments are not replicated (though samples may be) or replicates are not statistically independent”. In the present study, the HTG, MTG and LTG treatments were not adequately replicated in space and time. There were 30 samples (i.e. individual potted vegetable plant species) that were randomly interspersed on benches in each greenhouse as described for pseudoreplication (Schank and Kohnle 2009). The pots were re-arranged weekly on the benches to offset any unpredictable occurrence due to variations in environment. Data for daily light integral (i.e. daily photosynthetic active radiation integral), air temperatures and vapor pressure deficit were retrieved from the Argus Titan version 718 software for comparison. Data were subjected to independent 2-sample t-test at $\alpha=0.05$ as described for this type of pseudoreplication by Millar and Anderson (2004) using Minitab ver. 17 (Minitab Inc., State College, PA, USA). Graphs were plotted using Microsoft Excel. Data presented were the averages for the 2-year study since the data did not show significant variations between the two years i.e. $F = s_1^2/s_2^2 \leq 1.12$ for collard, ≤ 1.05 for carrot and ≤ 1.4 for tomato at $\alpha=0.05$; where s_1^2 and s_2^2 are mean yield variances for years 2013 and 2014, respectively.

RESULTS AND DISCUSSION

The differences in design technology created varied microclimates (Fig. 2A-C) that had differential impact on the different vegetable plant species as previously reported (Kont et al. 2003; Katsoulas and Kittas 2008; Li and Yang 2015). The mean monthly ambient temperature i.e. temperature outside of the greenhouse steadily increased from -7^{o}C in March to approximately 21^{o}C in July (Fig. 2A). The trend in the mean monthly ambient temperature was typical for the Prairie regions of Canada. The mean monthly air temperature in the HTG was generally maintained at 23±1^{o}C throughout the study period, which was close to the set daily temperature for all the three greenhouses. The stable temperature in HTG can be ascribed to the well-equipped natural and artificial heating and cooling systems, and the protection offered by the semi-rigid plastic glazing material. In March, the mean monthly air temperature in the LTG was lower but rose gradually to approximately 27^{o}C in July as the ambient temperature increased (Fig. 2A). The MTG was consistently warmer than the HTG or the LTG. The increase in air temperature in the MTG from 24^{o}C in March to approximately 29^{o}C in July was possibly due to the heat-sink strengths of the concrete floor, the black wall and the in-floor heating system. The observed changes in the mean monthly air temperatures in the LTG and the MTG were positively associated with the mean monthly ambient temperature, as suggested by the significantly ($P<0.05$) high positive coefficient of correlation (r) of 0.90. Maintaining the temperature set point in the LTG and the MTG within the same tolerances as the HTG was not possible throughout the entire course of the study. The relative air humidity (%RH) varied between greenhouse systems as a function of mean temperature within each greenhouse (data not presented). The differential effects of air temperature and relative humidity were demonstrated by the vapor pressure deficits (VPD) in Fig. 2B. The trend in VPD was LTG>MTG>HTG. The low mean VPDs can be ascribed to high humidity and low temperature conditions. Plants responses to these differences in environmental conditions may differ as the phenological response to variations in temperature is specific to genotype (Hatfield et al. 2011). These can also affect rhizosphere activities and root physiological processes (Tian et al. 2014) and ultimately, crop development and yield.

Ambient (sunlight) daily light integral (DLI) increased from March to July as the season changes but reduced in August (Fig. 2C) due to shortening of day length. Similar pattern was found for the greenhouse DLI, which refers to photosynthetic active radiation inside the greenhouses with wavelengths between 400 and 700 nm. Comparatively, the MTG recorded the highest DLI followed by the HTG and then the LTG. The high DLI in the MTG can be attributed to the reflected light from the concrete floor as compared to the interspaced gravel floor in the LTG (Table 1 and Fig. 1) since both have the same glazing and pitch. Possibly, the gravel floor absorbed some of the diffused light and/or reflected the light at wider obtuse angles and was not accessible to the plants. Diffused light into crop canopy is beneficial as it improves spatial light distribution in the crop canopy to enhance interception and ultimately, photosynthesis (Hemming et al. 2007; Li and Yang 2015). The light in the HTG was supplemented when needed and the DLI increased just slightly due to upsurge in solar radiation in July. As a result, high positive correlations were found between the ambient DLI and the DLIs for the MTG (r=0.84) and the LTG (r=0.91), but not the DLI for the HTG (r=0.79; P>0.05). It was established that the trophic limit i.e. the lowest limit of DLI below which most horticultural crops cannot survive to achieve their potential growth is about 97.2 W m^{-2} (FAO 1990). The DLI in all the greenhouses exceeded this critical trophic limit but in varied amounts, which differentially affected the three vegetable crop species.

Water loss by evaporation per unit time from the surface and pores of the Pro-mix BX™ soilless medium gradually increased with time (Fig. 3A). Evaporation from the LTG and the MTG showed similar trend and were progressively higher than that of the HTG. Similarly, cumulative water loss by evapotranspiration per unit time was less in the HTG as compared to the MTG and the LTG (Fig. 3B). The driving force for the water loss as depicted in Fig. 3A-B was the difference in vapor pressure deficit as determined by %RH and air temperature between leaf tissues and atmospheric air (Kont et al. 2007; Lihavainen et al. 2016).

The growth rates of collard 'Champion' and carrot 'Adelaide' were estimated by rates of leaf elongation (Fig. 4A-B). Comparatively, the rates of growth of collard plants were similar in all the greenhouse treatments until after day 10 when there was steady decline in growth rate in the HTG (Fig. 4A). However, the growth rate of carrot plants in the HTG was higher than those for plants in the other two greenhouses until it flattened off from day 15 (Fig. 4B). The growth rates of the collard and the carrot plants in the LTG were similar to their counterpart in the MTG although there was a short window of slower growth of the carrot plants between days 5 and 15. The carrot plants continued their growth trend in the MTG whereas growth of their counterparts in the HTG and in the LTG seemed to have terminated after days 15 and 25, respectively. The continued growth in the MTG delayed the maturation of the carrot roots. Thus, the growth of the different crop species were differentially affected by the variations in microclimates created in the different greenhouses as previously reported (Mercado et al. 2009; Pregitzer et al. 2013; Li et al. 2014; Lihavainen et al. 2016).

The leaf yield components were fairly similar among the collard plants in the different greenhouses; however, the mean number of leaves increased in the LTG (Fig. 5A). On the average, the mean diameter of carrot roots harvested in the HTG was the highest (Fig. 5B). Approximately 60% of carrots in the HTG had >15 mm root diameter as compared to 3% of their counterparts in the MTG and the LTG. Majority of the carrot roots harvested in the HTG and the LTG were <10 mm diameter. Generally, most of the carrot roots had diameters between 10 and 15 mm. The diameter of over 80% of the tomato fruits ranged between 35 and 65 mm (Fig. 5C). The mean fresh weight yield and percentage dry matter contents of the three different crop species were greatly impacted by the variations in conditions of the growth environment due to differences in greenhouse design technology (Fig. 6A-B). The mean fresh weight yields of collard plants in the HTG and the LTG were comparable, and were >28% higher than their counterparts in the MTG. Both the fresh weight yield (Fig. 6A) and the percentage dry-matter content (Fig. 6B) of carrot roots were increased by the HTG followed by the LTG. The high temperature, DLI and VPD conditions in the MTG favored growth and fruit yield of tomato ‘Beefsteak’, a warm season crop (Fig. 6A). The percentage dry-matter content of tomato fruits were not affected by the type of greenhouse.

The application of these technologies will have to be assess *vis á vis* understanding of traditions around food, social perceptions on food and nutrition security and economic analysis of greenhouse technology. The findings in the present study suggested an alternative way of pursuing sustainable food and nutrition security solutions and minimizing constraints due to limited access to finite land for food production and evolving diets, and the effect of climate change on food production. The findings also demonstrated the possibility of adoption of an appropriately designed and cost-effective greenhouse technology for controlled-environment production. Based on the findings of the study, MTG seemed to be an appropriate technology for Canadian northern and remote communities. Comparatively, MTG does not require high technical and external energy inputs to operate as compared to HTG. Inhabitants and governments in such communities recognize the dearth of food and nutrition security in their communities and as such, training and encouragement must be provided for adoption.

In conclusion, the responses of the different species of vegetable plants; namely, collard 'Champion', carrot 'Adelaide' and tomato 'Beefsteak' to variations in greenhouse microclimate created by differences design technology were demonstrated. The preliminary study suggested that structural features and design technology in addition to source of energy input as well as outside (ambient) conditions can determine climatic conditions in the greenhouse. These climatic conditions can influence the growth and development of plants differently in accordance with the genotypic characteristics of the plant. It was established that the medium technology greenhouse (MTG) consisting of a simple greenhouse design and minimum input with basic energy efficient systems can potentially be an appropriate system for sustainable food production in remote and northern communities in Canada and elsewhere. However, the production system need to be planned so that cool and warm season crops are grown at the appropriate times to avoid temperature stress and unfavorable vapor pressure deficit conditions. It can be suggested from the results that MTG can be used for warm season crops in summer months and cool season crops in the other seasons. However, HTG can be used for both warm and cool season crops throughout the year. Future work will be required to determine economic benefits of the different greenhouse design technologies.

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Figure Captions

Figure 1. A sketch of the layout, structural features and design of the high (HTG), medium (MTG) and low (LTG) technology sustainable greenhouses at Assiniboine Community College, Brandon, Manitoba.

Figure 2. Mean monthly temperature (A), vapor pressure deficit (B) and daily light integral (C) outside (ambient) and inside the high (HTG), medium (MTG) and low (LTG) technology greenhouses. Error bars are ± standard error of the mean estimate.

Figure 3. Evaporation (A) and evapotranspiration (B) from the high (HTG), medium (MTG) and low (LTG) technology greenhouses. Error bars are ± standard error of the mean estimate.

Figure 4. Cumulative leaf elongation of collard ‘Champion’ (A) and carrot ‘Adelaide’ (B) plants grown in the high (HTG), medium (MTG) and low (LTG) technology greenhouses. Error bars are ± standard error of the mean estimate.

Figure 5. Yield components of collard ‘Champion’ (A), carrot ‘Adelaide’ (B) and tomato ‘Beefsteak’ (C) plants grown in the high (HTG), medium (MTG) and low (LTG) technology greenhouses. Error bars are ± standard error of the mean estimate.

Figure 6. Fresh weight yield (A) and dry-matter content (B) of collard ‘Champion’, carrot ‘Adelaide’ and tomato ‘Beefsteak’ plants grown in the high (HTG), medium (MTG) and low (LTG) technology greenhouses. Error bars are ± standard error of the mean estimate.

Table 1. Design, dimension and technological input levels of the high (HTG), the low (LTG) and the medium (MTG) technology greenhouses.

Greenhouse features	HTG	MTG	LTG
Structure	A-frame, no curtain wall, gravel and concrete slab floor	Half-dome, lean-to, wood and dry-wall curtain wall, black metal wall, complete concrete floor	Half-dome, lean-to, wood and dry-wall curtain wall, black metal wall, gravel and concrete slab floor
Size	Floor area: 120.8 m^2 Volume: 616.6 m^3	Floor area: 45.8 m^2 Volume: 178.0 m^3	Floor area: 57.2 m^2 Volume: 231.5 m^3
Glazing material	6-mm twin polycarbonate Macrolux wall of 0.80 solar radiation transmissivity	23-mm double-layer polyvinyl fluoride (HiQual Engineering Ltd.) 0.80 solar radiation transmissivity (NovaSheild II^{TM} membrane fabrics with Armorkote^{TM})	23-mm double-layer polyvinyl fluoride (HiQual Engineering Ltd.) 0.80 solar radiation transmissivity (NovaSheild II^{TM} membrane fabrics with Armorkote^{TM})
Heating (source: solar, glycol/water mix (30%:70% w/w) with propane tank as backup	Three unit heaters, thermal screen, heat sinks: gravel floor, concrete slabs and water tanks	One unit heater, radiant in-floor heating, passive solar heat sinks: black wall and concrete floor	One unit heater, passive solar heat sinks: black wall, polyvinyl chloride water tubes, gravel and concrete slabs
Ventilation	Horizontal air flow, active convection tube, retractable roof	Small window at end (passive)	Small window at end (passive)
Supplemental lighting	High pressure sodium and metal halides lamps	None	None

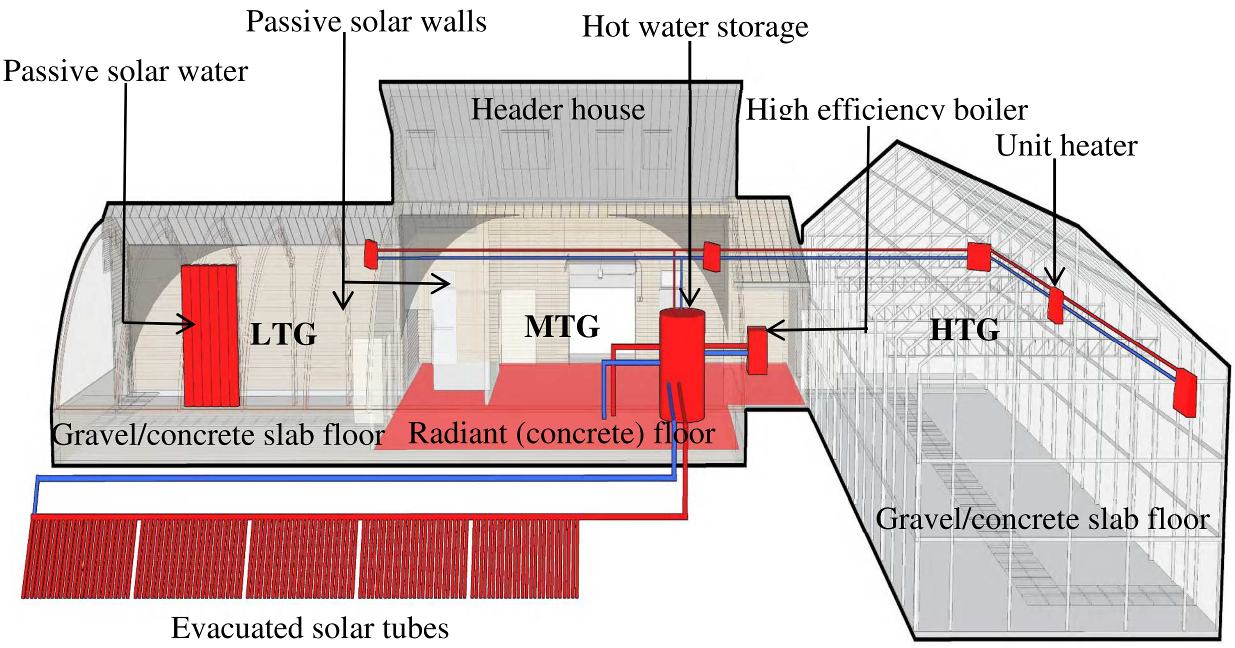
Passive solar walls
Hot water storage
Passive solar water
Header house
High efficiency boiler
Unit heater
LTG
MTG
HTG
Gravel/concrete slab floor
Radiant (concrete) floor
Gravel/concrete slab floor
Evacuated solar tubes

Fig. 1

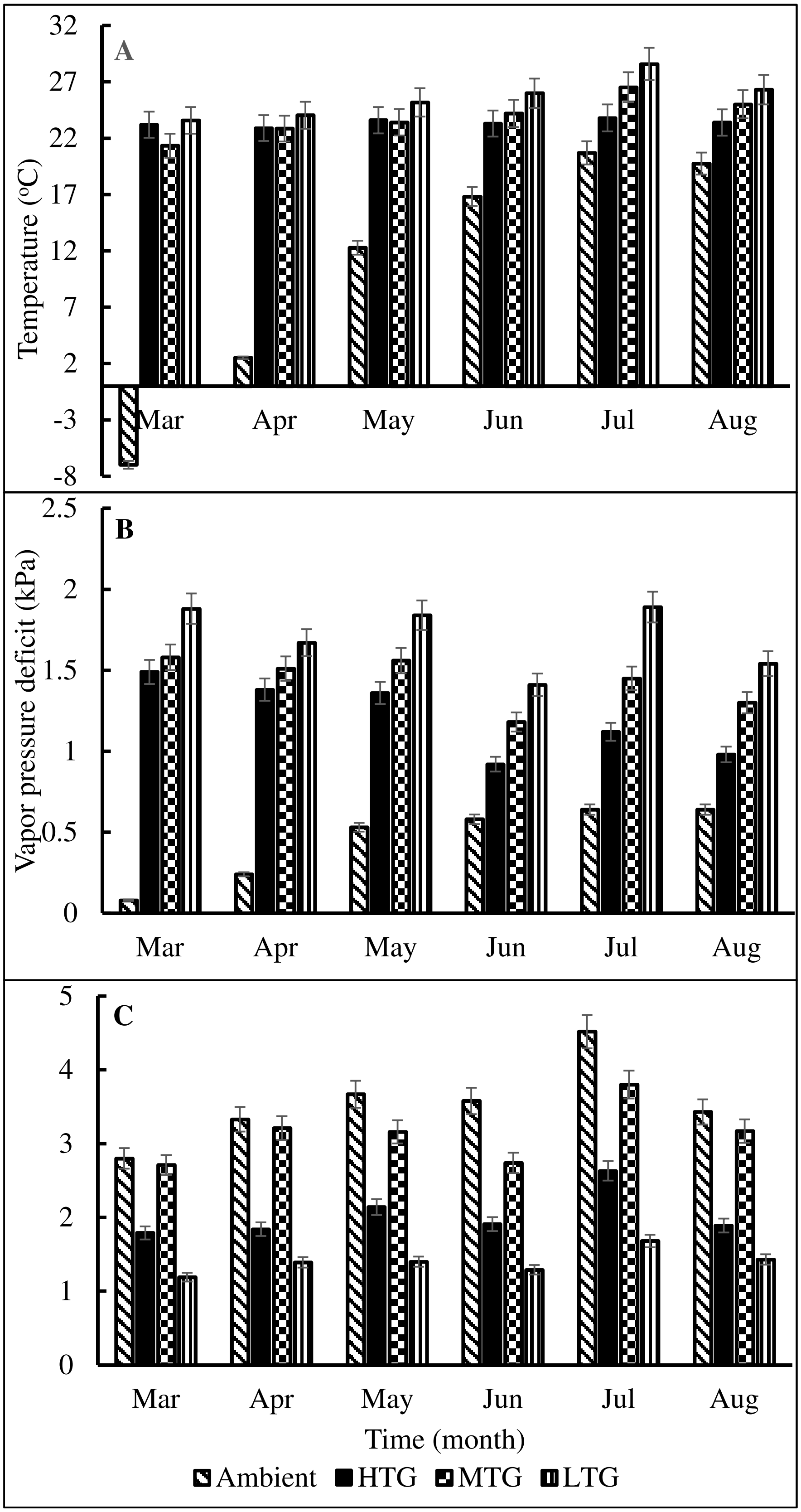
A
Temperature (°C)
32
27
22
17
12
7
2
-3
-8
Mar
Apr
May
Jun
Jul
Aug
B
Vapor pressure deficit (kPa)
2.5
2
1.5
1
0.5
0
Mar
Apr
May
Jun
Jul
Aug
C
5
4
3
2
1
0
Mar
Apr
May
Jun
Jul
Aug
Time (month)
Ambient
HTG
MTG
LTG

Fig. 2A-C

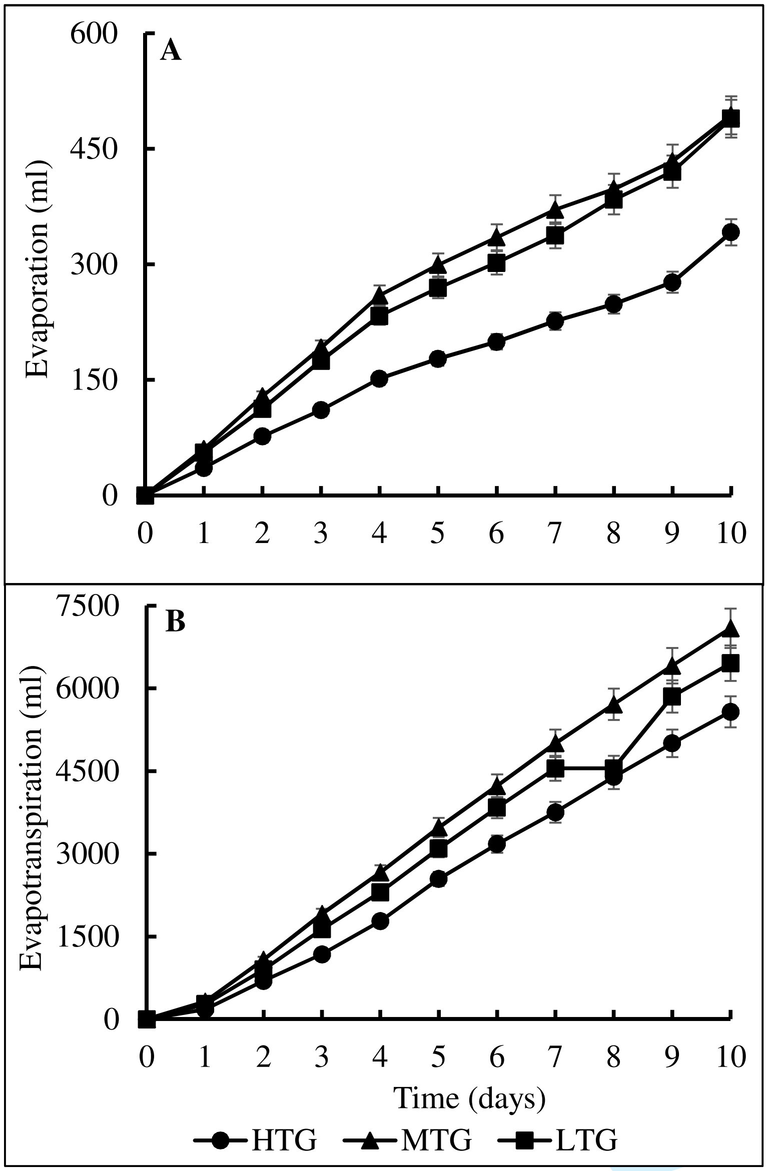
A
Evaporation (ml)
0
150
300
450
600
0 1 2 3 4 5 6 7 8 9 10
B
Evapotranspiration (ml)
0
1500
3000
4500
6000
7500
0 1 2 3 4 5 6 7 8 9 10
Time (days)
HTG
MTG
LTG

Fig. 3A-B

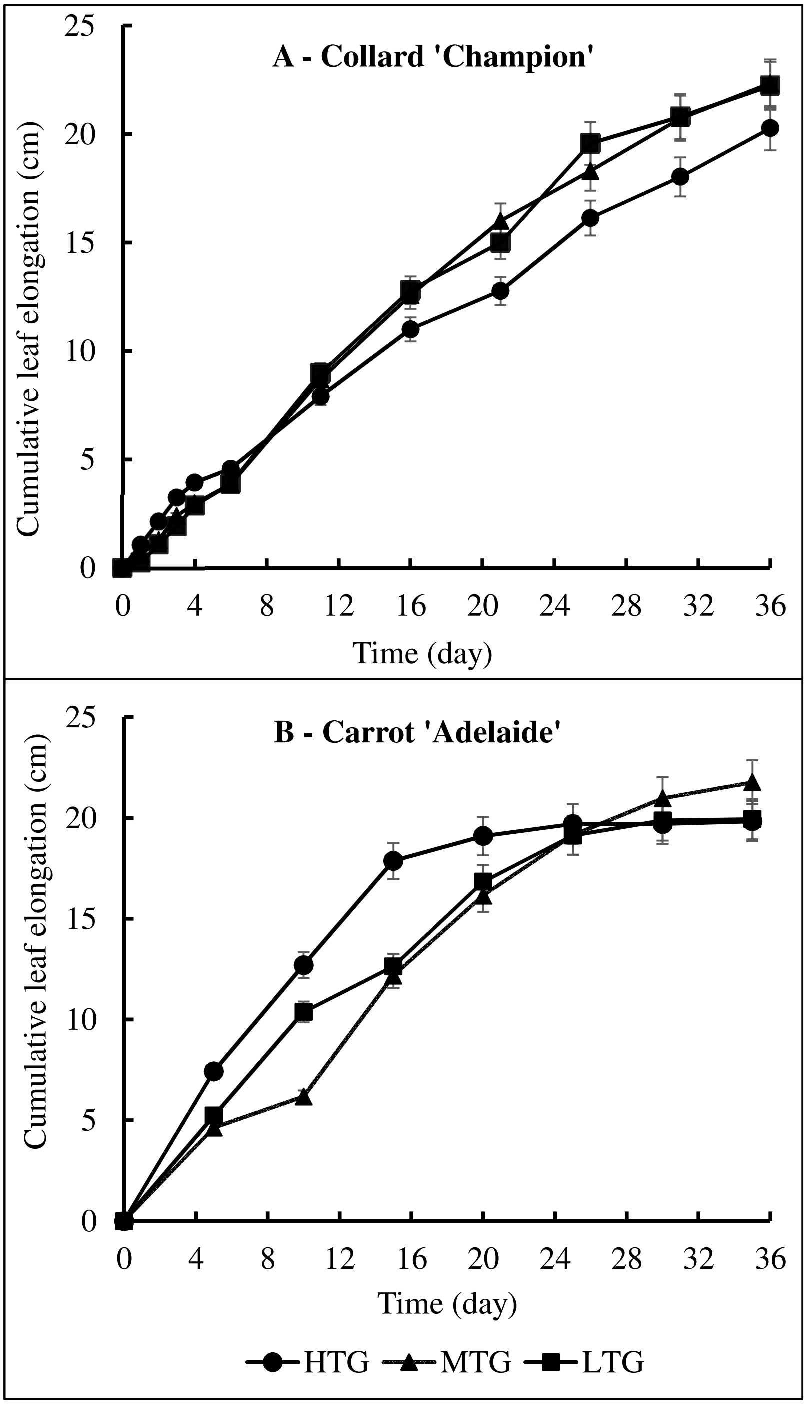
A - Collard 'Champion'
Cumulative leaf elongation (cm)
0
5
10
15
20
25
0
4
8
12
16
20
24
28
32
36
Time (day)
B - Carrot 'Adelaide'
Cumulative leaf elongation (cm)
0
5
10
15
20
25
0
4
8
12
16
20
24
28
32
36
Time (day)
HTG
MTG
LTG

Fig. 4A-B

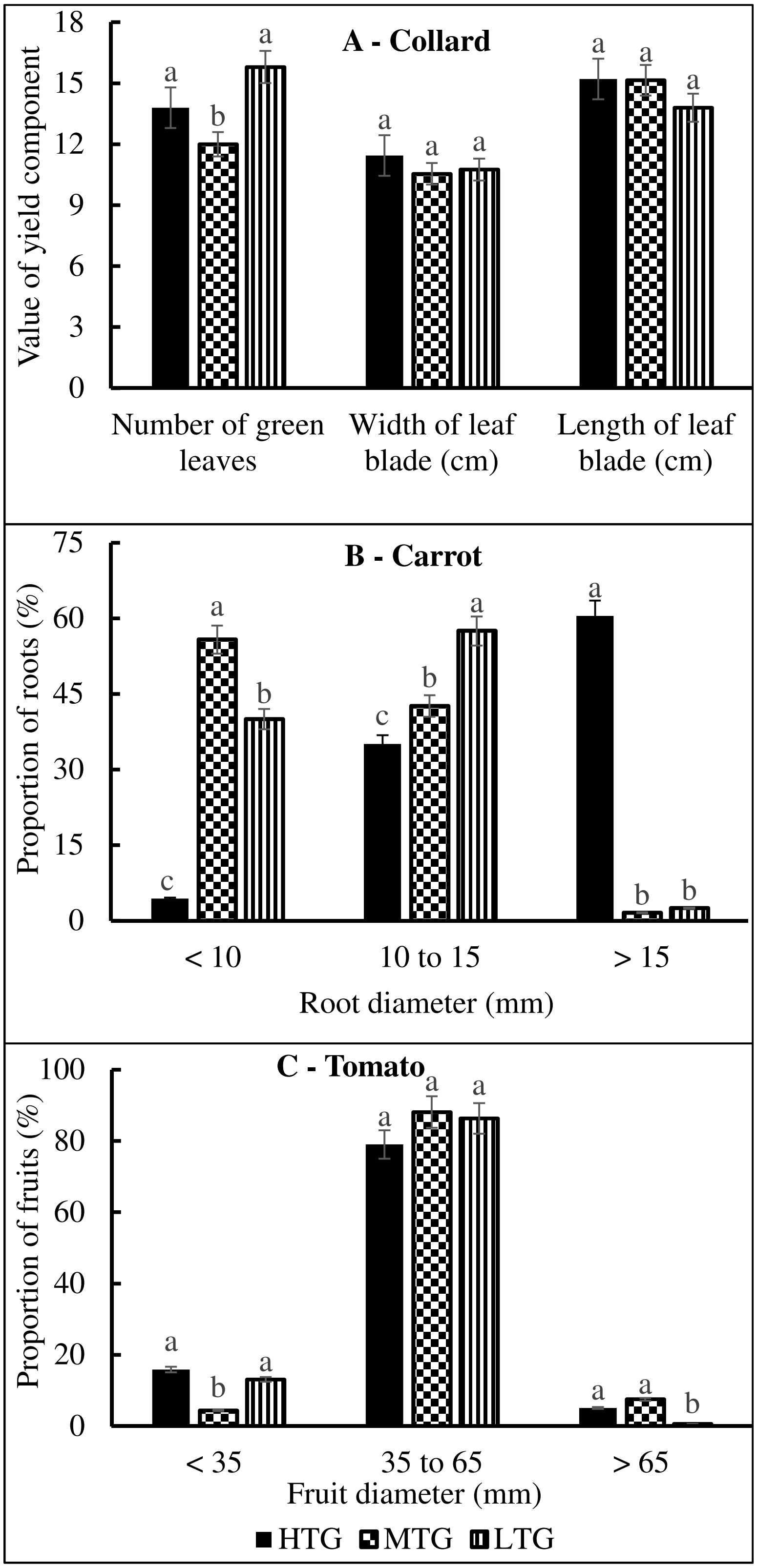
A - Collard
Value of yield component
0
3
6
9
12
15
18
Number of green leaves
Width of leaf blade (cm)
Length of leaf blade (cm)
a
b
a
a
a
a
a
a
a
B - Carrot
Proportion of roots (%)
0
15
30
45
60
75
< 10
10 to 15
> 15
Root diameter (mm)
c
a
b
c
b
a
a
b
b
C - Tomato
Proportion of fruits (%)
0
20
40
60
80
100
< 35
35 to 65
> 65
Fruit diameter (mm)
a
b
a
a
a
a
a
a
b
■HTG ▩MTG ▥LTG

Fig. 5A-C

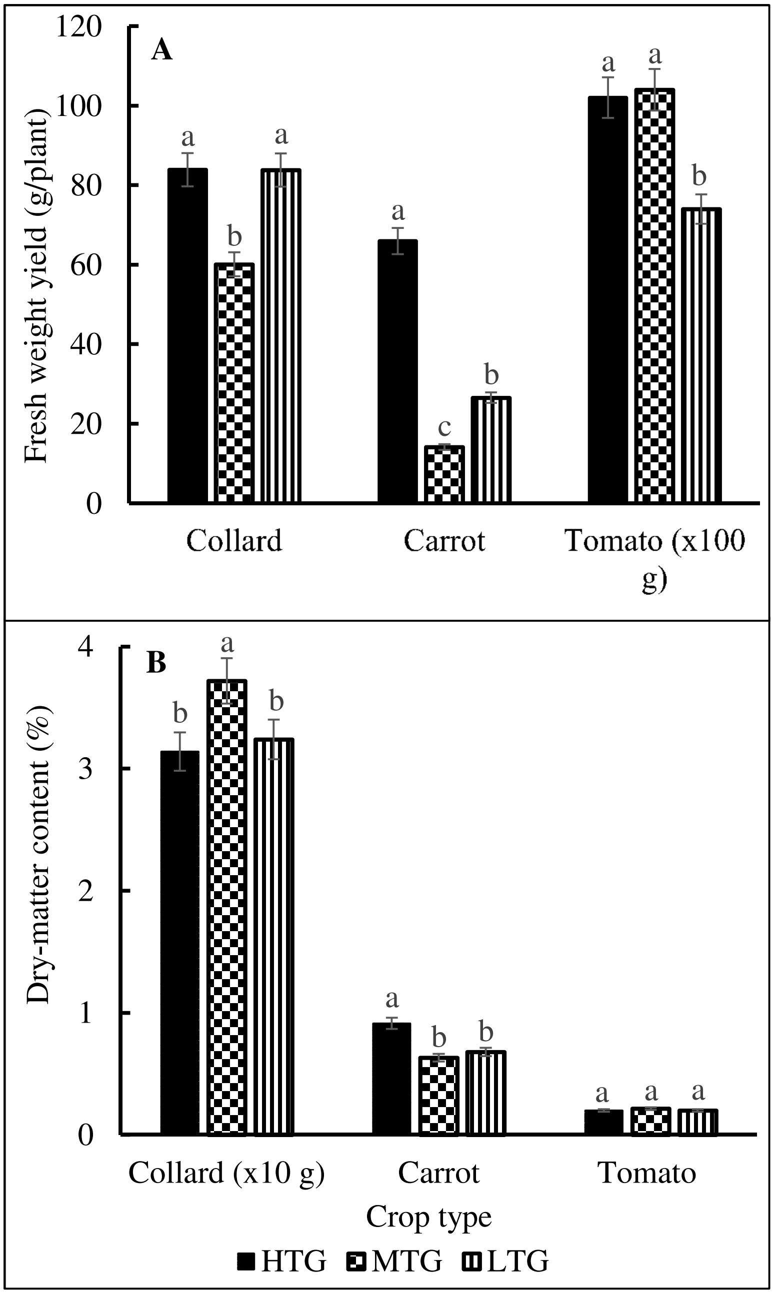
A
Fresh weight yield (g/plant)
120
100
80
60
40
20
0
a
b
a
a
c
b
a
a
b
Collard
Carrot
Tomato (x100 g)
B
Dry-matter content (%)
4
3
2
1
0
b
a
b
a
b
b
a
a
a
Collard (x10 g)
Carrot
Tomato
Crop type
■HTG
▩MTG
▥LTG

Fig. 6A-B