

**COMPARATIVE ANALYSIS OF TWO GREENHOUSE
MICROCLIMATES IN THE SUB-HUMID CLIMATE OF
SOUTH AFRICA**

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Master of Science in Engineering

Cum Laude

Submitted in fulfilment of the requirements for the degree of Master of Science in

Engineering

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March 2014

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ABSTRACT

Development of small-scale greenhouse facilities that are suitable for the southern African agro-climatic conditions is one of the options that can be adopted to help alleviate food insecurity and malnutrition in Southern African countries. A comparative study was undertaken to analyse the temperature and relative humidity (RH) of two types of greenhouse tunnels, namely, the fan-pad evaporatively-cooled (FPVT) and the open-ended naturally-ventilated tunnels (NVT). The effect of the microclimates on crop growth, yield and quality, using tomatoes during the summer months and lettuce in winter, were also investigated. The effects of the integrated agro-technologies involving greenhouse microclimate and storage conditions on the postharvest quality of four tomato cultivars was also studied.

The daytime temperature was lower in the FPVT than in the NVT during both summer and winter periods. Night-time temperatures were not significantly ($P>0.05$) different. The RH was higher in the FPVT than in the NVT, both during the day and at night. There was also a marked vertical and horizontal variation of temperature and relative humidity.

Tomato vegetative growth was significantly ($P<0.05$) higher in the FPVT, but there were no significant ($P>0.05$) differences in the total yield and the total marketable yield of tomatoes grown in the FPVT and the NVT. However, the total yield was 24% higher in the NVT, but the total marketable yield was 8.3% higher in the FPVT. Highly significant ($P<0.01$) cultivar differences were observed, with Bona performing the best in terms of total yield and total marketable yield under both NVT and FPVT microclimates. During winter, there were no significant ($P>0.05$) differences in the growth and yield of lettuce crops resulting from the effect of the microclimate, although there was a higher incidence (by 26.9%) of leaf tip-burn in the FPVT. Between the two lettuce cultivars, growth was faster and the yield was 11.5% higher for Ballerina than for Nadine. However, Ballerina also had 24 to 29.6% more leaf tip-burnt leaves than Nadine.

The integrated agro-technology study involving pre-harvest and postharvest treatments, which included the effect of greenhouse microclimate and postharvest storage environmental conditions on the texture, colour, TSS and pH of the four tomato cultivars, had significant ($P>0.05$) effects. NVT-grown tomatoes had and retained a firmer texture (by 7.4%) for a

longer period, had a higher TSS value (by 10.3%), but a more rapid colour change, from mature-green to red-ripe, than FPVT tomatoes. Among the four tomato cultivars, Bona was the least firm and changed colour from green to red more rapidly, but it had the highest TSS and acidity than of the other three cultivars. With cold storage conditions at 13°C and 85% RH, the firmness of Bona was improved by 24.1% and the colour changes were reduced by 18.6%, compared to those under ambient air conditions ($23 \pm 2^\circ\text{C}$ and $52 \pm 4\%$ RH). The cultivars Star 9037 and Star 9009 had the highest firmness and changed colour the least, but had the lowest TSS and highest pH values.

This study has provided information about the microclimate of two types of greenhouses and their performance, in terms of the effects on growth, yield and quality of four tomato cultivars in summer and two lettuce cultivars in winter. The microclimate in the FPVT encouraged vegetative growth and improved the quality of the tomatoes. In the NVT, although the total yields were higher, the higher temperatures and insect/pests reduced the quality of the tomatoes. In winter, although the daytime temperatures were higher in the NVT, lettuce growth was not negatively affected, whereas in the FPVT, high humidity resulted in lower quality lettuce. The study also provided information on the integrated agro-technologies, involving greenhouse microclimate and postharvest storage environmental conditions on the postharvest quality attributes of tomatoes available on the South African market. NVT-grown tomatoes need cold postharvest storage, to reduce the ripening, in terms of colour, whereas FPVT grown tomatoes need cold postharvest storage conditions, in order to maintain a firmer texture for a longer period. It has also shown that the selection of the most suitable cultivar is important for profitable cultivation of vegetable crops in greenhouses. The study has further shown that small-scale naturally-ventilated greenhouses can be used for commercially-oriented agriculture to produce crops, with the aim to reduce poverty, create employment and address malnutrition. In addition, the study has shown that there is a need for further research aimed at reducing the daytime heat load of the greenhouses during the summer months, and the night-time heat loss during winter and a cost-benefit analysis, to establish the cost of production associated with the two tunnels. Furthermore, greenhouse microclimate research can be extended to the other South African climatic regions, to provide extensive information about the performance of these facilities and their effects on other greenhouse crops such as peppers and cucumbers.

ACKNOWLEDGEMENTS

I wish to convey my sincere gratitude to the following people, without whom the successful completion of this dissertation would not have been possible:

Professor TS Workneh - School of Engineering, University of KwaZulu-Natal; Professor MD Laing - School of Earth, Agriculture and Environmental Sciences, University of KwaZulu-Natal; Dr AO Odindo - School of Earth, Agriculture and Environmental Sciences, University of KwaZulu-Natal, for their patient guidance, expert knowledge, constructive criticism and support throughout this study;

The Botswana College of Agriculture and the University of KwaZulu-Natal for funding the study;

Mr A Hill and Mrs S van der Merwe- University of KwaZulu-Natal, for their technical expertise and guidance;

Dr C Patrick - Botswana College of Agriculture, for the encouragement, guidance and support that he always provided whenever I needed it;

My fellow post-graduate students, in particular Stefanie Schutte and Chengetanai Mushonga-Mabhaudi, who were always there for me;

My family, in particular, my mom Keitumetse, my sister Neo and my brother Mopati, for believing in me and making me believe in myself;

Everyone else who was there when it mattered, and

Last but not least, GOD ALMIGHTY for making it all possible and carrying me when I faltered.

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1. INTRODUCTION

It is estimated that 842 million people world-wide were under-nourished in 2011-2013 (FAO, 2013). Of these, 26.4% are in the Sub-Saharan African region. The food and economic crises of 2006-2008 had serious impacts on the food security of countries dependent on imported food stocks. Most of these are found in Africa. In addition, the population growth in rapidly developing countries will likely increase the food demand in these countries and could exacerbate their food insecurity problems. In South Africa, about 35% of the population is considered to be food insecure (du Toit, 2011), particularly at the household level (Altman *et al.*, 2009), while 26% live below the poverty datum line (Kollodge, 2011). This is worsened by widespread unemployment and chronic poverty (HSRC, 2007). Interventions that are aimed at increasing agricultural production, targeting small-scale producers, would strengthen the food security and economic status of the most vulnerable communities (FAO, 2011). Small-scale commercially-oriented agriculture and technology transfer have been identified as some of the options that can be used for income generation and to combat food insecurity (Altman *et al.*, 2009). Greenhouse technology, one of the fastest growing food production systems in the world today (van Straten, 2011), has the potential for small-scale crop production, as one of the ways to mitigate food insecurity, poverty and malnutrition in developing countries.

The greenhouse was first developed in the cold climatic regions of North America and Europe, where extremely low temperatures limited the cultivation of most tropical crops (Castilla and Hernandez, 2007) and the main objective was to increase the air temperature in a controlled environment. The use of the greenhouse for commercial crop production began in the 19th century and accelerated after 1945 (von Elsner *et al.*, 2000). In recent years, its use on a commercial scale has spread to other climatic regions, notably Mediterranean and Asian countries (Jensen, 2002).

The choice of which greenhouse structure to use is influenced by the prevailing climatic conditions, socio-economic factors and the availability of infrastructural resources, including electricity, water and automated control technologies (Vanthoor *et al.*, 2011). In cold regions, low solar radiation, abundant water supplies and available technological resources have encouraged the development of highly advanced greenhouse facilities (Garcia *et al.*, 2011).

The lack of resources, such as water, electricity and technologies, have led to the development of simpler, less expensive types of greenhouse structures for poor farmers in the tropics, subtropics and temperate areas (Castilla and Hernandez, 2007). In the Mediterranean regions, where winters are mild and summers are warm, simple, naturally-ventilated greenhouses are widely used (Castilla and Montero, 2008). In South Africa, the most common type of greenhouse is the naturally-ventilated type, although the advanced fan-pad evaporatively-cooled type is gaining popularity (Maboko *et al.*, 2009).

The greenhouse modifies the internal microclimate, while at the same time protecting crops against adverse weather conditions such as rain, hail, frost, wind, extreme temperatures and air humidity (Bakker and Challa, 1995). The greenhouse also creates a physical barrier against pest invasion and diseases, reducing the use of chemicals for pest and disease control (Katsoulas *et al.*, 2006). Environmental conditions that are affected by greenhouse structures include air temperature, air humidity, carbon dioxide and air velocity (Bournet and Boulard, 2010).

In naturally-ventilated structures, control of the internal environmental conditions is achieved through the use of roof and/or side vents (Boulard *et al.*, 1997; Katsoulas *et al.*, 2006; Mashonjowa *et al.*, 2010a), although in South Africa, the open-ended tunnel is also in use. The other alternative involves the use of mechanical systems, which include extraction fans, fan-pad evaporative cooling, fogging and misting, to cool the greenhouse environment (Katsoulas *et al.*, 2001; Arbel *et al.*, 2003; Kittas *et al.*, 2003; Garcia *et al.*, 2011). These two cooling technologies may be used in conjunction with internal and external thermal curtains, internal aluminium folding shade screens (Callejón-Ferre *et al.*, 2009), near infrared reflecting screens (Stanghellini *et al.*, 2011) and whitewashing the cover with calcium carbonate (Baille *et al.*, 2001; Meca *et al.*, 2006; Jimenez *et al.*, 2010; Mashonjowa *et al.*, 2010b).

To date, there is a notable lack of technical information about the use, performance and effects of greenhouse microclimate on crop growth, yield and quality in Sub-Saharan Africa. This information gap suggests that opportunities offered by small-scale greenhouse technologies to mitigate food insecurity, unemployment and poverty, in Sub-Saharan countries, particularly South Africa, are not being fully exploited. In addition, integrated agrotechnologies which combine pre-harvest and postharvest practices that influence the quality

of vegetables are not well understood and the mitigation of the associated quality losses may not be in place. This study was undertaken to analyse the temperature and relative humidity of two greenhouse structures available in South Africa, viz. the open-ended naturally-ventilated and the fan-pad evaporatively-cooled greenhouse. The effects of these two microclimates on different crop cultivars, with regards to crop growth, yield, quality and postharvest storability were investigated concurrently.

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2. LITERATURE REVIEW

Abstract

The aim of this review was to assess the literature on low-cost greenhouses that have potential for use under the diverse Sub-Saharan Africa agro-climatic conditions. Development of small-scale greenhouse facilities that are suited for the Sub-Saharan agro-climatic conditions may help alleviate food insecurity and malnutrition. Control of the internal environment for optimum conditions is typically achieved through side and/or roof vents in naturally-ventilated facilities. Alternatively, fan-pad evaporative cooling may be used. Although natural ventilation is less costly and energy-efficient, it has limited capacity to reduce the heat load in warm climate regions. The use of the fan-pad evaporative cooling is limited in humid and sub-humid regions. The comparison of crop production under fan-pad versus natural ventilation in terms of crop growth and yield give conflicting results and needs further research. In South Africa, fan-pad cooling has performed better than natural ventilation, while in the tropical and Mediterranean climates, natural ventilation has performed better. This presents a knowledge gap about greenhouse facilities that needs to be addressed in order for the Sub-Saharan countries to benefit from greenhouse technology and to alleviate food insecurity and malnutrition.

2.1 Introduction

Sub-Saharan Africa (SSA) has great potential for fruit and vegetable production under controlled small-scale greenhouse environment. However, micro-level greenhouse systems at individual farmers' level have not significantly contributed to the alleviation of food insecurity in the SSA region. Small scale sustainable greenhouse facilities are amongst the controlled environment technologies that could assist developing countries to produce more vegetables even, during the off-seasons, to address malnutrition and food insecurity. In many of these countries, particularly in Sub-Saharan Africa, it is estimated that 26.4% of the population is undernourished (FAO, 2013). In South Africa, there are reports that 35% of the population is faced with food insecurity (du Toit, 2011) and 26% live below the poverty datum line (Kollodge, 2011). The rapidly growing greenhouse industry offers income generation opportunities for small-scale farmers in developing countries to diversify their production systems and reduce poverty. This could contribute to initiatives aimed at poverty reduction among resource-poor communities. However, limited information on the use of different types of low-cost greenhouses is available. This paper reviews the available greenhouse technologies; different types of greenhouse, such as naturally-ventilated and forced air cooled and ventilated greenhouses, and the possible effects of microclimatic conditions on the postharvest quality attributes of fresh produce, with particular emphasis on tomatoes.

2.2 Greenhouse Microclimate

The most important climatic parameters inside a greenhouse are air temperature, air velocity, relative humidity (RH), solar radiation and carbon dioxide concentration (Bournet and Boulard, 2010). These variables influence crop photosynthesis, evapo-transpiration, respiration and ultimately crop growth, yield and quality (van Straten *et al.*, 2011). In addition, the uniformity and distribution of these parameters inside the greenhouse, influence the uniformity of crop growth and development (Teitel *et al.*, 2010).

2.2.1 Solar radiation

The incident solar radiation reaching the earth comprises of ultraviolet, visible light, near infrared and far infrared radiations (Waaijenberg, 2006). Of these, photosynthetic radiation in the 400-700nm wavelengths of the visible light spectrum provides the energy required for plant growth and the pressure potential required for transpiration (Baxevanou *et al.*, 2007). On the other hand, the near infrared radiation in the 700-3000nm wavelengths is converted to sensible and latent long-wave heat radiation upon entry into the greenhouse. Depending on the properties of the cover, some of the heat may be lost through the cover, but most of the heat is reflected back into the greenhouse, causing an increase in the internal greenhouse temperature (Baxevanou *et al.*, 2007). This increase may be beneficial in cold regions and in the subtropics during winter, but it is undesirable in the sub-tropics in summer time when solar radiation is mostly high (Mashonjowa *et al.*, 2010b). If ventilation and cooling are insufficient, undesirable environmental conditions will be created inside the greenhouse and the crop evapo-transpiration demand may increase, possibly inducing water stress and inefficient use of irrigation water.

2.2.2 Temperature

Temperature is the most critical environmental factor in greenhouse cultivation (von Elsner *et al.*, 2000). The internal air temperature is influenced by several factors, including solar radiation, external air temperature and the type of covering material used (Sethi, 2009). High incident solar radiation and external air temperature result in higher internal air temperatures. The highest temperatures have been observed around the middle of the day, when solar radiation is at its maximum, as shown in Figure 2.1 (Wien, 2009).

High internal air temperatures reduce crop growth, yield and quality of produce (Shen and Yu, 2002), whereas frost can kill crops (von Zabeltitz, 2011). Most crops grown under controlled environment conditions thrive when the mean internal air temperature is between 17 and 27°C (von Zabeltitz, 2011). The optimum daytime temperatures range between 22 and 28°C and 15 to 20°C at night. Temperatures below 12°C or above 30°C negatively affect the growth, yield and quality of most fruit vegetables, such as tomatoes and peppers (Castilla and Hernandez, 2007). According to von Elsner *et al.* (2000), the risk of frost damage in

greenhouses is minimal in areas where the minimum ambient temperature is above 7°C. When the minimum mean temperature is below 7°C, heating is required to minimize the effects of cold temperatures. Von Zabeltitz (2011) suggested that the absolute mean minimum temperature should be 0°C and the mean maximums should range between 35 and 40°C.

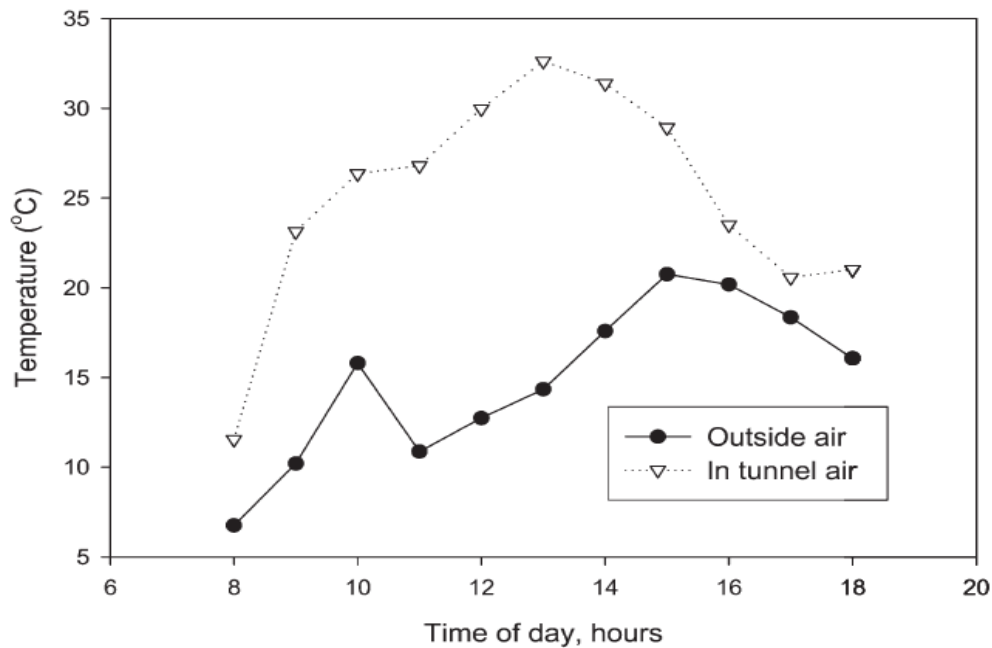


Figure 2.1 Tunnel greenhouse internal and ambient air temperature variation with time (after Wien, 2009)

In Southern Africa, internal greenhouse temperatures can be too high for optimum cultivation, due to high solar radiation, particularly in summer. Maboko *et al.* (2010) observed maximum temperatures ranging between 38.0 and 44.2°C in South Africa, while (Mashonjowa *et al.*, 2010a) observed temperatures as high as 45°C in Zimbabwe. According to Bailey (2006), when the maximum internal temperature exceeds 28°C, cooling is required. When the highest mean ambient air temperature is below 27°C, ventilation is adequate to maintain the optimum temperature levels.

2.2.3 Relative humidity

One of the aims of greenhouse cultivation is to increase the RH, while simultaneously reducing the vapour pressure deficit of the air (Kittas and Bartzanas, 2007). For most greenhouse crops, ideal RH levels range between 60 and 90% (von Zabeltitz, 2011). Values

below 60% induce high transpiration rates, leading to plant water stress, especially in young crops with low leaf area indexes (Bailey, 2006). González-Real and Baille (2006), observed a reduction in the growth rate of tomato fruit when the vapour pressure deficit was increased from 1.6 kPa to 2.2 kPa. On the other hand, RH values above 95% reduce plant transpiration rate and limit nutrient transport to the plant organs. This increases the incidence of physiological disorders, such as blossom end-rot in tomatoes, sweet peppers and cracked tomato fruits (Yaoi *et al.*, 2000; Gázquez *et al.*, 2006; Max *et al.*, 2009). High internal relative humidity can also result in an increased incidence of fungal diseases when condensation occurs on the crop canopy (Bailey, 2006; Max *et al.*, 2009).

2.2.4 Air velocity

Air velocity in the greenhouse is an important factor, since the distribution of temperature and relative humidity follows the air flow pattern (Bartzanas *et al.*, 2002; Li and Willits, 2008). A non-uniform distribution of air velocity leads to non-uniform temperature and RH, and consequently, non-uniform crop growth, development and maturity (Bailey, 2006). The ideal greenhouse airflow rates range between 0.5 and 0.7 m.s⁻¹ and air velocity values above 1 m.s⁻¹ result in high transpiration rates and water stress (ASHRAE Handbook, 2001).

2.3 Ventilation and Cooling in Greenhouses

Ventilation is an important design factor that assists in removing excess heat and gaseous pollutants and in maintaining relative humidity and CO₂ at levels that promote active crop development (Baptista *et al.*, 1999; Ould Khaoua *et al.*, 2006). The rate at which the air exchange between the inside and the outside occurs, influences the airflow pattern, distribution and uniformity of temperature and humidity, uniformity of plant growth, yield and produce quality (Boulard *et al.*, 1997; Bartzanas *et al.*, 2004; Sase, 2006). The following sections review the literature on natural ventilation and mechanical ventilation, using a fan-pad evaporative cooling system.

2.3.1 Natural ventilation

Natural ventilation is the cheapest, simplest and most energy-efficient method of controlling the microclimate in greenhouse facilities, as opposed to mechanical systems (Ould Khaoua *et al.*, 2006; Flores-Velázquez *et al.*, 2010). It is a direct result of the combined or singular effects of the wind forces and the buoyancy forces, due to temperature difference between the inside and the outside environments (Boulard *et al.*, 1997; Kumar *et al.*, 2009).

Natural ventilation is commonly achieved through the use of vent openings on the roof and/or side walls (Figure 2.2) along the main axis of the greenhouse (Teitel *et al.*, 2008a; Bournet and Boulard, 2010), which can either be continuous or discontinuous. The ventilation rate depends on external wind speed and direction, temperature gradient between the inside and outside, the presence or absence of insect-proof mesh screens, vent configuration and the height of the crop growing in the greenhouse (Ould Khaoua *et al.*, 2006).

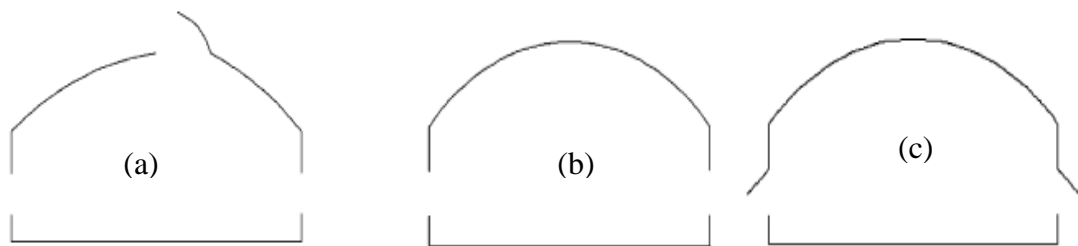


Figure 2.2 Typical vent opening arrangement (a) roof and side openings (b) roll-up side vents (c) pivot-door side vents (after Bartzanas *et al.*, 2004)

2.3.2 Effect of vent configuration on temperature and relative humidity

The most common vent arrangement is side and/or roof vents, continuous or discontinuous along the main axis of the greenhouse (Bournet and Boulard, 2010). According to Boulard *et al.* (1997), the discontinuous vent openings have lower ventilation efficiency, when compared to the continuous vent openings used in a Mediterranean climate.

Kittas and Bartzanas (2007) and Teitel *et al.* (2008a) found that, in a mono-span greenhouse with continuous roll-up side vents, the air velocity was higher, close to the ground, and lower close to the greenhouse cover. For a greenhouse with roof openings only, the air velocity was found to be highest at the vent opening with calmer conditions at the centre of the greenhouse

(Teitel *et al.*, 2008b). For a greenhouse with roof and side vents, air velocity was higher at the vent openings and almost constant throughout the greenhouse (Bartzanas *et al.*, 2004). Boulard *et al.* (2004) also observed high internal air velocity closer to side opening vents than in the tunnel interior and higher internal RH at the centre of the greenhouse. The air temperature profile and RH follow the air pattern, with lower air temperatures and RH observed at the vent openings than in the middle sections and in the corner areas of the greenhouse (Bartzanas *et al.*, 2004).

In addition, the internal air flow pattern induces vertical temperature and RH stratification in naturally-ventilated greenhouses, as shown in Figures 2.3 and 2.4. Teitel *et al.* (2008a) observed a temperature difference of about 5°C at a height of 0.15 m and 3 m above the floor in a tunnel greenhouse with continuous side vents. Teitel *et al.* (2008a) further observed high humidity ratio of about 18 g.kg⁻¹ at a height of 1.1 m and the lowest value of about 16 g.kg⁻¹ at a 2 m height. Furthermore, the size of the ventilation area influences the internal microclimate. Boulard *et al.* (2004) observed an 18% increase in internal RH for a 7% ventilation area, as compared to an 11% increase for an 18% ventilation area in a side-opening ventilated tunnel greenhouse.

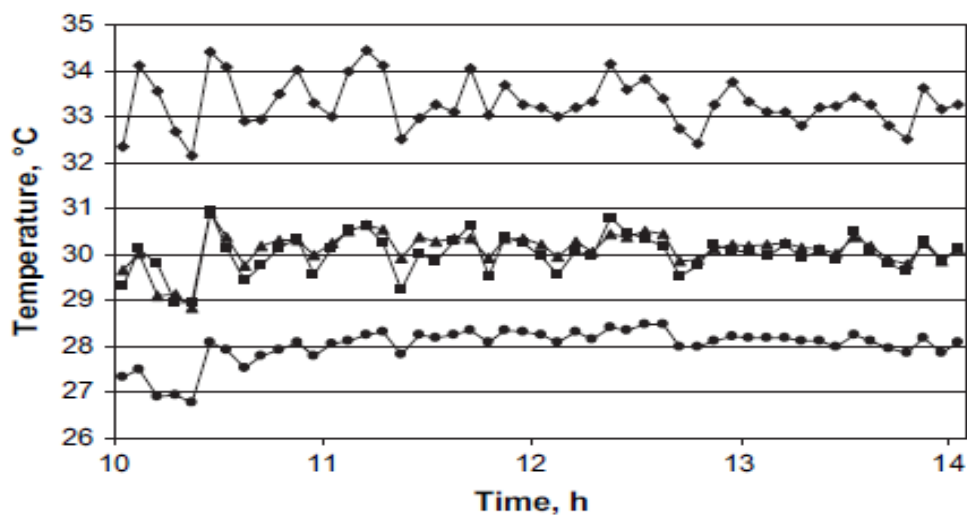


Figure 2.3 Time variation of temperature for a mono-span greenhouse on a typical day, • 0.15 m, ▲ 1.1 m, ■ 2 m, ◆ 3m (after Teitel *et al.*, 2008a)

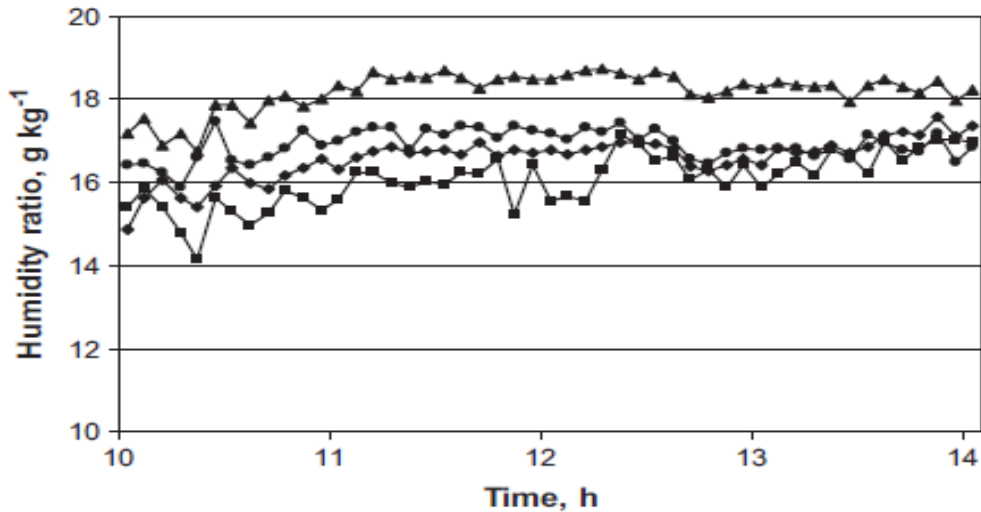


Figure 2.4 Time variation of relative humidity for a mono-span greenhouse on a typical day, ● 0.15 m, ▲ 1.1 m, ■ 2 m, ◆ 3m (after Teitel *et al.*, 2008a)

2.3.3 Effect of wind speed and direction on internal air temperature and RH

Natural ventilation depends on the wind and temperature difference to effect the air exchange between the inside and outside of greenhouse facilities. Buoyancy forces, which are a result of the internal and external air temperature difference, result in an air density gradient between the two air streams (Flourentzou *et al.*, 1998). Wind forces, on the other hand, create a pressure field at the vent openings (Boulard and Baille, 1995). Air exchange then occurs in response to these two factors. The wind and buoyancy forces seldom act singularly, but the wind effect is more dominant as a factor in the ventilation process when the external wind speed exceeds 1.5 m.s^{-1} in roof and side-ventilated facilities (Boulard and Baille, 1995; Kittas *et al.*, 1996). Kittas *et al.* (1996) suggested that, when the external wind speed exceeds 1.5 m.s^{-1} , the temperature effect can be neglected and the ventilation rate is then considered as a factor of wind and vent opening area only.

Greenhouse internal air velocity and ventilation rate have been found to be higher in high wind areas than in low wind areas (Boulard *et al.*, 1997). The ventilation rate varies linearly with increase in wind velocity (Kacira *et al.*, 2004; Teitel *et al.*, 2008a). Teitel *et al.* (2008b) investigated the effect of wind direction on ventilation rate in a multi-span roof-ventilated greenhouse. It was concluded that, for all wind directions, the air velocity inside the greenhouse was higher close to the ground and the cover, but lower at the centre of the structure. Fatnassi *et al.* (2009), on the other hand, suggested that wind direction has some

degree of influence on the ventilation rate and on the distribution of temperature and RH. It was concluded that the ventilation rate in a tunnel greenhouse with side vents is higher when wind direction is normal to the openings, as compared to oblique and parallel flows.

2.3.4 Effect of crop height on internal air temperature and RH

In addition to vent arrangements, it has been found that the presence of a crop and its development stage influence the ventilation rate and distribution of temperature and RH. Boulard *et al.* (1997) investigated six different greenhouses in the Mediterranean region and found that the presence of crops reduced the ventilation rate by up to 28%. This was observed to be of importance for tall crops, such as tomatoes, in greenhouses with side vents, where the plants obstruct the flow of air (Katsoulas *et al.*, 2006). Fatnassi *et al.* (2009) observed that the ventilation rates of 1 m and 2.13 m tall tomato crops were reduced by 46 to 48% and 72 to 85%, when compared to those of 0.1 m high plants, respectively. This was in a single-span side-ventilated tunnel greenhouse in the South of France.

In addition to influencing the ventilation rates in greenhouses, crop density and height also result in variations of air temperature in the greenhouse. Soni *et al.* (2005) observed that young tomato crops with a plant density of 17 000 plants.ha⁻¹ had a higher vertical temperature variation than mature crops with a plant density of 33 000 plants.ha⁻¹. It was also observed that the lowest temperature was within the plant canopy, while the air space above the plants was hotter (Soni *et al.*, 2005; Teitel *et al.*, 2008a). The lower canopy temperature was attributed to crop canopy cooling through transpiration and the higher temperatures in the greenhouse air space were attributed to accumulation of lighter warmer air in the space above the crops, coupled with inefficient ventilation by the side and roof vents.

2.3.5 Effect of insect-proof screens on internal air temperature and RH

One of the reasons for cultivating crops under enclosed covers is to eliminate pests and pest-borne diseases. In naturally-ventilated structures, where climate control is achieved through vent openings, porous plastic screens are used to prevent the entry of insects into the greenhouse (Bartzanas *et al.*, 2002; Klose and Tantau, 2004; Valera *et al.*, 2006). The efficiency of the screen in excluding pests from greenhouses depends on the dimensions of

the openings between the threads of the screen mesh (Valera *et al.*, 2006) and the choice of the screen to use depends on the pests to be eliminated (Teitel, 2007). The mesh screen openings have to be smaller than the pests being targeted (Klose and Tautau, 2004; Katsoulas *et al.*, 2006), with smaller mesh sizes targeting small insect pests and coarser mesh sizes for larger pests (Teitel *et al.*, 2009).

In spite of their usefulness, insect-proof screens have been found to have a negative effect on the ventilation rate, temperature and RH inside the greenhouse. The mesh screens reduce the ventilation area (Valera *et al.*, 2006) and provide extra resistance to the transport of heat, momentum and mass into and out of the greenhouse (Bartzanas *et al.*, 2002). The resulting pressure drop reduces the internal air velocity and ventilation rate, resulting in increased internal greenhouse temperature and RH and a possible increase of the incidence of plant diseases (Teitel, 2007).

It can be deduced from the above literature review that the common vent arrangements (roof and/or side wall vents), crop density and the effect of insect screens induce marked variations of temperature and relative humidity in the greenhouse. This variation of the microclimate defeats one of the purposes of controlled environment cultivation, i.e. uniformity of growth, yield and quality. As stated by Fatnassi *et al.* (2009) and Bournet and Boulard (2010), there is a need for the development of ventilator configurations that would improve the distribution of the microclimate parameters and improve the efficiency of ventilation, particularly in warm climate regions such as Southern Africa.

2.4 Fan-Pad Evaporative Cooling and Ventilation

Fan-pad evaporative cooling is effective in improving the greenhouse microclimate by reducing the temperature and increasing the RH, especially in hot and dry environments (Bailey, 2006; Kumar *et al.*, 2009). In fan-pad ventilation systems, ambient air is forced to pass through a wet porous media on the wall of the greenhouse (Kittas *et al.*, 2001). Upon contact with the wet pad, the sensible heat of the air stream is converted to latent heat, cooling the air to the wet bulb temperature of the incoming air stream. Conversely, the RH is increased, and depending on the efficiency of cooling, the air humidity can approach saturation levels (Fuchs *et al.*, 2006; Mutwiwa *et al.*, 2007; Max *et al.*, 2009).

The internal greenhouse temperature and RH distribution profile between the pad and the fan are influenced by the ventilation rate, crop transpiration, soil evaporation, cover shading, efficiency of evaporative cooling and the heat loss coefficient of the cover (Kittas *et al.*, 2003). However, temperature and RH respond more rapidly to changes in ventilation rate and solar radiation (Kittas *et al.*, 2003; Kittas *et al.*, 2005) than to the other factors. High ventilation rates seem to induce higher internal temperature reductions and high solar radiation results in lower temperature reduction (Fuchs *et al.*, 2006; Willits, 2003).

Lopez *et al.* (2010) investigated two fan-pad ventilated greenhouses: one had a 2.2 m tall tomato crop, while the other one was kept empty. It was observed that there was a greater air temperature reduction in the greenhouse with the tomato plants than in the empty one. This can be attributed to additional cooling of the greenhouse interior, due to crop transpiration (Max *et al.*, 2009). There was also a more uniform distribution of temperature in the presence of crops, as a result of airflow dispersion by the crop. This results in the mixing of the incoming air stream with the greenhouse air and a more uniform microclimate. The above observation may be important when crops are still at the early development stage and their transpiration rates are low (Willits, 2003).

It has been observed that there is heterogeneity in the microclimate parameters in fan-pad evaporatively-cooled greenhouses. Internal air temperatures and RH vary horizontally and vertically (Mutwiwa *et al.*, 2007; Li and Willits, 2008; Lopez *et al.*, 2010), which is a factor when placing temperature sensors for microclimate control (Li and Willits, 2008). The horizontal air temperature gradient depends on the distance between the inlet at the pad section and outlet at the fans. Lowest air temperatures have been observed at the pads section and increase progressively along the length of the greenhouse (Kittas *et al.*, 2005), as shown in Figure 2.5. Kittas *et al.* (2003) observed internal air temperature differences of up to 8°C, at noon, between the pad and fan sections in a 60 m long greenhouse and Oz *et al.* (2009) observed 6°C in a 24 m long greenhouse between the pad and the fan sections. The horizontal variation also seems to be highest around the middle of the day, when solar radiation is highest. Willits (2003) predicted that increasing the ventilation rate of fan-pad ventilated greenhouses, up to $0.13 \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, reduces the temperature gradient, thus increasing the efficiency of cooling for fan-pad systems.

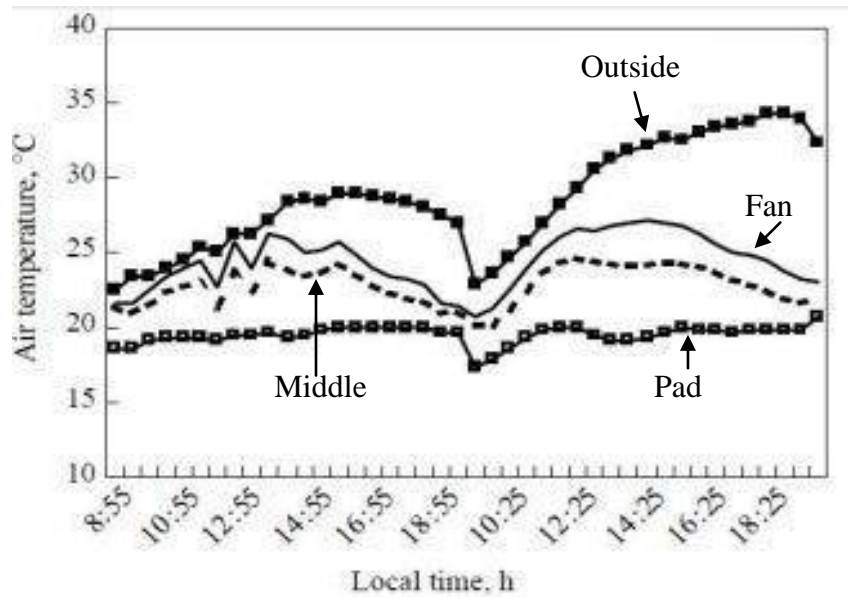


Figure 2.5 Horizontal variation of temperature in a greenhouse equipped with a fan-pad cooling system (after Kittas *et al.*, 2003)

Vertical temperature gradients were observed by Kittas *et al.* (2001), Kittas *et al.* (2003) and Li and Willits (2008). These variations depend on the presence or absence of a crop and on the ventilation rate. The presence of a tall crop reduces the spatial variation in the vertical and horizontal planes (Willits, 2003; Lopez *et al.*, 2010), due to the cooling effect of the crop canopy through transpiration (Bailey, 2006). Low vertical temperature variation was observed when the ventilation rate was high in a greenhouse with a 1.71 m tall tomato crop (Li and Willits, 2008). The spatial distribution of air water content depends on the presence of crops inside the greenhouse. Without a crop, the air water content was found to be highest at the pads, decreased progressively along the length of the greenhouse and was lowest at the fans (Kittas *et al.*, 2001; Kittas *et al.*, 2003). In the presence of crops, the humidity ratio was found to increase progressively, with the lowest values observed at the pads and highest values at the fans (Willits, 2003; Lopez *et al.*, 2010). This is due to the fact that the air picks up additional moisture from the crop canopy as it passes through the greenhouse.

Night-time internal temperatures are low in the greenhouse, as heat which accumulated in the greenhouse during the day is lost to the cooler external environment through the greenhouse cover (von Zabeltitz, 2011). Conversely, the RH tends to increase at night. The greenhouse cover has been found to be the coolest surface on the greenhouse environment and the crop canopy to be the warmest (Piscia *et al.*, 2012), which results in condensation of water on the

inside of the cover if the cover is cool enough. This increases the incidence of fungal disease attacks on crops (Piscia *et al.*, 2012).

2.5 Comparison of Natural and Fan-Pad Evaporative Cooling and Ventilation

Both fan-pad cooling and natural ventilation systems have disadvantages and advantages, but, as stated by Teitel *et al.* (2010), knowing performance strengths and limitations of both systems does not necessarily imply an easy choice. The following sections compare the performance of natural ventilation and fan-pad evaporative cooling in maintaining the temperature and RH inside greenhouses. The effect both systems have on crop growth and yield will also be discussed.

2.5.1 Comparison between natural and fan-pad evaporative cooling and ventilation on temperature and RH

Evaporative cooling is effective for temperature and humidity control, especially in dry and hot areas. In humid and sub-humid areas, this effectiveness can be hampered by low ambient vapour pressure deficits (Kumar *et al.*, 2009) and at RH values greater than 60%, there is little cooling benefit derived from using evaporative cooling (Fuchs *et al.*, 2006). Moreover, the internal microclimate is easier to control and predict, since the microclimate is less dependent on the external conditions and the ventilation rate is regulated by rated fans (Kittas *et al.*, 2005; Flores-Velázquez *et al.*, 2011). In spite of these advantages, fan-ventilation systems are expensive to install, maintain and operate. They have high water and power consumption rates (Teitel *et al.*, 2010) and need an adequate and constant supply of electricity and good quality water (Bailey, 2006). Teitel *et al.* (2010) observed a daily 3.0 to 4.0 kW power requirement for operating two fans and a water pump, in a greenhouse with 69 m² floor area and the need for a 0.3 to 0.4 m³.day⁻¹ water supply to wet the pads during a Mediterranean summer.

Conversely, natural ventilation has low equipment installation costs, low maintenance costs and low energy requirements (Kittas and Bartzanas, 2007), and is a simple technology for managing greenhouse microclimates (Teitel *et al.*, 2010; Flore-Velazquez *et al.*, 2011). However, the microclimate and ventilation rates are less predictable or well-controlled,

because natural ventilation is entirely dependent on external climate parameters that are notoriously variable (Willits and Li, 2005). The ventilation rate and microclimate may also be influenced by insect-proof screens (Valera *et al.*, 2006; Teitel, 2007), vent opening configurations (Katsoulas *et al.*, 2006; Kittas and Bartzanas, 2007) and crop height (Fatnassi *et al.*, 2009). Consequently, natural ventilation may not always be adequate to maintain optimum ventilation rates and microclimate parameters, especially in high solar radiation latitudes (Bailey, 2006).

Comparison between natural and fan-pad ventilation systems has shown that greenhouse temperatures in fan-pad systems are consistently lower than in naturally-ventilated greenhouses and outside ambient air. Conversely, RH is higher in fan-pad systems than in naturally-ventilated greenhouses (Willits and Li, 2005; Mutwiwa *et al.*, 2007; Max *et al.*, 2009; Maboko *et al.*, 2010), as shown in Table 2.1. In addition, temperatures in the naturally-ventilated greenhouse tend to fluctuate around ambient air temperatures (Teitel *et al.*, 2007), especially during the day. At night, Max *et al.* (2009) observed no significant differences between the temperatures in the fan-pad system, natural ventilation system and ambient environments, with the fan-pad switched off.

Table 2.1 Observed temperatures and relative humidity in naturally-ventilated and fan-pad cooled greenhouses

Vent Configuration	Natural Ventilation		Fan-pad Cooling and Ventilation		Reference
	T _{max} (°C)	RH (%)/ VPD (kPa)	T _{max} (°C)	RH (%)/ VPD (kPa)	
Side wall	44.2	N/O	38.0	N/O	Maboko <i>et al.</i> (2010)
Roof and side	32.1	1.2 kPa	29.0	0.4kPa	Mutwiwa <i>et al.</i> (2010)
Roof and side	40.0	73%	32.0	93%	Max <i>et al.</i> (2009)
Roof and side	30.9	68%	26.8	78%	Teitel <i>et al.</i> (2007)

N/O = not observed, T_{max} = maximum observed internal air temperature, VPD = internal vapour pressure deficit.

2.5.2 Comparison of natural ventilation and fan-pad ventilation on crop growth and yield

Several researchers have reported conflicting results regarding vegetative growth and yield of crops grown in naturally- and fan-pad ventilated greenhouses. Willits and Li (2005), Mutwiwa *et al.* (2007) and Max *et al.* (2009) all reported faster growth, higher yields and higher marketable yields from crops grown in a naturally-ventilated than fan-pad ventilated greenhouses. Tomato plants in a naturally-ventilated greenhouse were found to be 25.9 cm taller than those in a fan-pad system, even though the temperature was higher in the natural ventilated greenhouse (Mutwiwa *et al.*, 2007). Max *et al.* (2009) observed that for the first four weeks, tomato plant growth was faster in a fan-pad than in a naturally-ventilated greenhouse, after which, plants in the naturally-ventilated greenhouse started growing faster and accumulating a higher number of trusses per plant than in the fan-pad greenhouse. Teitel *et al.* (2007) observed a higher number of harvested rose stems per plant in a naturally-ventilated greenhouse than in a fan-pad evaporatively-cooled one. In addition, there were more defects, such as blossom end-rot and cracked fruit reported in fan-pad-grown tomatoes than in naturally-ventilated ones (Max *et al.*, 2009).

Although there is limited peer-reviewed literature on the performance of natural ventilation against fan-pad evaporative cooling for Southern Africa, Maboko *et al.* (2010) reported higher total and marketable yields in fan-pad evaporative cooling system than in a naturally-ventilated greenhouse in South Africa. A total yield of 6619 g.plant⁻¹, with an 88% marketable yield, was recorded in the fan-pad ventilated greenhouse, compared to 3978 g.plant⁻¹ total yield, with a 59% marketable yield, recorded in the naturally-ventilated greenhouse. In addition, the naturally-ventilated greenhouse had a higher number of cracked fruits, when compared to the fan-pad ventilated greenhouse. These results conflict with those reported by other researchers mentioned in the preceding paragraph.

Produce harvested from naturally-ventilated structures have been observed to be significantly smaller in size, than those from fan-pad ventilated structures (Willits and Li, 2005; Max *et al.*, 2009; Maboko *et al.*, 2010). Max *et al.* (2009) observed that 9.8% of the tomato fruit harvested from the naturally-ventilated greenhouse were undersized, as compared to 6.1% harvested from the fan-pad ventilated greenhouse. Teitel *et al.* (2007) observed that the mean

stem length, bud length and diameter of rose flowers grown in a naturally-ventilated greenhouse were 34.0 cm, 2.21 cm and 1.88 cm, respectively, as compared to the stem length, bud length and diameter of 41.3 cm, 2.03 cm and 2.41 cm, respectively, in a fan-pad ventilation system.

The conflicting results could be due to the different climatic conditions under which the experiments were conducted, as well as the different vent configurations, as shown in Table 2.1. Maboko *et al.* (2010) conducted their experiments in Pretoria, South Africa, Mutwiwa *et al.* (2007) and Max *et al.* (2009) conducted theirs in a tropical climate and Teitel *et al.* (2007) conducted theirs in a Mediterranean climate. This emphasises the dependence of the greenhouse microclimate on the ambient climate and on the greenhouse design. It also raises questions about the effectiveness of naturally-ventilated facilities developed for the milder climates in the northern hemisphere, when they are used under the warmer Southern African conditions. The different results could also be due to different levels of heat tolerance between the different cultivars grown in different agro-climatic conditions. Abdelmageed and Gruda (2009) observed that heat resistant tomato cultivars tend to perform better under high air temperature conditions, as compared to heat sensitive cultivars. This is an important factor which needs to be considered when comparing greenhouse crops. Heat tolerant cultivars may therefore perform better in a naturally-ventilated tunnel than in an evaporatively cooled tunnel (Maboko *et al.*, 2010).

2.6 Postharvest Quality Attributes of Tomatoes

Qualitative and quantitative losses associated with the postharvest handling and storage of fruits and vegetables constitute 10 to 50% of the total production in developing countries (BAR, 2010). The mitigation of these losses needs a thorough understanding of the causal agents, as well as the exact nature of the losses. Air temperature and relative humidity, the most important greenhouse environmental conditions, have been found to influence the postharvest quality attributes of most crops, including tomatoes (Matas *et al.*, 2005; Caliman *et al.*, 2010). The quality attributes are genetically programmed; however, their responses may be modified by the climatic conditions, as well as postharvest storage conditions.

Tomatoes are classified as climacteric crops. This is because they have the ability to complete the ripening process after detachment from the parent plant (Martinez-Romero *et al.*, 2007). However, this is only possible if the tomato fruits have reached physiological maturity and the earliest stage at which they can be harvested is the mature-green stage. During the ripening process, physiological changes occur within the fruit, which affect the postharvest storability of the tomatoes. These changes also affect the major attributes, namely, colour, texture and flavour, which are used to evaluate the quality and consumption readiness of the tomatoes. Texture and colour are the primary selection tools employed by consumers when making a purchase, whereas the flavour determines whether the same kind of tomato will be bought again (Kader *et al.*, 2008). During ripening, colour is the most obvious change that occurs in tomatoes, as shown in Figure 2.6. Cantwell (2000) investigated the ripening stages of tomatoes and classified the different colour stages in terms of the colour parameter L^* , a^* , b^* and the hue angle (Table 2.2).

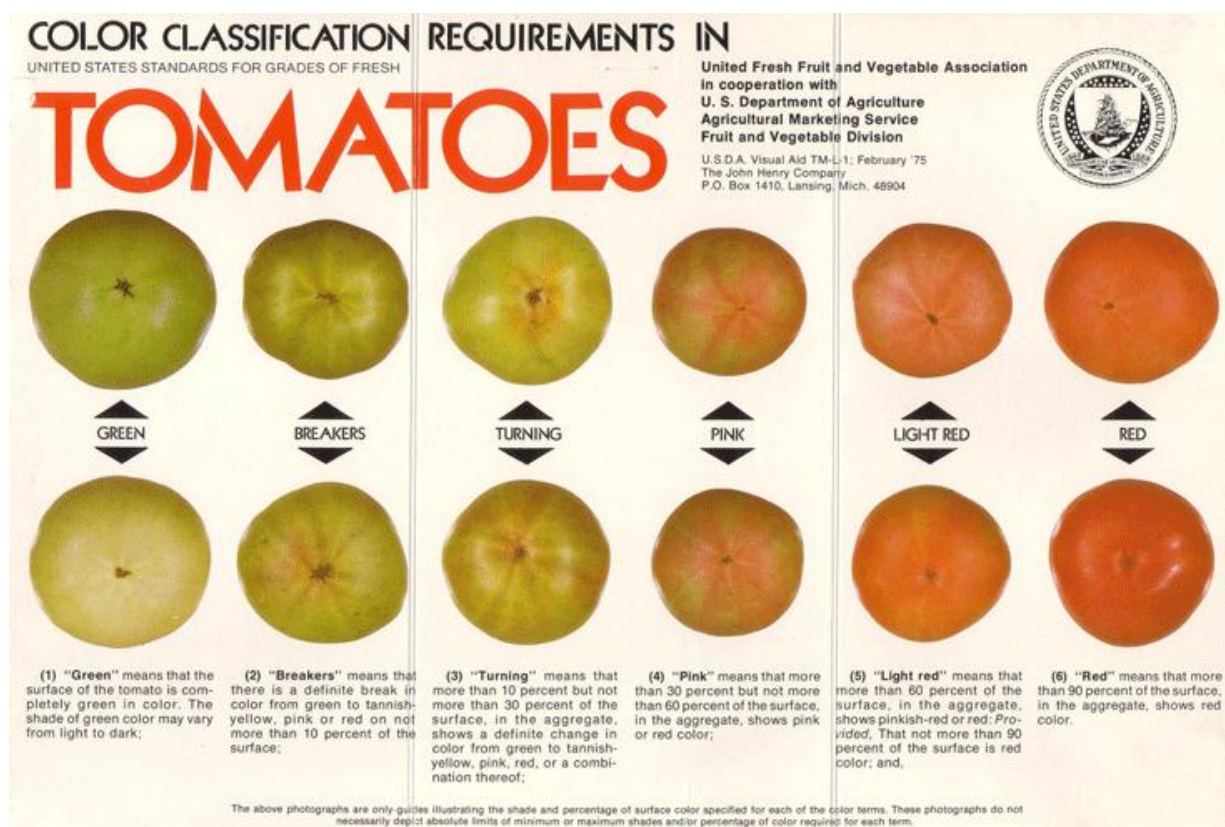


Figure 2.6 Tomato colour stages during the ripening process, (after USDA, 2011)

Table 2.2 Changes in the colour parameters (L*, a*, b* and the hue angle) during the ripening of tomatoes (after Cantwell, 2000)

Ripening Stage	L*	a*	b*	Hue angle (°)
Mature-green	62.7	-16	34.4	115.0
Breaker	55.8	-3.5	33.0	83.9
Pink	49.6	16.6	30.9	61.8
Light red	46.2	24.3	27.0	48.0
Red-ripe	41.8	26.4	23.1	41.3
Over-ripe	39.6	27.5	20.7	37.0

The important factors that have been shown to have a significant influence on the postharvest quality of tomatoes include pre-harvest climatic conditions, genotypic differences and postharvest storage conditions. These factors determine the fruit colour, texture and flavour of tomatoes, quality attributes used by consumers and producers alike to evaluate the maturity, ripeness and acceptability of the tomato fruits (Gorini and Testoni, 1990; Camelo *et al.*, 2004).

2.6.1 Influence of pre-harvest climatic conditions on postharvest quality of tomatoes

Temperature and relative humidity are the important climatic factors that influence the quality of tomatoes. Tomatoes are grown in open-fields, although they are also an important greenhouse crop, particularly in South Africa (Maboko *et al.*, 2009). The negative effects of pre-harvest temperature on the postharvest quality of fruit and vegetables have been observed on several fruit and vegetables. For example, low temperatures during the maturation stages of apples have been associated with the development of the water core disorder (Ferguson *et al.*, 1999). Woolf *et al.* (1999) reported that avocados exposed to direct sunlight and frequently experiencing fruit temperatures above 35°C, had a higher tolerance to postharvest chilling temperatures of 0°C than those which were shaded. In tomatoes, temperatures above 35°C inhibit the synthesis of lycopene in some tomato cultivars, by stimulating the conversion of lycopene to β -carotene (Dumas *et al.*, 2003). Lycopene is responsible for the red pigment of tomatoes, which is often expressed using the colour indicators L*, a* b* and the hue angle (h°). These parameters are an objective classification of the colour change than the USDA colour chart (Camelo and Gomez, 2004). Gruda (2005) reviewed the effects of environmental factors on the quality of fruits and vegetables and reported that, in greenhouse facilities where

temperature is not regulated, extreme high or low temperatures inhibit the normal development of colour in tomatoes. Temperature and RH have also been shown to be instrumental in the postharvest texture of tomatoes. Matas *et al.* (2005) showed that the mechanical properties of the cuticular membranes of tomato fruits are dependent on the temperature and RH, which could affect the textural characteristics of the tomatoes. Khanal *et al.* (2013) studied the effect of different day-night temperature regimes on the postharvest quality attributes of tomatoes. The same mean temperature was maintained, but there were three different day/night temperature regimes (24/17, 27/14 and 30/11°C). It was reported that tomatoes grown under the 27/14°C temperature regime, had a firmer texture, when compared to the other two regimes. Kang *et al.* (2002) also observed a higher firmness in cucumbers grown at higher temperatures. In apples, exposure to high temperature above 40°C, leads to loss of desirable texture (Ferguson *et al.*, 1999, Tustin *et al.*, 1993). The dependence of fruit texture on temperature was attributed to the temperature-dependent nature of cell-wall degrading enzymes (Meli *et al.*, 2010).

The interaction of sugars and acids determine the flavour of tomatoes. The taste and flavour of most horticultural crops, including tomatoes, is influenced by environmental conditions (Mattheis and Fellman, 1999). The accumulation and distribution of the photo-assimilates, mainly carbohydrates, and the partitioning of sugars to different plant organs, depend on the temperature, solar radiation and rainfall (Hewett, 2006). The sugar content of tomatoes is often expressed the total soluble solids (TSS). Gautier *et al.* (2008) reported a higher TSS content in cherry tomatoes grown at a higher temperature. Higher temperatures between 26 and 30°C resulted in an increase in the TSS content in tomatoes (Beckles, 2012). This was attributed to the translocation of sucrose to the fruit during the early stages of development (Ferguson *et al.*, 1999), increased biosynthetic enzyme activity during the ripening stages (Walker and Ho, 1977) and higher transpiration rates due to elevated temperatures (Gautier *et al.*, 2008).

2.6.2 Influence of postharvest storage conditions

Because of their climacteric nature, tomatoes have the capacity to complete the ripening process even after detachment from the parent plant. The physiological and biochemical process responsible for tomato fruit ripening are irreversible processes, which, once initiated,

cannot be stopped (Bapat *et al.*, 2010). However, in climacteric commodities, cold storage can delay the onset of ripening, increase the shelf-life and reduce the postharvest quality losses associated with high storage temperatures (Wills *et al.*, 2007). The processes that occur during the ripening process include transpiration, respiration and other enzyme-driven metabolic processes (Bapat *et al.*, 2010). Temperature and relative humidity (RH) have been found to be instrumental in the postharvest quality of tomato fruits. The minimum optimum postharvest storage of tomatoes depends on the maturity stage. Physiologically mature tomatoes, at the green mature stage, are susceptible to chill injury and prefer storage temperature above 13°C (de Castro *et al.*, 2005). Tomatoes at the red ripe stage are less sensitive to chilling injury and can be stored at 5 to 10°C, especially when under modified atmosphere storage conditions (Gharezi *et al.*, 2012). According to Maul *et al.* (2000), when storage temperature is below 10°C, chilling injury and loss of flavour are avoided. The preferred RH for the storage of tomatoes is 85 to 95% (Moneruzzaman *et al.*, 2009). High relative humidity results in low vapour pressure deficit (VPD), which limits the mass transfer transpiration between the tomato fruit surface and the surrounding environment (Tano *et al.*, 2005). Transpiration, together with respiration and other enzymatic activities that occur during the ripening process are reduced when tomato fruits are stored at the above-mentioned optimum conditions (de Castro *et al.*, 2005). As an example, the integrity of the tomato pericarp, tissues and cell walls are maintained, which allows the tomatoes to retain a firmer texture for an extended period. The colour changes that occur in tomatoes after harvest, from the mature-green stage to red ripe, as shown in Figure 2.1, are also slowed down (Wills *et al.*, 2007).

2.6.3 Genotypic variation effects on postharvest quality attributes

Different cultivars of tomatoes have been found to exhibit varying postharvest trends, although these may be modified by the environmental conditions under which the crop is being grown (Sams, 1999). In particular, tomato cultivars which possess the never-ripening (*Nr*), ripening inhibitor (*rin*), colourless non-ripening (*cnr*) and the non-ripening (*nor*) genes have been found to have an extended shelf-life, compared to those which do not have these particular genetic mutations (Seymour *et al.*, 2002). These genetic mutations affect the texture of tomatoes, particularly the *cnr*, which leads to a mealy tomato. In addition, the cultivars possessing these genes have inferior flavour quality attributes (Kader, 1984; Hewett, 2006). Genetic variations among genotypes have also been found to be a major determining factor,

with regards to differences observed in the acidity and sweetness of tomatoes (Stevens *et al.*, 1977; Mahakun *et al.*, 1979; Kader, 1984, Carli *et al.*, 2011). Relatively high sugars and high acidity produce a tomato with superior flavour (Kader, 1984; Malundo *et al.*, 1995). A high acid concentration and a low sugar content result in a tart-tasting fruit, while a tomato with a high sugar concentration and low acidity produce a bland-tasting tomato. A tasteless tomato results if both the sugar concentration and the acidity are low (Kader, 1984).

The postharvest development of colour has also been shown to be a factor of the genetic background of tomatoes. Varying development of colour has been reported for a substantial number of tomato cultivars (Kader, 1984; Sacks and Francis, 2001; Brandt *et al.*, 2006; Radzevičius *et al.*, 2009). According to Stommel and Haynes (1994), tomato colour pigmentation is controlled by many genes and genotypes with high concentrations of the pigment genes have a richer colour than those with less (Jarret *et al.*, 1984; Sacks and Francis, 2001). These genetic variations of tomato pigmentation are also subject to modifications by environmental conditions (Sack and Francis, 2001). Normal colour development occurs at temperatures between 12 and 30°C (Thai *et al.*, 1990; Camelo and Gomez, 2004). When the growth temperature exceeds 30°C, tomatoes tend to develop a yellow/orange pigment, due to accumulation of orange/yellow carotenoids, as normal synthesis of lycopene is inhibited. When temperatures are below 12°C, the degradation of chlorophyll and the simultaneous synthesis of lycopene are inhibited (Camelo and Gomez, 2004). Cold storage conditions have also been found to lower the TSS content of tomatoes. This has been attributed to lower respiration rates under conditions of cold storage. During respiration, cellulose, starch and other complex polysaccharides are broken down into simpler sugars, to provide energy for metabolic activities (Beckles, 2012). Soluble sugars constitute a substantial fraction of the TSS of tomatoes. Up to 65% of the TSS content of tomatoes is composed of the simple sugars fructose, sucrose and glucose (Kader, 2008; Beckles, 2012).

2.6.4 Storage time effects on the postharvest quality attributes of tomatoes

According to Wills *et al.* (2007), tomatoes are highly perishable commodities and when stored at a minimum storage temperature of 10°C, have a shelf-life of between one and three weeks. The end of the shelf-life often coincides with the onset of decay, due to attack by microorganisms, including fungi and bacteria. For tomatoes harvested at the mature-green

stage, the postharvest storage time is also used for ripening as well as transport from the farmers to the markets. In addition to colour changes and fruit softening discussed in the preceding sections, tomato fruit flavour and acidity are also affected by storage time. Studies have shown that, the TSS content of tomatoes increases with increasing storage time and fruit maturity (Salunkhe *et al.*, 1974; Žnidarčič *et al.*, 2010). Cantwell (2000) reported TSS values of 2.37, 2.42 and 5.15°Brix for tomatoes at the mature-green, breaker and the red-ripe stages, respectively. This increase has been attributed to the breakdown of complex sugars into simple sugars, driven by the respiration process taking place during the ripening process. The acidity, accompanied by a simultaneous reduction in the pH of tomatoes, has also been shown to increase with maturity and an increase in storage period (Davies and Hobson, 1981; Žnidarčič and Požrl, 2006; Caliman *et al.*, 2010). The pH of maturity green tomatoes was found to be 4.20, 4.17 at the breaker stage and 4.12 at the red-ripe stage (Cantwell, 2000).

2.7 Discussion

The microclimate conditions that are important for crop growth are solar radiation, temperature, RH, internal air velocity and CO₂ levels. Of these environmental factors, temperature and relative humidity are the most critical parameters, which can be controlled to ensure optimum growth conditions and improved yields. These factors are functions of the latitude, climate and ventilation system of a greenhouse. Natural ventilation is the most common method of internal environmental control, since it is less costly to install and has lower energy requirements for the manipulation of the internal environment. The common side and/or roof ventilation system in naturally-ventilated structures was developed for the milder environmental conditions prevalent in the northern hemisphere (Boulard *et al.*, 1997). The internal microclimate has been observed to be variable, with higher air velocity at the vent openings and calmer conditions at the centre of the greenhouse. The internal air temperature and RH, which tend to depend on the internal air flow pattern, are also non-uniform, thus creating non-optimum growth conditions. Because of this variation, the crop growth and yield may also be variable.

Although there is limited literature on greenhouse ventilation systems for any of the variable agro-climatic conditions in Sub-Saharan Africa, the performance of the roof and/or side naturally-ventilated structures may be hampered by high solar radiation and external

temperatures that are characteristic of Southern Africa. Maboko *et al.* (2010) and Mashonjowa *et al.* (2010) both measured high internal air temperatures in naturally-ventilated greenhouse facilities, which were non-optimal for crop performance.

The fan-pad evaporative cooling and ventilation system may be used as an alternative system to natural ventilation, for modifying the micro-environmental conditions in greenhouse structures. However, this system has high installation, operational and maintenance costs (Ould Khaoua *et al.*, 2006; Flores-Velaquez *et al.*, 2010). Furthermore, in humid and sub-humid climatic zones, such as the coastal areas of Southern Africa, its performance may be limited by high relative humidity (Kumar *et al.*, 2009). Comparison between these two systems shows that fan-pad evaporative cooling maintains lower internal temperatures and higher relative humidity levels than natural ventilation using roof and/or side ventilators. The temperatures in naturally-ventilated structures are often above, or fluctuate around, external ambient air conditions. Although the relative humidity in the naturally-ventilated greenhouse is consistently lower than in the fan-pad evaporative cooled system, it falls within the optimum range recommended for greenhouse crops.

Different researchers report conflicting crop growth and yield results from these two systems. Although extensive research on greenhouse facilities has not been done in Southern Africa, investigations conducted in South Africa indicated that crops grown in a fan-pad evaporatively-cooled and ventilated greenhouse grew faster and produced higher marketable yields than in a naturally-ventilated greenhouse (Maboko *et al.*, 2010). Investigations conducted in countries in the northern hemisphere indicate that although the naturally-ventilated facilities produced smaller sized produce, the produce was of better marketable quality than in the evaporative cooled facilities (Teitel *et al.*, 2007; Max *et al.*, 2009). Although it is possible that the difference in the quality of produce could have been due to varying cultivar heat tolerance levels, the internal microclimate also has a profound effect on the quality of the crop. The conflicting results clearly illustrate the dependence of the internal environmental microclimate conditions on the external environment and the need to develop structures that are less expensive and more suited for the variable agro-climate conditions in the Southern African region.

Pre-harvest climatic conditions have a profound effect on the postharvest quality of tomatoes. Growth temperatures above 32°C and below 12°C inhibit the normal development of the red colour of tomatoes (Gruda, 2012). The temperature and RH also affect the cuticular membranes of the tomatoes, influencing the texture of tomatoes (Matas *et al.*, 2005). This has been attributed to the temperature-dependence of the enzymatic activity on the cell wall of tomatoes (Meli *et al.*, 2010). High temperatures during the developmental stages of the fruits, aid the translocation of sugars, mainly sucrose, to the fruits, whereas increased enzymatic activity during the ripening stages results in tomato fruits with high sugar contents.

In addition to pre-harvest climatic conditions, the postharvest qualities of horticultural crops are also subject to genetic variations and postharvest storage temperature and RH. However, genetic responses may be modified by pre-harvest conditions. For example, instead of the normal red colour of tomatoes, a yellow colour may be synthesized in response to high growth temperatures (Camelo and Lopez, 2004). Cold storage temperature and high RH delay the ripening process and extend the shelf-life of tomatoes. Cold temperatures reduce the respiration and transpiration rates and the accompanying biochemical activities, which delays the change in colour and texture that occurs in postharvest. Understanding the response of tomatoes to the greenhouse microclimates of greenhouse facilities available in South Africa, can provide information for selection of both greenhouse type and cultivar. It can also help to minimize the losses that occur after harvesting, as well as the type of storage facilities required.

2.8 Conclusions

In spite of the potential for income generation and the alleviation of poverty and malnutrition offered by greenhouse agriculture in Southern Africa, very little research has been carried out on the performance of common greenhouse designs. In conclusion, the current passive ventilation configuration on greenhouse structures is more suitable for mild climatic conditions where solar radiation and external air temperatures are lower than those experienced in South Africa. In warmer climates, these facilities may under-perform and create non-optimum crop growth conditions. The lack of information could mean that non-optimum choices are being made by farmers when selecting which greenhouse to use. It is therefore imperative to generate data on greenhouse microclimates in South Africa,

specifically the passive and fan-pad evaporatively cooled systems, which can be used to inform the selection and development of appropriate ventilation systems suited for the various South African agro-climates.

2.9 References

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3. A COMPARISON OF TWO GREENHOUSE STRUCTURES (OPEN-ENDED AND FAN-PAD VENTILATED) UNDER SUB-HUMID CONDITIONS AND THE EFFECTS ON TOMATO PRODUCTION

Abstract

Ventilation is important for the reduction of solar heat gain in greenhouse structures, especially in the sub-tropics and tropics. The two main techniques used in the ventilation of agricultural greenhouses are natural and fan-pad evaporative cooling. The microclimate in a fan-pad evaporative cooled tunnel (FPVT) and an open-ended, naturally-ventilated tunnel (NVT) was investigated during the summer of 2012-2013. The effect of the microclimate on crop growth, yield and quality, using four tomato cultivars, was also investigated. The experiment consisted of two greenhouse ventilation systems, the FPVT and the NVT, without replications. Two microclimate variables, air temperature and relative humidity, were measured inside the tunnels. Crop growth was measured in terms of plant height, leaf number, leaf area and vegetative biomass. Crop yield was measured in terms of total yield (TY) fresh mass, total marketable yield (TMY) fresh mass and total unmarketable yield (TUY) fresh mass. The quality of the tomatoes was measured in terms of undersized (US), blossom end-rot (BER) affected, insect damaged (ID), cracked (CR) and deformed (DF) fruit mass. There were significant differences in the daytime air temperatures and relative humidity levels between the FVT, NVT and the outside. The temperature in the NVT was 4 to 5°C higher than in the FPVT at midday, when solar radiation was at its peak. The relative humidity was higher in the FPVT than the NVT. At night, there was no significant difference in temperature. The relative humidity differed significantly between the FPVT, NVT and the outside. The microclimate in both tunnels was non-uniform. During the daytime, the air temperatures were lower in the crop canopy than close to the cover. At night, air temperatures were lower close to the cover than within the crop canopy inside both tunnels. TY and TMY from the FPVT were not significantly different from TY and TMY from the NVT. TUY was significantly ($P < 0.001$) higher in the NVT than in the FPVT. Under-sized and insect-damaged fruit were significantly higher in the NVT than in the FPVT. A cost benefit analysis for FPVT and NVT needs to be conducted for these two tunnels. Whitewashing and near infrared reflective screens could be investigated as tools to reduce the extreme solar heat gain of the greenhouses.

3.1 Introduction

Greenhouse technology has been widely adopted for the modification and control of the aerial environment of high value crops (Jensen, 2002). It has been driven primarily by the demand for high quality fresh commodities in developed countries, including fruit, vegetables, herbs and flowers (Waaijenberg, 2004; van Henten *et al.*, 2006). In Sub-Saharan Africa, where an estimated 26.4% of the population is under-nourished (FAO, 2013), small-scale greenhouse facilities can assist in the production of quality fruit and vegetables, to mitigate food insecurity and malnutrition.

Greenhouse microclimates are dependent on the prevailing climatic conditions, as well as the latitude, and the design and functional characteristics of the greenhouse. While greenhouse microclimate research has mostly been conducted in the Mediterranean (Boulard *et al.*, 1997; Bartzanas *et al.*, 2004; Boulard *et al.*, 2004; Kittas and Bartzanas, 2007; Lopez *et al.*, 2011) and the Indian sub-tropical areas (Ganguly and Ghosh, 2007; Shukla *et al.*, 2008; Kumar *et al.*, 2010), few recent studies have been done in the African sub-tropical areas (Mills *et al.*, 1990; Mashonjowa *et al.*, 2010b; Maboko *et al.*, 2010).

Greenhouse structures protect crops from adverse climatic conditions, including wind, rain, hail, frost and pest infestation and allow the microclimate to be controlled (Bakker and Challa, 1995). The greenhouse cover needs to be transparent, to allow photosynthetic active radiation to enter the greenhouse. However, the near infrared radiation spectrum of the solar radiation entering the greenhouse is converted to long-wave heat radiation (Baxevanou *et al.*, 2007). This long-wave radiation is trapped inside and increases the air temperature and vapour pressure deficit. In the sub-tropics, particularly in summer, when solar radiation is high, this leads to undesirably high internal greenhouse air temperatures and vapour pressure deficits (Mashonjowa *et al.*, 2010b).

Several ventilation measures have been used to control the microclimate and maintain the temperature and relative humidity at desirable levels. The most common include fan-pad evaporative cooling, fogging and misting (Katsoulas *et al.*, 2001; Arbel *et al.*, 2003; Kittas *et al.*, 2003; Garcia *et al.*, 2011) and natural ventilation (Boulard *et al.*, 1997; Katsoulas *et al.*, 2006; Mashonjowa *et al.*, 2010a). These techniques may be used, together with internal

aluminium folding shade screens (Callejón-Ferre *et al.*, 2009), near infrared reflecting screens (Stanghellini *et al.*, 2011) and whitewashing the cover with calcium carbonate (Baille *et al.*, 2001; Meca *et al.*, 2006; Jimenez *et al.*, 2010, Mashonjowa *et al.*, 2010b), to reduce the greenhouse solar heat gain.

Comparisons between greenhouses with fan-pad (FPV) or natural ventilation (NV) have shown that evaporative cooling can maintain lower temperatures and vapour pressure deficits than naturally-ventilated structures (Willits and Li, 2005; Mutwiwa *et al.*, 2007; Teitel *et al.*, 2007; Max *et al.*, 2009; Maboko *et al.*, 2009). FPV systems are particularly effective in hot and dry areas, but their effectiveness in sub-humid and humid areas may be hampered by low vapour pressure deficits (Kumar *et al.*, 2009). In addition, the microclimates in fan-pad systems have been found to vary horizontally between the pad and the fan, as well as vertically. Temperatures and vapour pressure deficits tend to be high near the fan section and low, closer to the pad section (Kittas *et al.*, 2003; Oz *et al.*, 2010). Similarly, temperatures tend to increase with height inside the greenhouse (Kittas *et al.*, 2003; Li and Willits, 2008).

Natural ventilation, a function of air convection and temperature gradients, is usually achieved through roof and/or side vents (Boulard *et al.*, 1997; Kumar *et al.*, 2009). As with the FPV structures, the microclimate in NV greenhouses have also been found to have a non-uniform microclimate. Temperatures and vapour pressure deficits have been found to be low near the vent openings and higher in the interior (Boulard *et al.*, 2004). Temperatures also increase with increasing height inside the greenhouse, especially in side-wall ventilated structures (Teitel *et al.*, 2008a). Natural ventilation is entirely dependent on external climatic parameters and may consequently be inefficient in maintaining desirable temperature and air moisture contents, especially in high solar radiation latitudes (Bailey, 2006).

The effect of these two microclimates on crops has been investigated by several authors. Willits and Li (2005), Mutwiwa *et al.*, (2007) and Max *et al.* (2009) reported faster growth from a NV tunnel, with higher marketable crop yields. On the other hand, Maboko *et al.* (2010) reported higher total and marketable crop yields from a FPV than from a NV tunnel. In addition, physiological disorders such as blossom end rot (BER), undersized fruits, deformed or misshapen and cracked fruits in greenhouse tomatoes have been associated with greenhouse temperature and relative humidity (Blanc, 1986; Waquant, 1995; Adams *et al.*,

2001; Estergaard *et al.*, 2001; Max *et al.*, 2009). These disorders have the potential to reduce marketable yields in greenhouses.

In South Africa, the most common method of cooling in greenhouses is roof and/or side ventilation, although fan-pad evaporative cooling is gaining popularity (Maboko *et al.*, 2010; DAFF, 2012). However, FPV systems are expensive to install, operate and maintain and require a constant and adequate supply of good quality water and electricity. This may render them unaffordable to small-scale, resource-poor farmers in a country where 26% of the population lives below the poverty datum line (Kollodge, 2011). Although cheaper and simpler to use (Teitel *et al.*, 2010; Flores-Velázquez *et al.*, 2011), the microclimate in the common side and/or roof ventilated structures is entirely dependent on the external weather variables (Bailey, 2006). In addition, these structures were developed to suit the agro-climatic conditions in the milder climates of the northern hemisphere (Garcia-Alonso *et al.*, 2006). This may render them inefficient in maintaining the desirable microclimate, especially under high solar radiation conditions, such as those prevalent in South Africa.

Naturally-ventilated greenhouses with screen-covered open ends may offer a cheaper alternative to summer production in high temperature areas, such as the Pietermaritzburg area in KwaZulu-Natal. Pietermaritzburg falls on the periphery of the humid eastern coast of KwaZulu-Natal. It experiences warm summers, with mean daily maximum temperatures of up to 32°C (Schulze, 2007), but absolute maximums can reach 40°C. Solar radiation is high in summer, reaching >1000 W.m⁻² on clear summer days (Mills *et al.*, 1990). A study was undertaken with the following objectives:

- To compare the microclimate in an open-ended naturally-ventilated tunnel (NVT) and a fan-pad evaporatively-cooled tunnel (FPVT) in Pietermaritzburg, KwaZulu-Natal South Africa, during summer.
- To investigate the effect of the two above-mentioned microclimates on the growth, yield and quality of tomatoes.

3.2 Materials and Methods

The following sections describe the experimental site, greenhouses, experimental design and materials and methods that were used for the research project. The research project was

conducted at the Ukulinga Research Farm of the University of KwaZulu-Natal, Pietermaritzburg, South Africa (29.67°S and 30.40°E, 840 m above sea level), during summer, from October 2012 to January 2013. The long-term mean maximum and minimum temperature ranges between 20.6-27.8 C and 6.0-16.4°C, respectively. The daily mean relative humidity is between 61.1-75.3% and solar radiation is from 15.1-27.8 MJ.m⁻².day⁻¹ (Schulze and Maharaj, 2007).

3.2.1 Greenhouses

All experiments were conducted in two identical greenhouse tunnels, with floor areas of 144 m² and ridge heights of 3.5 m. Both greenhouses were 18 m in length, with a floor width of 8 m. They had an east-west orientation and were 4.4 m apart. The tunnels were made of galvanized steel frames, covered with a 200 µm ultra-violet treated, low density polyethylene film. The naturally-ventilated tunnel was open-ended and the open ends were covered with black and white Knittex[®] 40 insect screen netting. The other tunnel was fan-pad evaporatively cooled by a fan-pad system, with a 0.1 m × 5.3 m × 1.15 m Celdek[®] wet-wall on the east side at 0.95 m from the ground. On the west side, the tunnel had a 1.13 m, 1100 W single-speed fan, placed 0.95 m from the floor, as shown in Figure 3.1.

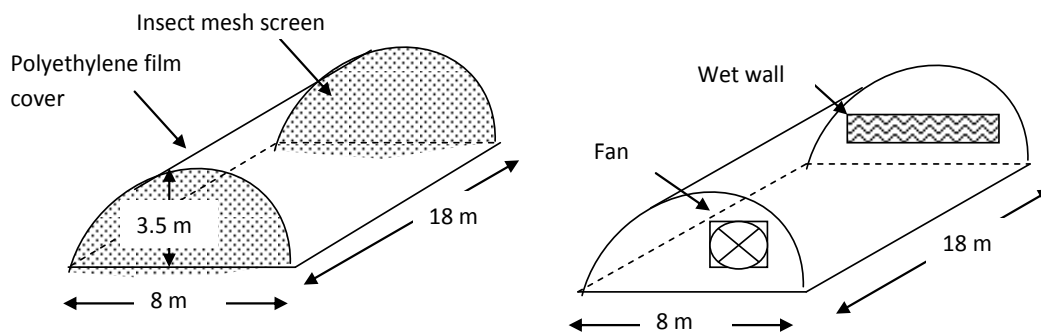


Figure 3.1 Schematic diagrams of the greenhouse tunnels.

3.2.2 Experimental design

The experiment consisted of two greenhouse ventilation system treatments, one being a fan-pad evaporatively cooled tunnel (FPVT) and open-ended naturally-ventilated tunnel (NVT), without replications. The fan-pad evaporative cooling was set to switch on when the internal temperature exceeded 28°C or when the relative humidity fell below 60%, and off, when the

minimum temperature reached 20°C or the relative humidity exceeded 90%. Internal temperature and relative humidity were measured, using six sensors/data loggers placed in a grid pattern along the centre of each greenhouse, as shown in Figure 3.2. On the horizontal plane, two data loggers were placed 3 m from each end and along the main axis of the greenhouse and the other two at the centre of the greenhouse, 6 m from the other two sets of data loggers. On the vertical plane, the lower sensors were placed 1.15 m from the greenhouse floor and, on the upper level, 1.15 m from the roof, with one sensor at each position. The positions of the sensors/data loggers were labelled upper 1 (U1), upper 2(U2), upper 3 (U3), lower 1(L1), lower 2 (L2) and lower 3 (L3).

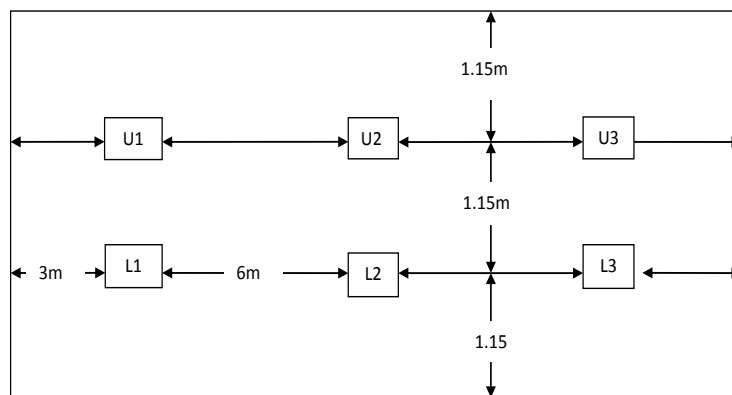


Figure 3.2 Arrangement of the sensors inside the tunnels

In the FPVT, Positions 1, 2, 3 refer to the fan, middle and pad sections, respectively, and in the NVT, Positions 1 and 3 refer to the west and east sections of the tunnel and Position 2 is the middle of the tunnel. This arrangement was selected, in order to facilitate the observation of the vertical and horizontal stratification and non-homogeneity of the internal temperature and relative humidity distribution inside the tunnels. The greenhouse internal air temperature and relative humidity in each tunnel was measured throughout the plant growing period, using six Hobo[®] Pro v2 optic data loggers (Onset Computer Corporation, Bourne, USA) with temperature and relative humidity sensors (Lopez *et al.*, 2010). The temperature sensors had a measurement capacity of between -40 and 70°C, with an accuracy of $\pm 0.2^\circ\text{C}$. The relative humidity sensors had a measuring capacity of between 0 and 100%, with $\pm 2.5\%$ accuracy. The internal temperature and relative humidity were logged every 30 minutes and the measurements averaged hourly. The external climate variables were measured from a local meteorological weather station situated 60 m from the greenhouses.

3.2.3 Crop production

Four tomato cultivars, shown in Table 3.1, were grown in the two tunnels. Seven-week old seedlings of the four cultivars, sourced from a local nursery, were transplanted into 10 L plastic bags containing potting media on the 27-28th September 2012. The plastic bags were placed in double rows, with 1.2 m between the double rows and an intra-row spacing of 0.5 m and 0.5 m between individual plants within the rows (Maboko *et al.*, 2010). The tomato plants were pruned by removing suckers once a week, in order to maintain a single stem. The plants were supported by training the single stem using twine, which was secured to an overhead galvanized wire running parallel to the rows, 2 m above the floor (Snyder, 2003). The plants in both tunnels were sprayed to control early blight, using the fungicide Folicur[®], and late blight, using Ridomil Gold FLO[®] and Amistar[®]. In the NVT, tomatoes were sprayed for the control of tomato fruit caterpillar and against red spider mite, using the insecticides cypermethrin (Karate[®]) and abemectin (Vertimec[®]), respectively.

Table 3.1 A list of the tomato cultivars used to assess the effect of the tunnels' microclimates on crop growth, yield and quality. The suppliers of the seeds and the growth habit of the cultivars are also indicated.

Cultivar	Supplier	Growth habit
Bona	Alliance Seeds	Indeterminate
Star 9037	Starke Ayres	Indeterminate
Star 9009	Starke Ayres	Determinate
Zeal	Sakata Seeds Southern Africa	Determinate

3.2.4 Irrigation and fertigation

The tomato plants were irrigated, using one arrow dripper per plant connected to spaghetti tubing, which supplied 2.1 L.hr⁻¹. The plants were irrigated six times a day every two hours for 12 minutes per irrigation event, with the first irrigation at 7.00 am, supplying 2.52 L.plant⁻¹.day⁻¹. Fertilizers were applied through a bulk tank system, using Hygroponic[®] and Solu-cal[®] (Hygrotech Pty. Ltd, South Africa), delivering N (68 mg.kg⁻¹), P (42 mg.kg⁻¹), K (208 mg.kg⁻¹), Mg (30 mg.kg⁻¹), S (64 mg.kg⁻¹), Fe (1254 mg.kg⁻¹), Cu (22 mg.kg⁻¹), Zn (149 mg.kg⁻¹), Mn (299 mg.kg⁻¹), B (373 mg.kg⁻¹), Mo (37 mg.kg⁻¹), N (117 mg.kg⁻¹) and Ca (166 mg.kg⁻¹),

respectively. The plants were also supplied with potassium nitrate, delivering K (38.6 mg/kg) and N (13.8 mg.kg⁻¹). The target EC for the tomatoes was 2.2µS from transplanting until the first flowers appeared during which time 0.722 kg.1000L⁻¹ and 0.622 kg.1000L⁻¹ Hygroponic[®] and Solu-cal[®] were applied. From the appearance of the first flower truss until the third truss, Hygroponic[®] and Solu-cal[®] were applied at 1.080kg.1000L⁻¹ and 0.56 kg.1000L⁻¹, respectively. After the third flower truss appeared, 0.938 kg.1000L⁻¹ Hygroponic[®], 0.628 kg.1000L⁻¹ Solu-cal[®] and 0.234 kg.1000L⁻¹ potassium nitrate were applied.

3.2.5 Data collection

Vegetative plant growth data (plant height, number of leaves, dry matter and leaf area) were collected, starting from the first week after transplanting. Plant height and leaf number were collected on a weekly basis, from 10 randomly-selected plants per cultivar per greenhouse. Destructive sampling was carried out fortnightly, on four randomly-selected plants per cultivar per greenhouse, to determine the leaf area and dry matter accumulation. Leaf area was determined, using a LI-3000C[®] (Li-Cor Environmental, Nebraska, USA) leaf area meter, with an accuracy of ±1%. Dry matter was determined by oven-drying the whole plant, including leaves, stems and roots, at 80°C for 48 hours (Max *et al.*, 2009).

The yield and quality of produce was determined by harvesting tomato fruits from the 10 randomly-selected plants at breaker stage once a week, from December 2012 until February 2013. The harvested fruits were assessed for total yield fresh mass, which was further divided into total unmarketable yield (TUY) and total marketable yield (TMY). The total marketable yield included all fruits which were undersized (US), those <50 g, blossom end-rot (BER) affected, cracked (CR), insect-damaged (ID), or otherwise deformed (DF) (Max *et al.*, 2009).

3.2.6 Analysis

Statistical analysis of temperature, relative humidity, growth, yield and quality parameters was done by analysis of variance (ANOVA), using Randomized Complete Block Design (RCBD) in the MSTAT-C statistical and data management package (Michigan State University, 1993). Comparisons between treatment means were done, using Duncan's Multiple Range Test (Duncan, 1955), with evaluations based on a P=0.05 significance level.

3.3 Results

Daytime and night-time temperatures, relative humidity and plant growth, yield and quality are presented in this section.

3.3.1 Daytime temperature and relative humidity

Daytime hourly means of temperatures measured between 6.00 am and 18.00 pm for the NVT, FPVT outside (EXT) for the months of October, November, December and January, are shown in Figure 3.3.

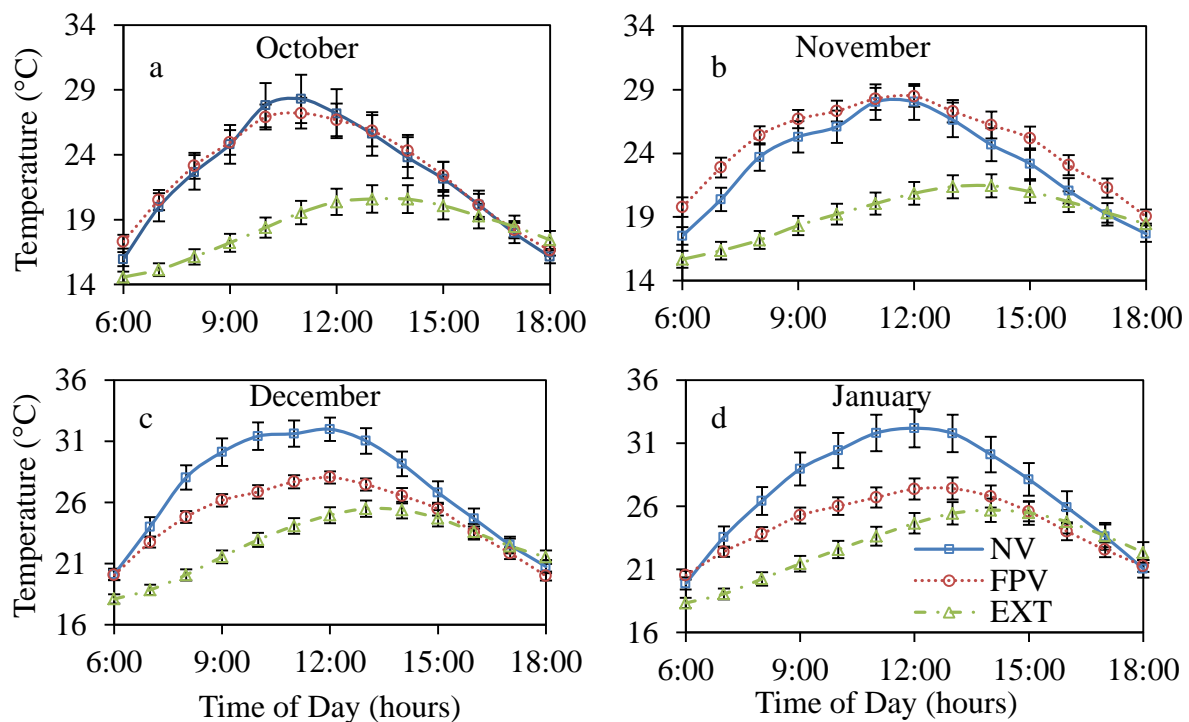


Figure 3.3 Mean daytime hourly temperature variations in the naturally-ventilated (NV), the fan-pad evaporatively cooled (FPV) tunnels and outside (EXT) for the months of October to January

These Figures show that, the daytime mean hourly internal temperatures in the FPVT and NVT tunnels for all four months, were significantly ($P < 0.01$) higher than the external temperatures. The peak internal air temperatures in the tunnels coincided with the peak solar radiation (R_s) for all four months, while the peak external temperature lagged FPVT, NVT

and R_s by one to two hours, as shown by Figure 3.4. In October and November, there were no significant differences ($P>0.05$) between FPVT and NVT (Figure 3.3a and b). In December and January, the FPVT internal air temperature was significantly lower ($P<0.001$) than the NVT internal air temperature (Figures 3.3c and 3.3d). In December, the peak temperature in the NVT was 3.6°C higher than the FPVT peak temperature. In January, the peak temperature difference between the FPVT and the NVT was 4.8°C .

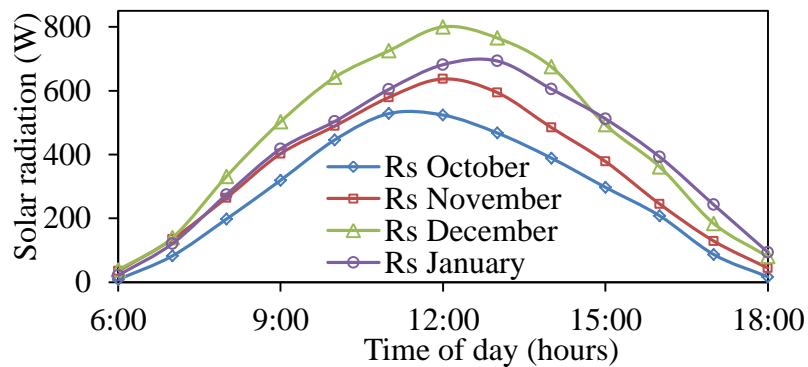


Figure 3.4 Mean hourly solar radiation (R_s) during the day for the months from October to January

Figure 3.5 shows the hourly mean daytime relative humidity in the FPVT and the NVT. The relative humidity decreased significantly with increasing solar radiation, starting from the morning, and increased with decreasing solar radiation in the afternoon. The difference in the relative humidity between the two tunnels was highest in the middle of the day when solar radiation was at its peak, particularly in December and January. There were significant differences ($P\leq 0.01$) in the relative humidity between the two tunnels throughout the observation period. The air humidity in the NVT ranged from 49-90% and 59-95% in the FPVT. In the NVT, air humidity was lowest in December, with 49% (Figure 3.5c). In the FPVT, the lowest relative humidity was in October and November at 59% (Figure 3.5a and b). Relative humidity levels were lower in October and November than in December and January. In October and November, the difference in relative humidity was small, when compared to December and January (Figures 3.5c and 3.5d). There was a 10% relative humidity difference between the two tunnels in October and November (Figure 3.5a and b). In December and January, the air humidity in the NVT was 20-26% less than in the FVT at midday (Figure 3.5 c and d).

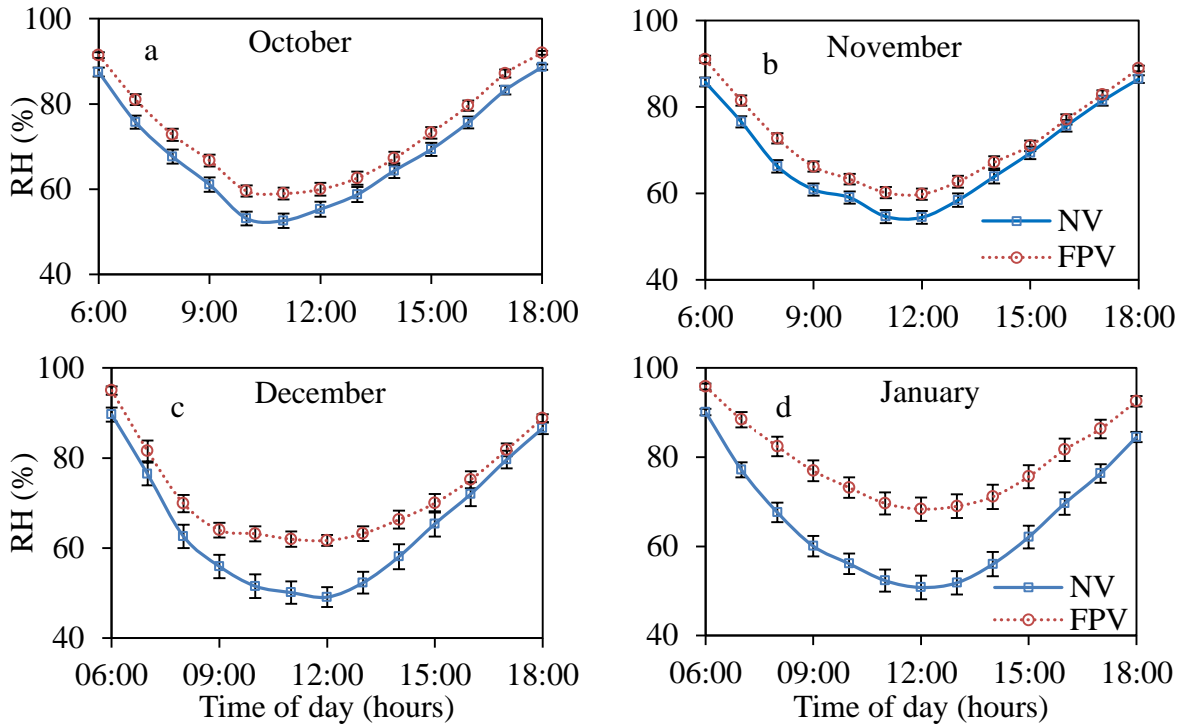


Figure 3.5 Mean hourly daytime relative humidity in the fan-pad evaporative cooled (FPV) and the naturally-ventilated tunnel (NV) tunnels.

3.3.2 Night-time temperature and relative humidity

The night-time (19:00 pm - 5:00 am) air temperatures in the NVT, FPVT and outside are shown Figure 3.6. There were no significant differences ($P>0.05$) between the NVT, FPVT and external temperatures throughout the study period. However, the air temperature in the NVT was lower than in both the FPVT and outside, whereas in the FPVT, the temperature was more or less the same as outside. The air moisture content was significantly different between the FPVT, NVT and the outside air, as shown in Figure 3.7. The relative humidity was consistently higher in the FPVT, followed by the NVT, and was lowest outside. The FPVT air humidity levels ranged between 94 and 100%. The NVT air humidity was between 91 and 96%, while the external air humidity ranged between 85 and 91%. In the NVT, the relative humidity trends followed the outside trend, increasing when the external relative humidity increased and decreasing when the outside relative humidity decreased.

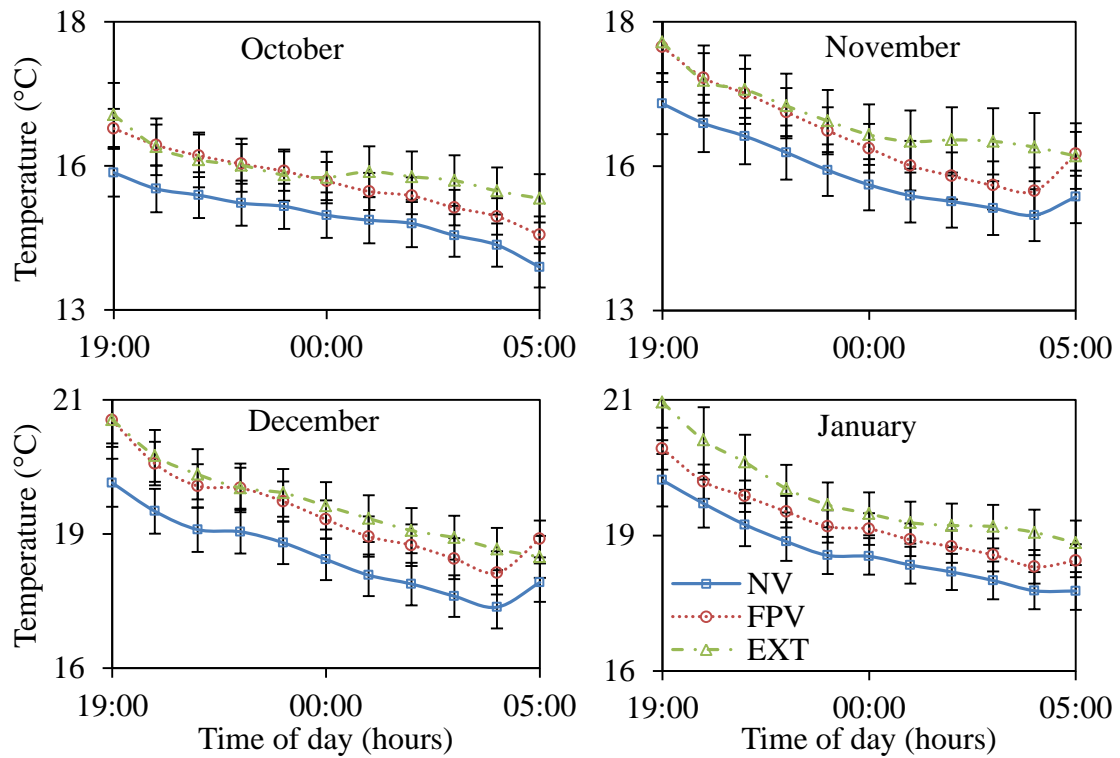


Figure 3.6 Mean hourly night-time temperatures in the naturally-ventilated (NV) tunnel, the fan-pad evaporatively cooled (FPV) tunnel and outside (EXT).

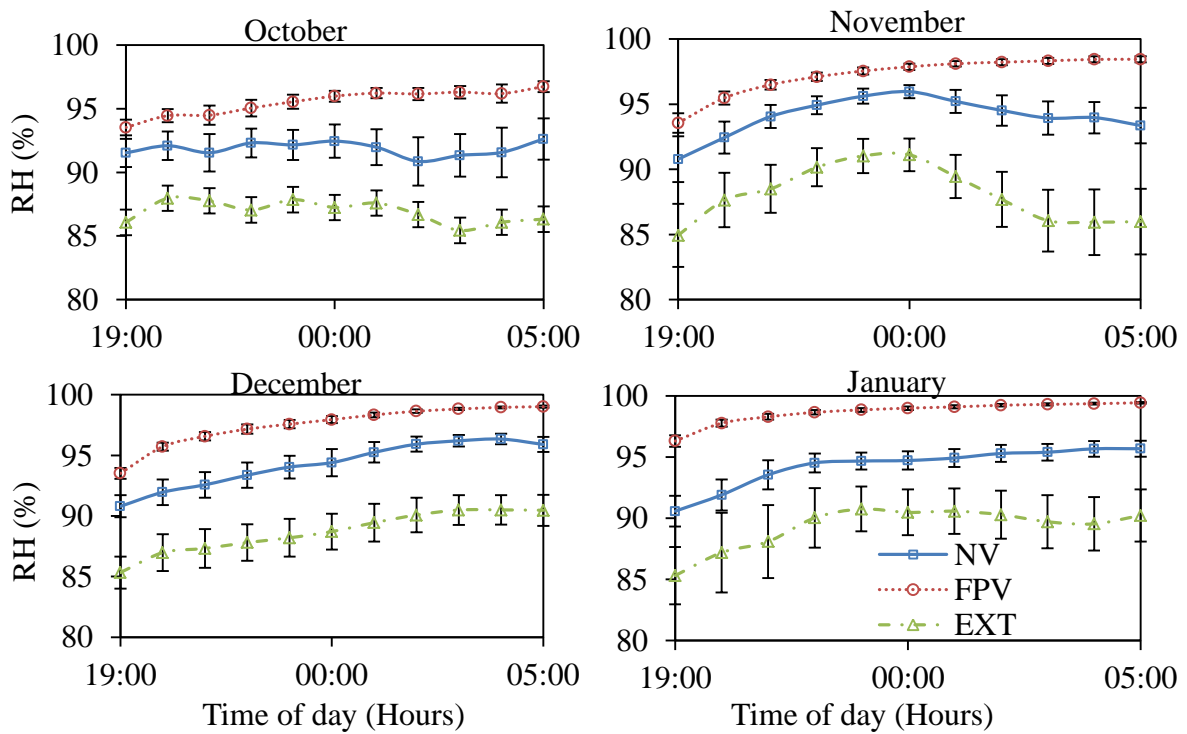


Figure 3.7 Mean hourly night-time relative humidity in naturally-ventilated (NV) and the fan-pad evaporatively cooled (FPV) tunnels and outside (EXT).

3.3.3 Stratification of internal microclimate conditions

Figure 3.8 shows the hourly mean temperatures and relative humidity at different positions inside the tunnels. The positions were selected to represent the vertical and horizontal profiles of temperature and relative humidity along the centre of the greenhouses and allowed the investigation of the stratification and microclimate distribution inside the tunnels

Figure 3.8 shows that there was more variation in temperature and relative humidity throughout the observation period during the daytime than at night, in both the NVT and the FPVT. The daytime and night-time temperatures and relative humidity at the different positions were significantly different ($P < 0.001$) in both tunnels. The highest temperature and relative humidity differences were observed at midday, when solar radiation was at its highest. However, in October and November, there were no significant differences ($P > 0.05$) in the night-time temperature between the lower and upper levels in the NVT.

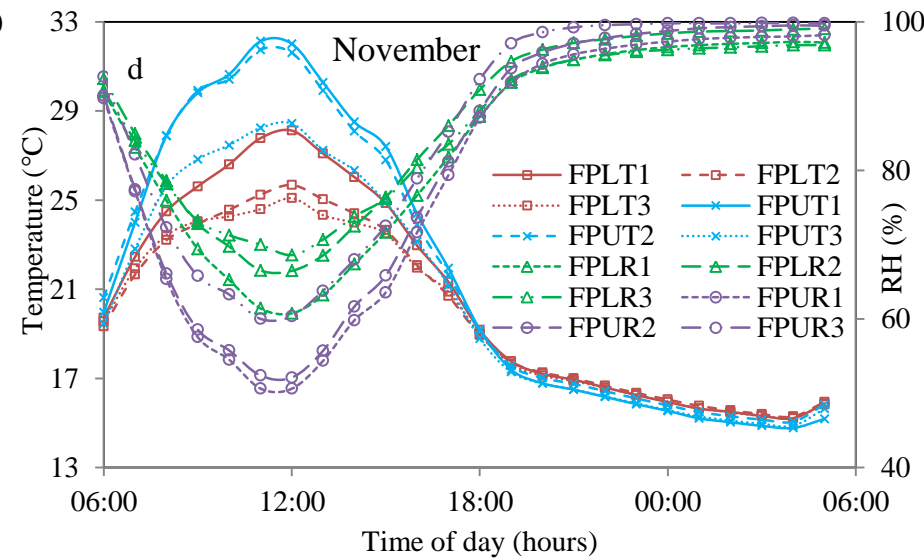
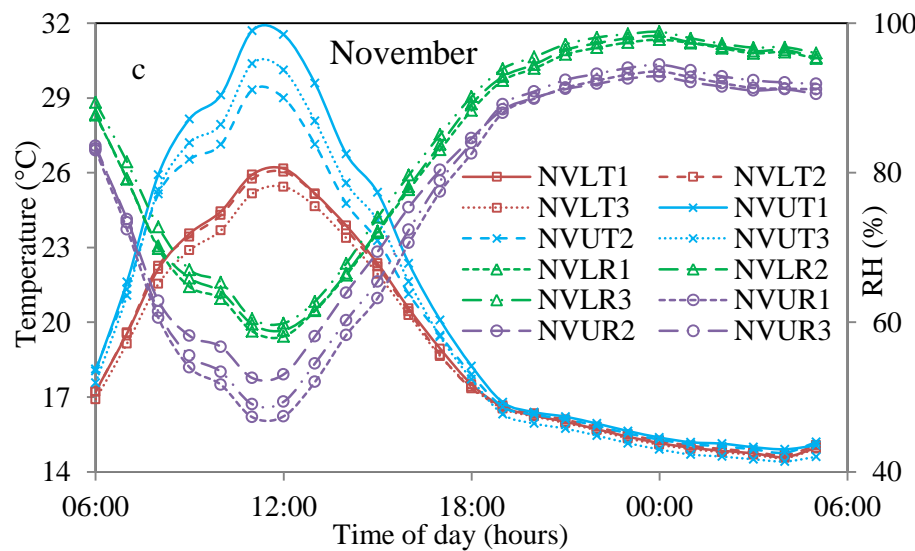
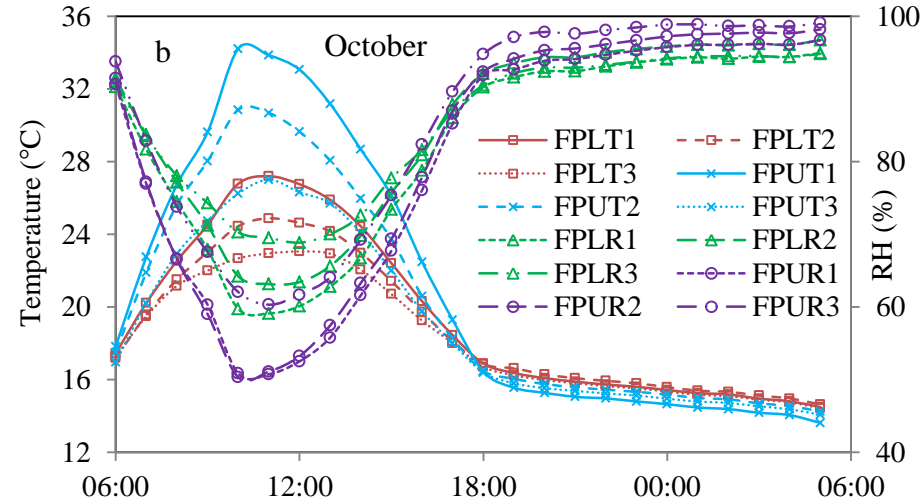
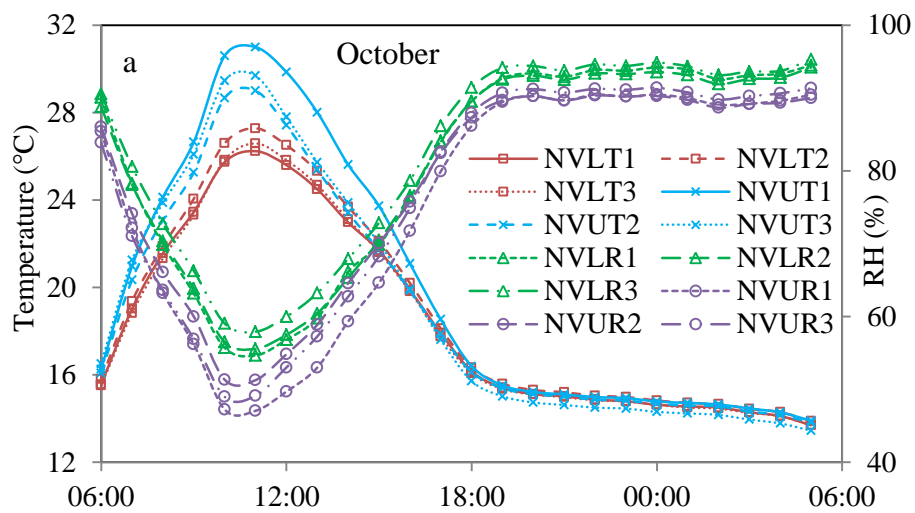
Inside the FPVT, the air temperature was significantly ($P < 0.001$) lower at the pad section and highest at the fan section, on both the lower and the upper levels, as shown in Figures 3.8b, 3.8d, 3.8f and 3.8h. The horizontal difference was significantly ($P < 0.001$) higher at the upper than at the lower level. The highest temperature differences were observed in October (Figure 3.8b). The highest horizontal temperature difference between the pad and fan sections was 7.97°C and 4.25°C at the upper and lower levels, respectively. At the upper level, the highest temperature difference between the pad and the fan was in October. The highest vertical temperature difference between the upper and lower levels was 7.43°C .

The daytime relative humidity in the FPVT was significantly higher ($P < 0.01$) at the pad section than at the middle and fan sections. The air humidity level was also significantly higher at the lower level than at the upper level. The highest relative humidity level was at the lower pad section and was lowest at the upper fan section. As in the NVT, the air humidity was significantly higher at the lower level than the upper level. There were smaller differences in the relative humidity between the recording points at the lower level in the NVT. At the upper level, the relative humidity was significantly higher ($P < 0.01$) at the east-end than the middle and west-end of the NVT.

Inside the NVT, the temperature differences were significantly higher ($P<0.001$) at the upper level than at the lower level in all months, except in December. The highest temperature difference between the upper and the lower levels was 5.78°C in November. There were also significant ($P<0.01$) differences between Positions 1, 2 and 3. At the upper level, the air temperature was highest at the west end (Position 1) and lowest at the east-end (Position 3) of the tunnel. At the lower level, the air temperature was lowest at the east end of the tunnel in all months except October. During the months of November, December and January, the temperature in the middle of the tunnel was at the same level as the west-end of the tunnel.

Similarly, there were significant differences ($P<0.01$) in the night-time air temperatures and air humidity levels at the various positions inside both tunnels. The air temperatures were significantly lower ($P<0.001$) at the upper levels (2.3 m from the floor) than at lower levels (1.15 m above the floor) inside the FPVT. Similarly, the air temperature was significantly ($P<0.001$) higher at the middle section than the pad and fan sections. Similarly, the upper level in the NVT was significantly ($P<0.001$) cooler than the lower level, except in November and December. The lowest temperatures were at the upper east-end and the highest temperatures were at the lower middle section.

The night-time relative humidity levels were significantly ($P<0.01$) higher at the upper than the lower level in the FPVT. The middle section air moisture content was significantly ($P<0.01$) higher than the pad and the fan sections. Conversely, in the NVT, the air humidity levels were significantly higher at the lower levels than at the upper levels, as shown in Figures 3.8c, 3.8e and 3.8g. At the upper levels, the relative humidity was significantly ($P<0.01$) lower at the middle section than the east and west ends of the NVT. At the lower level, the relative humidity was significantly ($P<0.01$) lower at the west of the tunnel than the middle and the east end.



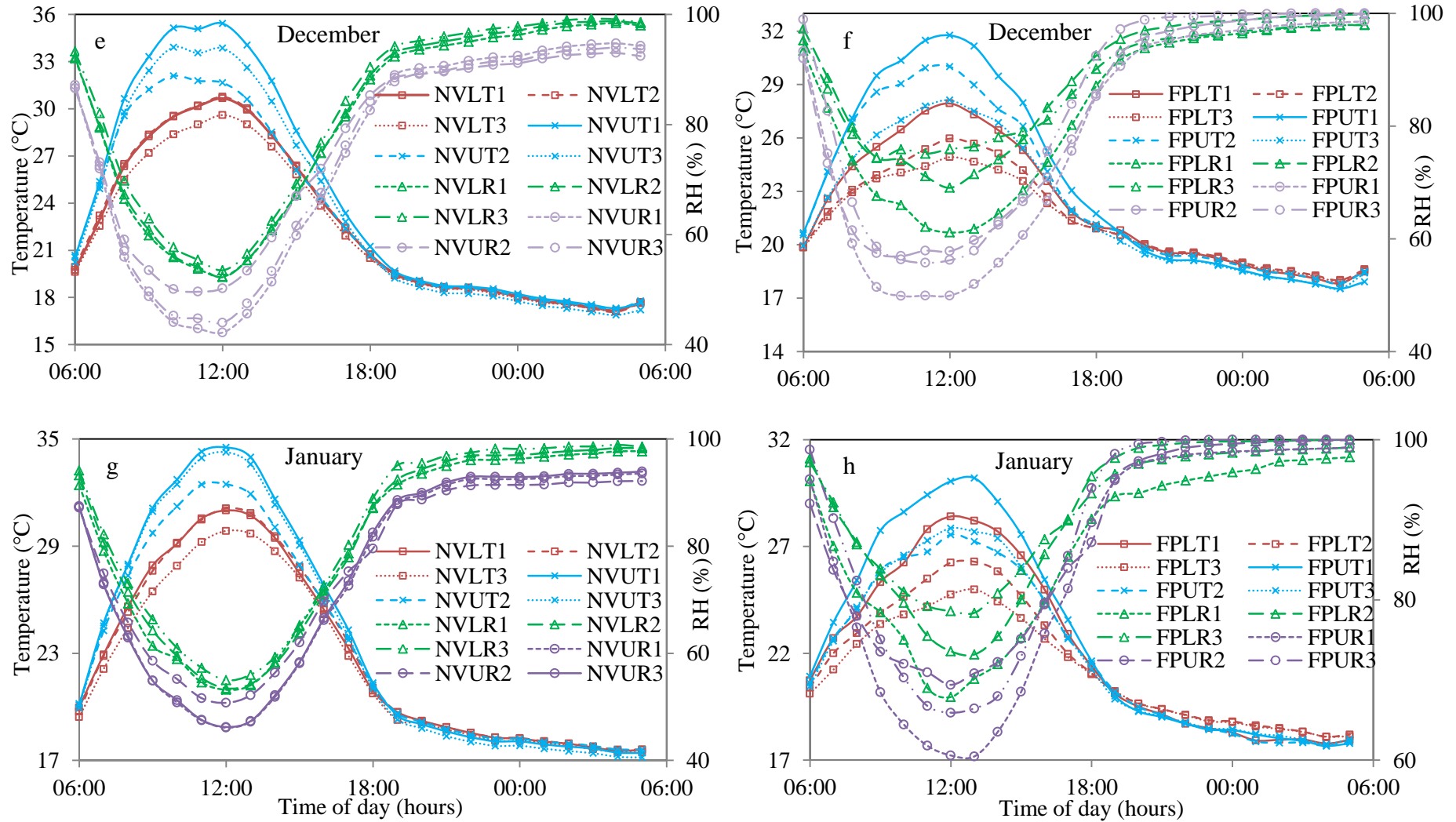


Figure 3.8 Twenty four hour mean hourly temperatures (T) and relative humidity (R) at Positions 1 (fan section), 2 (middle section), and 3 (pad section) on the lower (L) and the upper (U) levels in the naturally-ventilated (NV) and fan-pad evaporative cooled (FP) tunnels.

3.3.4 Plant growth

Figures 3.9, 3.10, 3.11 and 3.12 show the growths of tomato plants in the NVT and FPVT measured between Week 1 and Week 11 after transplanting the seedlings. Figure 3.9 shows the weekly plant height of the four tomato cultivars grown in the FPVT and the NVT. There were significant differences ($P < 0.001$) in the height of the tomato, due to the effect of the microclimate and the cultivar. As can be expected, the increase in the heights of the indeterminate cultivars (Bona and Star 9037), were greater than the determinate ones (Star 9009 and Zeal). Plants grown under the FPVT conditions were 8.7% taller than those grown under the NVT conditions. Among the indeterminate cultivars, Bona was 10.8% taller than Star 9037, whereas among the determinate cultivars, Star 9009 was 12.4% taller than Zeal. The microclimate \times cultivar interaction had a significant ($P < 0.05$) effect on the plant height. Cultivars Bona, Star 9037 and Star 9009 were 11.9%, 7.1% and 12.7% taller, respectively, when grown under FPVT conditions. Only cultivar Zeal was taller, when grown under NVT conditions. Under NVT conditions, the plant height for Zeal was 7.7% higher, in comparison to plants grown in the FPVT. With regards to the increase in plant height over the 11-week observation period, the increase in plant height was significantly ($P < 0.001$) faster under the FPVT environmental conditions. All the cultivars, with the exception of Zeal, had a faster increase in plant height when grown in the FPVT than in the NVT.

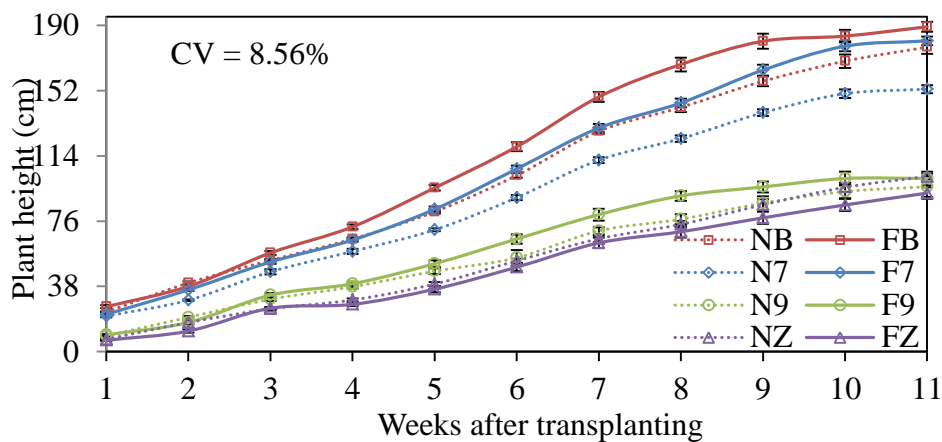


Figure 3.9 The height of tomatoes growing in NVT and FPVT measured weekly between weeks 1 and 11. The prefixes F and N represent the FPVT and the NVT. B= cultivar Bona, 7 = cultivar Star 9037, 9= cultivar Star 9009 and Z= cultivar Zeal

The weekly increase in height for Bona was significantly ($P < 0.01$) faster under the FPVT than under the NVT environmental conditions. Similarly, under the FPVT conditions, the increase in the plant height of Star 9037 was significantly ($P < 0.0$) faster, when compared to Star 9037 grown in the NVT. Cultivar Bona grown under the FPVT conditions had the highest weekly increase in height, whereas the plant height increase of Star 9037 from the NVT was the lowest. Among the determinate cultivars, the fastest increase in height was observed on the FPVT-grown Star 9009, whereas Zeal from the FPVT had the slowest increase in height. The increase in the height of Zeal grown in the NVT and the FPVT and the increase in height of Star 9009 from the NVT was almost the same. Over the first four weeks of growth, there was a consistent increase in plant height for all the cultivars, but significant microclimate and cultivar effects were observed from Week 4 after transplanting.

Figure 3.10 shows the weekly accumulation of leaves by the four cultivars grown in the FPVT and NVT. There were no significant ($P > 0.05$) microclimate effects on the weekly accumulation of leaves significant, however, significant ($P < 0.001$) cultivar differences were observed.

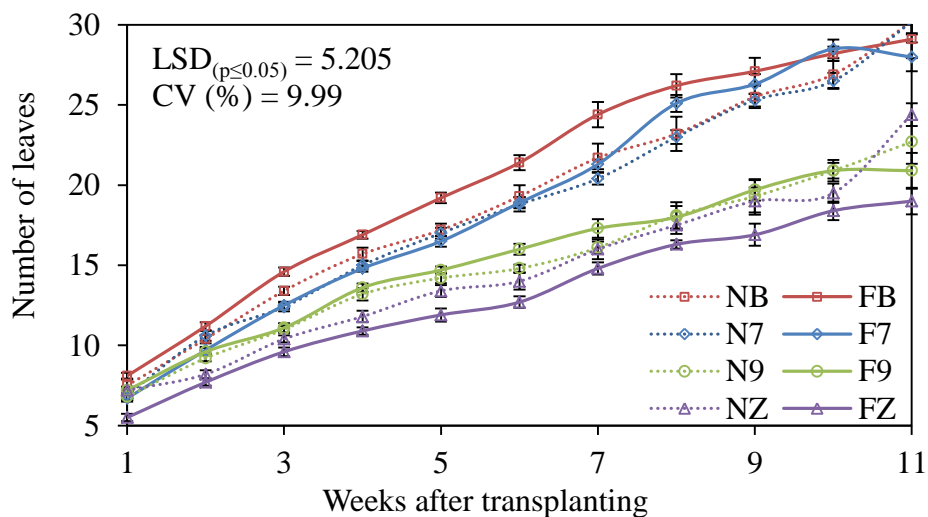


Figure 3.10 Number of leaves in the FPVT and the NVT between Weeks 1 and 11 after transplanting the seedlings. The prefixes F and N represent the FPVT and the NVT. B= cultivar Bona, 7 = cultivar Star 9037, 9= cultivar Star 9009 and Z= cultivar Zeal

As with plant height, the indeterminate cultivars, Bona and Star 9037, accumulated 19.1-31.0% more leaves than the determinate cultivars. Among the indeterminate cultivars, Bona accumulated 5.6% more leaves than Star 9037. Among the determinate cultivars, Star 9009 accumulated 10.0% more leaves than Zeal. These differences were also reflected by the effect of the ventilation \times cultivar interaction. The indeterminate cultivars had more leaves under both environmental conditions than the determinate cultivars. There were significant ($P < 0.001$) differences due to the interaction effects of the growing period with the microclimate and the cultivar \times growing period. The weekly leaf accumulation was higher for the plants grown under FPVT conditions, when compared to those grown in the NVT. Bona weekly leaf accumulation was faster than that for Star 9037. Similarly, Star 9009 weekly leaf accumulation was faster, when compared to that for Zeal.

Figure 3.11 shows the increase in leaf area of the four cultivars grown under the NVT and the FPVT environment over a 10-week observation period. There were significant ($P < 0.001$) cultivar effects on the leaf areas of the four cultivars.

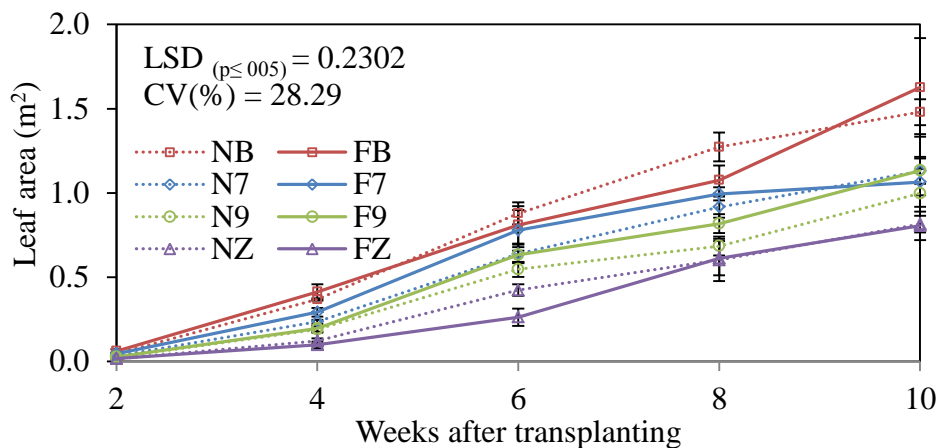


Figure 3.11 Leaf area in the FPVT and the NVT measured fortnightly between Weeks 2 and 10 after transplanting the seedlings. The prefixes F and N represent the FPVT and the NVT. B= cultivar Bona, 7 = cultivar Star 9037, 9= cultivar Star 9009 and Z= cultivar Zeal.

Cultivar Bona leaf area was significantly higher than that of Star 9009 and Zeal, while Zeal leaf area was significantly lower than that of Star 9009, Bona and Star 9037. Bona leaf area was 34.6% and 52.9% higher, when compared to that of Star 9009 and Zeal, respectively. Zeal leaf area was 38.3% and 52.9% lower, when compared to those of Star 9037 and Bona,

respectively. The leaf area of Bona was not significantly different from that of Star 9037. Similarly, the leaf area of Star 9037 was not significantly different to those of Star 9009 and Zeal. There was also a significant ($P < 0.001$) effect, due to the interaction of cultivar with growing period. The increase in leaf area of Bona was the fastest, followed by Star 9037, Star 9009 and lastly, Zeal. No significant ($P > 0.05$) microclimate effects were observed.

As with leaf area, the cultivar and cultivar \times growing period interaction had significant ($P < 0.001$) influences on the vegetative biomass accumulated by the tomato plants, as shown in Figure 3.12. The vegetative dry matter of Bona was 48.0% higher than that of Zeal. The vegetative dry matter of Star 9037, Star 9009 and Bona did not differ significantly, although Bona dry matter was highest. Cultivar Star 9037 had the next highest vegetative biomass, followed by Star 9009 and lastly Zeal.

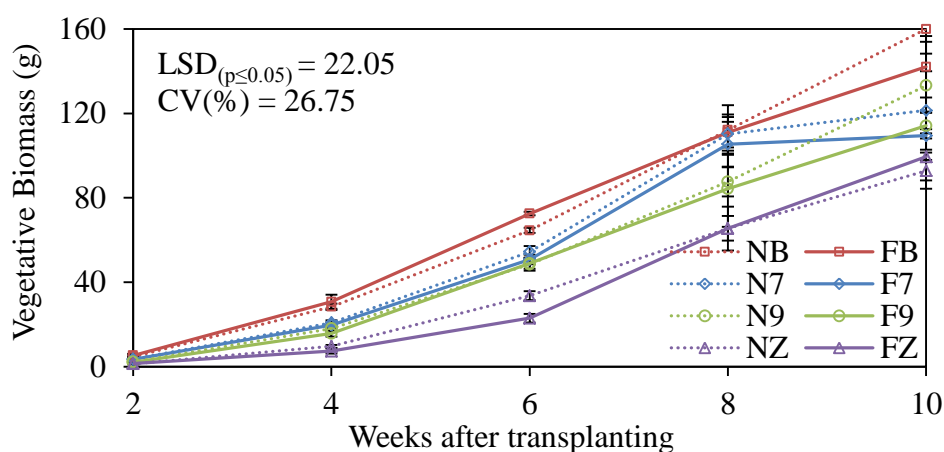


Figure 3.12 Vegetative biomass in the FPVT and the NVT, measured fortnightly between Weeks 2 and 10 after transplanting the seedlings. The prefixes F and N represent the FPVT and the NVT. B= cultivar Bona, 7 = cultivar Star 9037, 9= cultivar Star 9009 and Z= cultivar Zeal.

3.3.5 Fruit yield and quality

Table 3.2 shows the yield and quality parameters of the four cultivars grown under the FPVT and NVT environmental conditions. There was no significant difference ($P > 0.05$) in total yield harvested from the FPVT and NVT, although the total yield from the NVT was 23.8% higher than the total yield from the FPVT. The effect of the cultivar ($P < 0.01$) and its interaction with the microclimate ($P < 0.05$) significantly influenced the total yield of the

tomatoes. Cultivar Bona total yield was the highest, with 4.09 kg.plant⁻¹, followed by Star 9037, with 3.30 kg.plant⁻¹, then Star 9009, with 3.24 kg.plant⁻¹, whereas Zeal had the lowest total yield, with 2.09 kg.plant⁻¹. Bona total yield was significantly higher (by 48.9%), when compared to Zeal's total yield, but did not vary significantly with Star 9009 and Star 9037. The microclimate × cultivar interaction significantly influenced the total yield (Table 3.2). Under FPVT conditions, Bona out-performed the other cultivars with 4.51 kg.plant⁻¹, when compared to 2.61 kg.plant⁻¹ for Star 9037, 2.49 kg.plant⁻¹ for Star 9009 and 1.39 kg.plant⁻¹ for Zeal. Bona total yield was also significantly higher (by 38.4%) than Zeal's total yield from the NVT.

There were no significant ($P>0.05$) differences in the total marketable yield of tomatoes harvested from the FPVT and the NVT. However, highly significant ($P<0.001$) differences were observed in the total marketable yield among the four cultivars. Both determinate cultivars Bona and Star 9037 showed significantly higher marketable yields than the determinate cultivar Zeal. However, the marketable yields of the indeterminate cultivars did not differ significantly from Star 9009 (also a determinate cultivar). The total marketable yield for Zeal was only 36.2% of the yield of Bona and 47% of that of Star 9037.

Highly significant ($P<0.001$) differences were observed between the ventilation types with regards to the total unmarketable yield. The total unmarketable yield from the FPVT was 15.4% of the total yield, compared to 29.9% of the total yield from the NVT. Similarly, cultivar differences, with respect to the total non-marketable yield, were significant ($P<0.05$). Star 9009, which had the highest non-marketable yield of 0.94 kg.plant⁻¹, was significantly different from the unmarketable yield of Bona, but not those of Star 9009 and Zeal. However, Zeal had the highest percentage of unmarketable yield to total yield, with 39.4% of the total yield being unmarketable. It was followed by Star 9009, which had 28.9% of its total yield being unmarketable. These values compare to those of the indeterminate cultivars, Bona and Star 9037, the total unmarketable yields of which were 14.8% and 19.5% of the total yields, respectively. The effect of the microclimate × cultivar interaction also had a significant ($P<0.05$) influence on the total unmarketable yield. Under NVT conditions, the unmarketable yield for Star 9009 was significantly higher than that of the indeterminate cultivars (Bona and Star 9037), but not significantly different to that of the other determinate cultivar (Zeal). The unmarketable yield of Star 9009 was 1.41 kg.plant⁻¹, compared to Star 9037 and Zeal, of

which the unmarketable yields were 1.00 kg.plant⁻¹ and 0.77 kg.plant⁻¹. The non-marketable yields for Star 9037, Star 9009 and Zeal were significantly higher under the NVT microclimate, as opposed to the FPVT environment. In the FPVT, the unmarketable yield for Star 9037 was only 0.28 kg plant⁻¹, while under NVT conditions it was 1.00 kg.plant⁻¹. As for Star 9009, under the FPVT environmental conditions, the unmarketable yield was only a third of that from the NVT. With regards to Zeal, the non-marketable yield was 54% higher under NVT conditions.

Table 3.2 Yield and quality parameters for ventilation × cultivar interaction in the FPVT and the NVT.

Ventilation	Cultivar	TY kg.p ⁻¹	US kg.p ⁻¹	BER kg.p ⁻¹	ID kg.p ⁻¹	CR kg.p ⁻¹	DF kg.p ⁻¹	TUY kg.p ⁻¹	TMY kg.p ⁻¹
FPVT	Bona	4.51 ^a	0.33 ^{ab}	0.02 ^b	0.01 ^d	0.04 ^b	0.05 ^b	0.44 ^{de}	4.07 ^a
	Star 9037	2.61 ^{bc}	0.12 ^c	0.00 ^b	0.01 ^d	0.11 ^{ab}	0.04 ^b	0.28 ^e	2.33 ^b
	Star 9009	2.49 ^{bc}	0.12 ^c	0.10 ^b	0.01 ^d	0.10 ^{ab}	0.14 ^{ab}	0.47 ^{de}	2.02 ^{bc}
	Zeal	1.39 ^c	0.10 ^c	0.13 ^{ab}	0.04 ^d	0.14 ^{ab}	0.11 ^b	0.52 ^{de}	0.87 ^c
NVT	Bona	3.67 ^{ab}	0.50 ^a	0.01 ^b	0.13 ^{cd}	0.02 ^b	0.10 ^b	0.77 ^{cd}	2.90 ^{ab}
	Star 9037	3.99 ^{ab}	0.41 ^a	0.06 ^b	0.34 ^b	0.15 ^{ab}	0.05 ^b	1.00 ^{bc}	2.99 ^{ab}
	Star 9009	4.00 ^{ab}	0.38 ^a	0.06 ^b	0.54 ^a	0.10 ^{ab}	0.32 ^a	1.41 ^a	2.59 ^b
	Zeal	2.78 ^{bc}	0.18 ^{bc}	0.24 ^a	0.26 ^{bc}	0.20 ^a	0.25 ^{ab}	1.13 ^{ab}	1.65 ^{bc}
LSD _(p≤0.05)		1.369	0.190	0.127	0.153	0.127	0.18	0.318	1.288
Ventilation		NS	Sig	NS	Sig	NS	NS	Sig	NS
Cultivar		Sig	Sig	Sig	Sig	Sig	NS	Sig	Sig

Where TY= total yield; US = undersized; BER= blossom end-rot affected; ID = insect damaged; CR = cracked; TMY = total marketable yield; TUY= total unmarketable yield; kg.p⁻¹= kg per plant; LSD = least significant difference. Mean values with the same superscripted letter are not significantly different (P>0.05) using Duncan Multiple Range Test. NS= no significant differences resulting from that treatment were observed; Sig= Significant differences were observed

The total unmarketable yield was analysed in terms of the total mass of undersized, blossom end-rot, insect-damaged, deformed and cracked fruits. The mass of undersized fruits was significantly (P<0.001) higher in the NVT, than in the FPVT. In the NVT, 10.2% of the total yield was <50g, compared to 6.0% in the FPVT. The mass of undersized tomato fruits (<50 g)

was significantly ($P < 0.001$) lower for Zeal ($0.14 \text{ kg} \cdot \text{plant}^{-1}$), as opposed to Bona ($0.42 \text{ kg} \cdot \text{plant}^{-1}$) and Star 9037 ($0.26 \text{ kg} \cdot \text{plant}^{-1}$). The interaction between microclimate and cultivar also had a significant ($P \leq 0.05$) influence on the undersized fruit mass of the cultivars Star 9037 and Star 9009, but not on cultivars Bona and Zeal. Under NVT conditions, cultivar Star 9037 had $0.41 \text{ kg} \cdot \text{plant}^{-1}$, compared to $0.12 \text{ kg} \cdot \text{plant}^{-1}$ in the FPVT. Similarly, under the NVT microclimate, undersized fruit mass of Star 9009 was $0.38 \text{ kg} \cdot \text{plant}^{-1}$, as opposed to $0.12 \text{ kg} \cdot \text{plant}^{-1}$ in the FPVT.

Cultivar differences with respect to the occurrence of blossom end-rot were significant ($P < 0.01$). The occurrence of blossom end-rot on the cultivar Zeal was significantly higher, when compared to the other cultivars. In this cultivar (Zeal), 8.8% of the fruits were affected by blossom end-rot, compared to $< 2\%$ in the other three cultivars.

Yield losses resulting from insect pest attack in the NVT, were high and differed significantly ($P < 0.001$) from those in the FPVT. Losses due to insect attack in the FPVT were 5% of those in the NVT, where insect attack accounted for 29.5% of the total unmarketable yield. Cultivar differences were also observed to be significant ($P < 0.01$), with respect to yield losses from insect attack. The cultivar Star 9009 had a significantly higher fruit mass loss than Bona, but it was not significantly different from Star 9037 and Zeal. The fruit mass of Star 9009 that was unmarketable as a result of insect attack was $0.27 \text{ kg} \cdot \text{plant}^{-1}$, compared to Bona $0.07 \text{ kg} \cdot \text{plant}^{-1}$. Similarly, there was a significant ventilation \times cultivar effect on the yield loss due to insect damage. Cultivars Star 9037, Star 9009 and Zeal, grown in the FPVT, had significantly lower insect-damaged yield masses, than plants of the same variety grown under NVT conditions. The percentage yield loss from these cultivars ranged between 1.7 to 14.7% of those harvested from the NVT.

The occurrence of cracked fruits did not differ significantly ($P > 0.05$) between the two ventilation types. Cracked fruits constituted 3.2% and 3.6% in the NVT and the FPVT, respectively. Similarly, the ventilation \times cultivar interaction did not have a significant effect on the occurrence of cracked fruit. There was a significant ($P \leq 0.05$) cultivar effect on the occurrence of cracks on the tomato fruits. Significant differences were observed between Bona and Zeal, but both these cultivars were not significantly different to either Star 9037 or Star 9009. The cracked fruit mass of Bona was 16.1% that of Zeal. Yield losses resulting from

deformed fruits were not significantly ($P>0.05$) influenced by the effects of the microclimate and the interaction between microclimate and cultivar. The occurrence of deformed fruit was significantly influenced by cultivar differences. The deformed fruit mass for Star 9009 was significantly higher than that of Bona, but both these cultivars did not differ significantly from either Star 9037 or Zeal. The deformed yield of Bona was 32.6% that of Star 9009.

3.4 Discussion

3.4.1 Daytime temperature and relative humidity

The increase in greenhouse temperature is influenced by solar radiation and the radiative properties of the cover material (Papadakis *et al.*, 2000). Solar radiation provides the radiative energy required for photosynthesis and the heat energy required to drive other processes, such as transpiration (Sethi *et al.*, 2009). Greenhouse covers need to be transparent, in order to allow the solar radiation to enter the greenhouse. However, upon entry into the greenhouse, the near infrared radiation spectrum of the solar radiation leads to an increase in internal greenhouse temperature (Waaijnenberg, 2006). Polyethylene covers, which are used as greenhouse covers, allow 80-89% of the solar radiation to pass through them (CIPA, 1992). In addition, polyethylene covers allow up to 60% of the solar heat inside the greenhouse to pass through and escape into the atmosphere (Waaijnenberg, 2006; Alhamdan *et al.*, 2009). The retained long-wave heat radiation led to the substantial temperature increase inside the tunnels (Figure 3.3). This suggests that, in the southern sub-tropical regions such as Pietermaritzburg, solar radiation and cover are more influential on internal greenhouse temperature than external temperatures, as suggested by Sethi (2009). Ventilation in greenhouses is driven by temperature gradients and wind effects (Boulard and Baille, 1995). The substantial temperature gradient between the inside and the outside in the NVT did not induce sufficient heat transfer, to maintain the internal air temperature fluctuating around the external temperature, as reported by Teitel *et al.* (2007). The air temperature inside the FPVT was always higher than outside, unlike other fan-pad cooled polyethylene structures, as reported by Arbel *et al.* (2003), Kittas *et al.* (2003), Perret *et al.* (2005) and Max *et al.* (2009). Inside the FPVT, the high solar heat gain by the polyethylene cover could have limited the effectiveness of the wet wall in reducing the internal air temperature. This agrees with Willits

(2003) and Fuchs *et al.* (2006), who reported that the microclimate in a FPVT responded rapidly to changes in solar radiation.

Figures 3.5a and 3.5b indicate that in October and November, when the incident solar radiation was the lowest of the four months, there was no significant ($P>0.05$) difference in air temperatures inside FPVT and NVT. During these two months, the mean daytime internal hourly temperatures ranged between 21°C and 28°C, which are ideal temperatures for greenhouse tomato crop growth (Snyder, 2003). In December and January, solar radiation was at its highest of the four months, as shown in Figure 3.4. Similarly, the internal air temperature difference was the highest during these months (Figures 3.3c and 3.3d). In December and January, the maximum temperatures in the FPVT were 28.1°C and 27.9°C, which fall within the temperature range that are optimum for tomato crop growth. In the NVT, however, the maximum temperature was 32°C during both months, 4°C above the upper optimum temperature threshold that was suggested by Castilla and Hernandez (2007) and von Zabeltitz (2011) for the production of greenhouse crops, including tomatoes. However, 32°C was less than the 35°C absolute mean maximum air temperature for the production of tomatoes suggested by von Zabeltitz (2011). Bailey (2006) suggested that when the external ambient air temperature is below 27°C, ventilation is adequate to maintain optimum temperatures in Mediterranean greenhouses. In this study, although the highest mean hourly external temperature was 25°C in January, the natural air ventilation through the open ends of the NVT was inadequate to maintain acceptable temperatures for tomato production. The values observed in this study were lower than those reported by Maboko *et al.* (2010), in Pretoria, South Africa, during the same months in a side wall NVT and an FPVT. This could possibly be attributed to the different climatic conditions prevailing in Pretoria and Pietermaritzburg. However, the results are comparable to those reported by Mutwiwa *et al.* (2010) for a humid sub-tropical area in a side and roof ventilated greenhouse and fan-pad cooled tunnel. Other temperature control measures, such as aluminium folding shade screens (Callejón-Ferre *et al.*, 2009), near infrared reflecting screens (Stanghellini *et al.*, 2011) and whitewashing (Baille *et al.*, 2001; Meca *et al.*, 2007; Jimenez *et al.*, 2010; Mashonjowa *et al.*, 2010b), could be used to reduce the solar heat gain in the greenhouses in the Southern African latitudes during the summer months.

At daybreak, the internal relative humidity in both tunnels started to reduce from high levels (>90%) at night and reached minimum values of at least 60% in the FPVT and less than 60% in the NVT at midday, coinciding with the peak solar radiation (Figure 3.4). This agrees with Kittas *et al.* (2003), who stated that relative humidity responds rapidly to solar radiation. In the NVT, the lowest relative humidity (49%) was in December and the next lowest was in January (51%). In the FPVT, the lowest relative humidity values were in October and November (59%) and increased progressively. For greenhouse tomatoes, the ideal relative humidity is between 60-90% (von Zabnitz 2011). In the NVT, the relative humidity fell below 60% between 9:00 am and 14:00 pm in all the four months. Relative humidity levels below 60% induce high transpiration rates and plant water stress (Bailey, 2006). This could lead to the non-optimum use of irrigation water, which has been found to be optimised under controlled environment cultivation (Mashonjowa *et al.*, 2010a). In the FPVT, the minimum relative humidity was 60%, thus the relative humidity was acceptable for the tomatoes at all times.

3.4.2 Night-time temperature and relative humidity

The night-time trends (Figure 3.6) show that there were no significant differences between the external, NVT and FPVT air temperatures. The results are consistent with those reported by Max *et al.* (2009), who found no significant differences between night-time temperatures in a side- and roof-ventilated and a fan-pad evaporative cooled greenhouse in a tropical climate. Although the differences between external and the NVT air temperature were not significant, the lower NVT temperatures are typical of polyethylene covered tunnels, as reported by Montero *et al.* (1985), Baytorun *et al.* (1994) and Wien (2009). At night, solar radiation was at its lowest and the solar heat input into the greenhouse was negligible. Polyethylene transmits back up to 60% of long-wave heat radiation trapped inside the plastic covered structures (Waijenerg, 2006; Alhamdan *et al.*, 2009). The heat loss through the cover exceeded the heat input into the greenhouse, resulting in lower temperatures in the NVT (Montero *et al.*, 2005; Wien, 2009). The open ends of the tunnel did not facilitate adequate movement of heat between the inside and the outside to maintain the same temperature inside and outside. The heat transfer could have been hampered by the insect screens, which were fitted at the open-ends of the NVT. Insect screens have been found to reduce the ventilation area (Valera *et al.*, 2006) and provide extra resistance to the transport of heat and momentum in to and out of the greenhouse (Bartzanas *et al.*, 2002).

In October, the night-time temperature ranged between 13.7-15.4°C in the NVT and 14.3-16.6°C in the FPVT. These temperature ranges were below the optimum night-time levels of 16-18°C, suggested by Snyder (2003) for greenhouse tomatoes. However, they were above the night-time threshold level of 12°C, suggested by Castilla and Hernandez (2007), below which crop growth, yield and quality are negatively affected in the greenhouse.

Throughout the observation period, the night-time relative humidity levels inside the tunnels were significantly higher than the external levels (Figure 3.7). At night, the fan was switched off and there was no air exchange between the inside and the outside, in order to remove any excess air moisture content from the FPVT. This led to the formation of condensation on the inside of the polyethylene cover, as shown in Figure 3.13. The greenhouse cover has been found to be the coolest surface of the greenhouse (Piscia *et al.*, 2012), which, combined with high internal relative humidity, resulted in condensation forming on the inside of the FPVT cover. This observation was in agreement with Teitel *et al.* (2007), who observed that, when night-time temperatures reach dew point temperature levels and the air was saturated, condensation occurred inside the tunnel and dew formed on the inside of the greenhouse cover and on plant foliage.

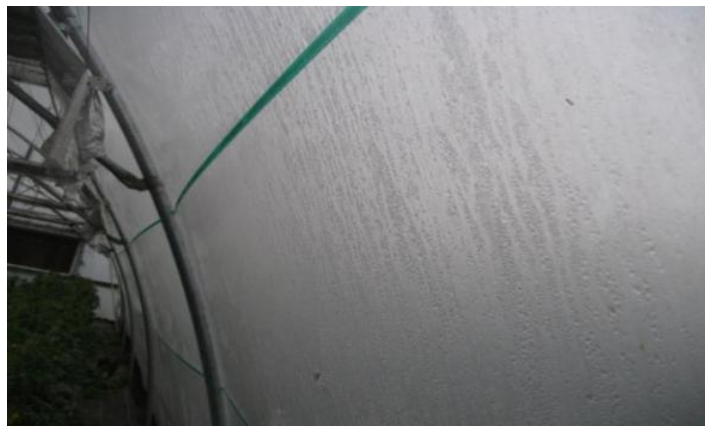


Figure 3.13 Condensation on the inside of the polyethylene cover in the FPVT

Conversely, the relative humidity inside the NVT was between 91-96% and did not reach saturation point, thus no condensation was observed on the cover. The relative humidity was influenced by the external conditions, which was to be expected, since the ends of the tunnel were always open, even at night. Although significantly higher than outside, the relative

humidity trend in NVT followed that of the outside air, increasing when the outside increased and vice-versa, as can be seen clearly from Figures 3.7a and 3.7b.

3.4.3 Microclimate stratification

There was significant temperature and relative humidity stratification in both tunnels throughout the study period (Figure 3.8). The horizontal and vertical variation of the microclimate was the highest at peak solar radiation (Figure 3.4). In the FPVT, the incoming air, cooled by the exchange of sensible for latent energy while passing through the wet wall, cools the tunnel as it travels through it. The incoming air, being cooler and heavier, settled at the bottom, causing the warmer air to rise and to be trapped in the upper sections of the greenhouse. In addition, as the cooler air moves along its path, the air stream gains heat that has developed inside the greenhouse, due to the conversion of infrared radiation to long-wave heat radiation. By the time the air stream reaches the exhaust section at the fan, it is warmer than air entering through the wet wall. The 4.3°C and 7.8°C temperature gradients between the pad and the fan at heights of 1.15 m and 2.3 m, respectively, in this 18 m long tunnel, compare with the 8°C reported by Kittas *et al.* (2003) in a 60 m greenhouse and 6°C observed by Oz *et al.* (2010) in a 24 m long greenhouse. The highest vertical and horizontal temperature differences were in October, when the tomato plants were still young. Young tomato plants have low transpiration rates and thus, contribute less to the cooling of the greenhouse (Willits, 2003; Max *et al.*, 2009). As crops grew taller, there was more air-flow dispersion and mixing of the cool incoming air stream with the warmer internal air, which resulted in far less temperature variation inside the greenhouse, in agreement with Willits (2003). Because of the warmer upper section of the FPVT, the top-most part of the tallest tomato plants were wilting when they reached a height of 2 m (Figure 3.14).

A smaller fan fitted above the larger fan, to increase the ventilation rate and remove the warmer air trapped below the plastic cover, might have helped to reduce the vertical stratification and may have led to a more uniform temperature distribution in the FPVT. In addition, reducing the solar radiation heat load on the greenhouse by whitewashing or using near infrared reflecting screens, as shown by Kittas *et al.* (2003), could have induced a more uniform microclimate in the FPVT. Whitewashing and the use of NIR reflective screens could

also reduce the energy use of the FPVT for operating the fan and the water pump (Mashonjowa *et al.*, 2010b).



Figure 3.14 Wilting tomato shoots due to higher temperature at 2 m in the FPVT

In the NVT, on the other hand, the maximum vertical temperature difference was observed in November (Figure 3.8c). The peak solar radiation was 9% higher in November than in October (Figure 3.4), and the tomato plants had not yet reached full maturity. Thus, the cooling effect of crop transpiration and air dispersion among fully-grown crops could have led to a higher vertical difference in November. This vertical stratification observed in the NVT is in agreement with the findings of Soni *et al.* (2005) and Teitel *et al.* (2008a), who observed lower temperatures within the plant canopy and warmer temperatures in the space above the crop. The 5.78°C temperature difference between the lower and upper levels was lower than the 7.43°C in FPVT. The open ends, particularly the upper section, allowed heat movement from the inside to the outside of the NVT tunnel, compared to the FPVT, where heat removal was achieved by the one fan only. Although there was much less horizontal gradient observed in the NVT, as opposed to the FPVT, the east-end was consistently cooler than the rest of the greenhouse on both levels, while the west-end was warmer most of the time (Figures 3.8a, 3.8c, 3.8e and 3.8g). The expectation would have been that both open ends would be cooler than the middle section, as observed by Bartzanas *et al.* (2004) in a roof- and side-ventilated greenhouse. The effect of wind direction, which was predominantly from the south-east during the observation period, could have led to the east-end being cooler than the west-end. As reported by Fatnassi *et al.* (2009), the effect of wind on the ventilation and microclimate in naturally-ventilated structures is higher when wind direction is normal to the vent openings rather than parallel.

There was much less variation of temperature in both tunnels at night, as shown in Figure 3.17. In the FPVT, the middle section was warmer than the pad and fan sections (Figures 3.8b, 3.8d, 3.8f and 3.8h), which was in agreement with Piscia *et al.* (2010), who stated that the crop canopy is the warmest section of the greenhouse at night. In the NVT, on the other hand, the east end was consistently cooler and the middle section was the warmest. Similar to the FPVT, the middle section was warmer than the east and west ends. The expectation would be that, since the outside air was warmer than the inside air, the temperature at the east and west ends would be the warmest, as heat moves from outside to the inside. However, the effect of the insect screen fitted at the ends of the tunnel could have hindered the balance of heat between the inside and the outside of the NVT tunnel.

Similarly, for relative humidity, there was more vertical stratification than horizontal stratification in both tunnels, especially in October and November (Figures 3.8a, 3.8b, 3.8c and 3.8d). In the FPVT, the pad section had higher relative humidity levels on both the lower and the upper levels during the daytime, due to the effect of the wet wall. The relative humidity was lowest at the fan section throughout the observation period, unlike observations by Willits (2008) and Lopez *et al.* (2010), who stated that in the presence of crops, humidity ratio increased progressively as the incoming air picked-up additional moisture from crop transpiration, the relative humidity reduced progressively between the pad and the fan. The addition of moisture to the incoming air stream seemed to be limited, although the lower level relative humidity was consistently above the set threshold of 60%.

In the NVT, there was less variation of relative humidity on the lower level, as compared to the FPVT. The highest relative humidity was recorded at the lower east end of the tunnel and the lowest at the west end. This distribution of relative humidity on the lower level is contrary to what was reported by Bartzanas *et al.* (2004), who showed that relative humidity tends to be lower at the vent openings and higher in the middle of the tunnel. Air dispersion within the crop canopy could have led to a more distributed profile of relative humidity at 1.15 m. At 2.3 m, there was more variation in relative humidity, with the middle section having the highest relative humidity. There was more exchange of moisture with the outside through the upper part of the open ends than the lower part, which led to the middle section having a higher relative humidity than the end sections. This is in agreement with Bartzanas *et al.*

(2004), who had stated that relative humidity tends to be lower close to the vent openings than in the interior sections of the greenhouse.

During the night, there was less variation in the air moisture content than during the day (Figure 3.8). The relative humidity variation has been found to be driven by solar radiation (Kittas *et al.*, 2003), therefore, at night, when solar radiation effect was zero, there was less variation. The relative humidity was higher at 2.3 m than at 1.15 m. At night, the cover has been found to be the coolest surface in the greenhouse (Piscia *et al.*, 2012). The higher relative humidity closer to the polyethylene cover, combined with the cooler cover, would have been the cause of the condensation on the inside of the tunnel, as mentioned in Section 3.6.2 and shown in Figure 3.13. Inside the NVT, as during the daytime, the relative humidity was higher at 1.15 m within the crop canopy, than at 2.3 m.

3.4.4 Effects on tomato plant growth, fruit yield and quality

As can be seen from the results presented in Section 3.3.4, the increase in plant height and leaf accumulation were faster under the FPVT microclimate conditions than under the open-ended NVT for three of the four cultivars, starting from Week 4. During the first four weeks after transplanting the seedlings in October, there were no significant differences in the internal temperatures between the FPVT and the NVT (Figure 3.3a). This may explain why the indeterminate cultivars (Bona and Star 9037) and the determinate cultivars (Star 9009 and Zeal) had the same height during this period. After Week 5, the weekly increase in plant height was faster in the FPVT than in the NVT. Five weeks after transplanting the seedlings, the internal air temperatures were significantly higher and above the 28°C optimum threshold level in the NVT, especially in the middle of the day (Figures 3.3b, 3.3c and 3.3d). Conversely, the relative humidity was significantly lower in the NVT than in the FPVT and the 60% optimum level (Figure 3.5). These non-optimum conditions could have negatively affected the growth of the plants in the NVT. On the other hand, the optimum microclimate conditions in the FPVT enhanced the vegetative growth of the plants grown under evaporative cooling conditions. Starting from Week 10, the increase in height for Bona and Star 9037 in both tunnels decreased. This might have been due to the effect of the increase in temperature with height in both tunnels. High temperatures induce heat stress and low relative humidity levels induce high transpiration in tomato plants, slowing down vegetative growth (Morales *et*

al., 2003). These results differ from those reported by Willits and Li (2005), Mutwiwa *et al.* (2007) and Max *et al.* (2009), who reported faster growth rates in tomatoes grown in a naturally-ventilated greenhouse than those in fan-pad ventilated greenhouses in a tropical climate. The differences could have been due to the different climatic regions under which the studies were conducted.

The differences in the growth rate among the cultivars could have been due to genotypic differences. The indeterminate cultivars were consistently taller and generated more leaves than the semi-determinate cultivars. The increase in the height of Bona, Star 9037 and Star 9009 was faster in the FPVT, when compared to their growths in the NVT. The consistently lower temperatures and higher air moisture content (Figures 3.3 and 3.5) in the FPVT enhanced the vegetative growth of these three cultivars (Figures 3.9-3.12). Zeal plant height and leaf generation were not influenced by environmental conditions in the two tunnels. Abdelmageed and Gruda (2009) reported that heat tolerant cultivars would perform better under high temperature conditions than non-heat tolerant cultivars. Zeal was more heat tolerant than Bona, Star 9037 and Star 9009. These results are in agreement with Max *et al.* (2009), who also observed no significant differences ($P>0.05$) in tomato leaf area and vegetative biomass in a fan-pad ventilated and a naturally-ventilated greenhouse.

Although the total and marketable yields did not differ significantly ($P>0.05$) between the two tunnels (Table 3.2), the total yield was 24% higher in the NVT than in the FPVT. Conversely, total marketable yield percentage was higher in the FPVT, with 84% of the total yield, compared to 70% in the NVT. These results agree with those reported by Willits and Li (2005), Mutwiwa *et al.* (2007), Teitel *et al.* (2007) and Max *et al.* (2009), who reported significantly higher total yields from naturally-ventilated greenhouses in tomato and rose plants. On the contrary, Maboko *et al.* (2010) reported higher total yield from a FPVT than a NVT. The differences could possibly be attributed to the different cultivars used and their responses to climatic conditions (Carli *et al.*, 2011). The total yield for the cultivar Bona was higher than that of Zeal. The higher rate of vegetative growth observed in Bona may have resulted in the higher total yields, compared to those of Zeal.

The high unmarketable yield in the NVT was mainly due to the large quantity of deformed, undersized and insect-damaged fruit yields (Table 3.2) that were observed in this tunnel.

These results agree with those of Maboko *et al.* (2010), who reported 41% and 12% unmarketable tomato yield from a NVT and a FPVT, respectively. The mean mass of undersized fruits was found to be significantly higher ($P < 0.001$) in the NVT than in the FPVT. These results are in agreement with those of Willits and Li (2005), Max *et al.* (2009) and Maboko *et al.* (2010), who all reported significantly higher ($P < 0.05$) undersized yields from the NVT than the FPVT. The development of smaller sized fruits has been associated with higher temperatures, as reported by Adams *et al.* (2001), who observed a lower mean fruit size at higher temperatures. In addition, temperatures above 30°C impair the development, release and viability of pollen (Abdul-Baki and Stommel, 1995; Peet *et al.*, 2003), leading to poor fertilization and the production of misshapen fruits (Waquant, 1995; cited by Dorais *et al.*, 2001). Temperatures in NVT were above 30°C for up to 4 hours during the daytime in December and January. This would have had an effect on the development of pollen and fruit-set in the NVT, resulting in the high percentage of undersized and deformed fruit in this tunnel. The high difference in undersized fruit mass between Bona and Zeal could be attributed to genotypic differences. According to Hanson *et al.* (2002), the possession of the heat tolerant gene, would allow fruit set under high temperature environments. Cultivar Bona could be lacking the heat tolerant gene, thus the higher undersized fruit mass, compared to Zeal.

The microclimate in the FPVT did not have a significant effect on the development of blossom end-rot and fruit cracking, physiological disorders that are often associated with high relative humidity in fan-pad evaporative cooled greenhouses (Dorais *et al.*, 2004). High relative humidity, particularly at night, has been shown to be positively correlated to tomato fruit cracking (Estergaard *et al.*, 2001). Under conditions of high relative humidity, leaf transpiration rates are reduced and the water supply to the cells and tissue of other organs, such as fruit, are increased (Peet and Willits, 1995; Dorais *et al.*, 2004). The resulting increase in turgor pressure and stress on the skin of the tomatoes has the potential to cause fruit and skin cracks in tomatoes (Dorais *et al.*, 2004). The higher relative humidity, especially in the early morning, late afternoon and at night observed in both tunnels, could have led to approximately the same mass of total cracked fruits. The results are contrary to those reported by Max *et al.* (2009), who found a higher number of cracked fruits in a FPVT than in a NVT. Zeal was the most susceptible to cracking, with 8.3% of its total yield rendered unmarketable due to cracking. Bona was the most tolerant to cracking, with <1% of its total yield rendered

unmarketable as a result of fruit cracking. These differences were most probably due to genotypic differences.

The incidence of blossom end-rot has been associated with low relative humidity and high vapour pressure deficits (Max *et al.*, 2009). Insufficient translocation of calcium to the fruits under dry air conditions has been identified as the main cause of blossom end-rot (Blanc, 1986). At low relative humidity and high vapour pressure deficit, leaves tend to out-compete fruits in the competition for water supply (Adams and Holder, 1992; Bertin *et al.*, 2000), thus limiting the supply of calcium to the fruit. In spite of the fact that the relative humidity was low in the NVT, especially in the middle of the day (Figure 3.5), this did not increase the incidence of BER in this tunnel, when compared to the FPVT. These results agree with those reported by Leonardi *et al.* (2000) and Max *et al.* (2009), who reported no significant differences at two different levels of vapour pressure deficit. Zeal grown in the NVT was the most affected by blossom end-rot, which would suggest that it is vulnerable to low relative humidity at high temperatures in the NVT.

There was a higher percentage of insect-damaged fruit in the NVT than in the FPVT. Although this has little to do with greenhouse microclimate, it highlights some of the additional problems that may arise in controlled environment crop production. Naturally-ventilated greenhouses are often fitted with porous plastic insect screens to eliminate insect pests from the greenhouse and reduce the use of chemicals (Bartzanas *et al.*, 2002; Klose and Tantau, 2004; Valera *et al.*, 2006). However, insect screens will only keep out those insects which are larger than the openings between the threads of the screen mesh (Klose and Tantau, 2004; Katsoulas *et al.*, 2006; Teitel, *et al.*, 2009). For this experiment, Knittex® 40% netting, with irregularly-shaped openings was used to keep insect pests out of the NVT. While this screen was effective against most tomato insect pests, it was ineffective against red spider mite. Up to 13.5% of tomatoes harvested in the NVT, compared to 2.75% in FPVT were rendered unmarketable, due to red spider mite attack. Red spider mite has been found to thrive under hot and dry conditions (Gotoh *et al.*, 2010; Suzuki *et al.*, 2012), the conditions which were more prevalent in the NVT than in the FPVT. Consequently, the tomato crop in the NVT was sprayed three times, in an attempt to control the red spider mite. This suggests that there might be a need for more pest control measures in the NVT than the FPVT, which might raise the costs for growing crops in the NVT.

3.5 Conclusion

The internal greenhouse microclimate was most influenced by solar radiation. The temperature increased in response to increasing solar radiation and the peak temperature coincided with peak solar radiation. Similarly, the tunnels' air moisture content reduced with increasing solar radiation, even with evaporative cooling. The lowest relative humidity levels were in the middle of the day, coinciding with peak solar radiation. At night, when solar radiation was negligible, temperatures were lowest and relative humidity was highest in both tunnels.

Daytime temperatures were significantly higher in the NVT than in the FPVT in December and January. Conversely, the evaporative cooling process maintained higher relative humidity levels in the FPVT than in the NVT, especially in December and January. High night-time relative humidity led to condensation in the FPVT. There was marked variation of the temperature and relative humidity in both the horizontal and vertical planes inside both tunnels. This variation responded to solar radiation, with the highest variation occurring at the middle of the day, when solar radiation was at its peak. Whitewashing, using near infrared reflective screens and fogging could reduce the solar heat gain of the greenhouse and reduce the high temperature increase and microclimate variation in both greenhouses. In the FPVT, it would also help to reduce the energy use of the fan and the pump required for the evaporative cooling process.

The microclimate was more favourable for plant growth in the FPVT than in the NVT, especially in December and January, which led to faster increases in plant height and leaf accumulation for three of the four tomato cultivars. However, the optimum growing conditions in the FPVT did not lead to significant yields, but served to improve the quality of the tomato fruits. A cost-benefit analysis may be needed to establish whether the costs associated with operating and maintaining the FPVT are offset by the reduced non-marketable yield. Unmarketable yield was high in the NVT, mainly due to insect attack and under-sized fruits resulting from the higher temperatures in the NVT. The high incident of insect attack may increase the operational costs in naturally-ventilated structures. Among the four cultivars, Bona grown in the FPVT had the highest total and marketable yield, as well as the lowest non-marketable yield. Cultivar Zeal had the lowest yield in both tunnels, while

Star 9009 was the most vulnerable to insect attack. In the NVT, Star 9009 and Star 9037 were the best performers in terms of total yield, although 25-35% of this yield was non-marketable.

3.6 References

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4. RESPONSE OF POSTHARVEST QUALITY ATTRIBUTES AND CULTIVARS TO GREENHOUSE MICROCLIMATE AND STORAGE CONDITIONS

Abstract

The postharvest quality management of tomatoes is important to limit the amount of losses that occur due to deterioration between harvest and consumption. This study was undertaken to investigate the effects of pre- and postharvest integrated agro-technologies, involving greenhouse microclimate and postharvest storage conditions, on the postharvest quality attributes of four tomato cultivars. Tomato fruit firmness, colour (hue angle (h°) and L^* value), pH and total soluble solids (TSS) for the cultivars Bona, Star 9037, Star 9009 and Zeal, grown in a fan-pad evaporatively-cooled (FPVT) and an open-ended naturally-ventilated tunnel (NVT), were harvested at the mature-green stage. The tomatoes were stored for 28 days under cold storage conditions, with a temperature of 13°C and RH of 85%, and under ambient air conditions, with a temperature of $23 \pm 2^\circ\text{C}$ and RH of $52 \pm 4\%$. Sampling was done every seven days, starting on day zero. Statistical analysis was done using the MSTATC statistical package to perform ANOVA, and the Duncan's Multiple Range Test was used to separate the means. The greenhouse microclimates and the postharvest storage conditions significantly ($P \leq 0.05$) influenced the firmness, colour, TSS content and pH values of the four tomato cultivars. The NVT-grown tomatoes had a higher (by 7.4%) firmness which was retained for a longer period, while having an overall 10.3% higher TSS content for the 28 days of storage for all the cultivars, but lower L^* and h° values, compared to the FPVT-grown tomatoes. Among the four tomato cultivars, Bona had the least firmness, which was found to be 21.5% lower than the firmest cultivar, Star 9009. It also had the highest TSS content (up to 8.3% higher) and the lowest pH, with 3.64, up to 5.0% lower than the other cultivars. Furthermore, Bona tomatoes had the lowest L^* (by up to 17.5%) and hue angle (by up to 20.9%), and thus, ripened and deteriorated faster than the other three cultivars. Under ambient air storage conditions, the tomatoes had 13.6% lower firmness, 6.4% and 8.8% lower L^* and hue angle, respectively, 17.7% higher TSS and 18.8% lower pH than the tomatoes in cold storage. This signalled rapid ripening and loss of acceptable quality. The interaction effects showed that cold storage conditions maintained the firmness of Bona tomatoes by 24.1%, whereas the firmness of the other cultivars were not significantly ($P > 0.05$) influenced by the storage condition treatments. FPVT-grown tomatoes had higher L^* (by 10.4%) and h° (by

12.7%), when stored under ambient air storage conditions, compared to NVT-grown tomatoes stored under the same conditions. The three-way interaction effect of microclimate and cultivar with storage conditions led to 14.9% and 22.7% higher firmness, respectively, for Bona and Zeal tomatoes grown in the NVT, and stored under cold storage conditions, than those under ambient air conditions. Further, under cold storage conditions, FPVT-grown Bona was 33.9% firmer than FPVT-grown Bona stored under ambient air conditions. Similarly, the TSS content for the NVT-grown tomatoes was 20.0 to 26.2% higher under ambient conditions than cold storage conditions, for all the cultivars. The changes in colour of FPVT-grown Bona and NVT-grown Zeal were slowed down under cold storage conditions. Star 9009 and Star 9037 were the least affected by the interaction effects, retaining higher firmness with the least colour changes, although they had lower TSS and higher pH values.

This study has provided information on the effect of integrated pre-harvest and postharvest agro-technologies, involving greenhouse microclimate and postharvest storage environment on the postharvest quality attributes of four of the tomato cultivars in South Africa. NVT-grown tomatoes retained better textural qualities, but ripened faster by changing from green to red faster, although these were reduced under cold storage conditions. FPVT-grown tomatoes had lower firmness, but ripened slowly with higher colour attributes. With cold storage conditions, the firmness of FPVT-grown tomatoes was maintained. Cultivar Bona firmness and colour qualities depreciated the fastest, but it had higher TSS content and lower pH values. Star 9009 and Star 9037 presented better quality, by retaining higher firmness and ripening slowly, but they had the lowest TSS contents and high pH values, especially Star 9037. Cold storage improved the firmness of tomato cultivars with poor textural quality and faster colour changes.

4.1 Introduction

Tomatoes are climacteric crops and once they have attained physiological maturity, they continue ripening after detachment from the parent plant. Because of their climacteric nature, the shelf-life of tomatoes is limited to two to three weeks in postharvest storage (Kader, 2008). The changes that occur during the ripening process determine the shelf-life, quality and acceptability of the tomatoes by the consumers (Gorini and Testoni, 1990; Camelo *et al.*, 2004). The loss of quality and postharvest spoilage of tomatoes leads to significant losses to producers, retailers and consumers (Bapat *et al.*, 2010). Thus, the most important role of postharvest quality management is to limit the losses that occur, due to deterioration, between the producer and the consumer, as much as possible, (Genanew, 2013)

The most important postharvest qualities in tomatoes include, but are not limited to, fruit colour, firmness (Gorini and Testoni, 1990; Batu, 2004), soluble sugars content, acidity level and pH (de Castro *et al.*, 2005). Fruit firmness (or texture) (Sams, 1999) and colour (Gorini and Testoni, 1990) are the primary attributes used by consumers to evaluate the maturity stage and quality when making a purchase. The soluble sugars content and pH determine the sensory or flavour attributes (sweetness or sourness) (Beckles, 2012) and influence repeated purchases by the consumers (Kader, 2008). These may also be used as a measure of the ripeness of physiologically-mature tomatoes (de Castro *et al.*, 2005). Producers, on the other hand, are more concerned with colour, firmness and shelf-life (Kader, 2002).

In order to reduce the losses and maintain acceptable quality levels, it is important to understand the factors that influence the quality attributes. Genotypes, growth environment, stage of maturity at harvest (Moneruzzaman *et al.*, 2009), harvesting methods, as well as postharvest handling and packaging methods, are some of the factors that determine the shelf-life of tomatoes (Bapat *et al.*, 2010; Vinha *et al.*, 2013). The quality attributes are genetically programmed, but these can be modified by the environment under which the tomato is grown (Abou-Aziz *et al.*, 1976; Hannah *et al.*, 2009). The storage conditions under which the ripening process of tomatoes is delayed or halted, increase the shelf-life. These include modified and controlled atmosphere storage, packaging, low temperature storage conditions and ethylene inhibition (Wills *et al.*, 2007). However, the quality attributes of most crops is

determined during the growth stages and storage conditions can only maintain the quality, in order to reduce the losses associated with postharvest deterioration (de Castro *et al.*, 2005).

Tomatoes are the second most important vegetable crop in South Africa, contributing about 24% of the country's vegetable production (DAFF, 2013). Most of the tomato production in South Africa's is carried out in open fields, although protected cultivation is gaining popularity. Protected environment cultivation is mostly carried out in naturally-ventilated tunnels, although the use of the fan-pad evaporatively cooled facilities is gaining popularity (Maboko *et al.*, 2010). Fan-pad evaporative cooling technology is costly to install, operate and maintain and a constant and reliable supply of electricity and good quality water are required. Naturally-ventilated facilities are less expensive, but there is limited control of the microclimate. The effect that the microclimate in these facilities has on the postharvest quality of tomatoes under South African conditions is limited. In addition, a substantial number of new tomato cultivars are released on to the South African markets every year. The selection of which cultivar to use is primarily based on information provided by the seed companies (Maboko *et al.*, 2010). Failure to select the correct cultivar for a particular production method can lead to the production of an inferior quality product (Hanna, 2009) and may lead to rejection by consumers (Snyder, 2003).

This study was undertaken to establish the influence of two different greenhouse microclimates, the cultivar, storage conditions and time on the effect of postharvest quality attributes of fresh market tomatoes available on the South African market.

4.2 Materials and Methods

Four fresh market tomato cultivars (Bona, Star 9037, Star 9009 and Zeal) were grown in two polyethylene covered tunnels at the Ukulinga Research Farm of the University of KwaZulu-Natal, Pietermaritzburg, South Africa (29.67° S and 30.40° E, 840 m above sea level), during summer, from October 2012 to January 2013. One tunnel was a fan-pad evaporatively cooled tunnel (FPVT), while the other was an open-ended naturally-ventilated tunnel (NVT), with the open ends covered with black and white Knittex[®] 40 insect screen netting. The air temperature and relative humidity (RH) inside both tunnels were monitored throughout the growing season, using Hobo[®] Pro v2 optic data loggers (Onset Computer Corporation,

Bourne, USA), equipped with temperature and relative humidity sensors (Table 4.1). Seven-week old seedlings, bought from a local nursery, were transplanted into 10 L black plastic bags on the 26th September 2012. The tomatoes were drip-irrigated and fertilizers were applied through the irrigation water.

Table 4.1 The maximum, minimum and mean temperatures and relative humidity in the naturally-ventilated (NV) and the fan-pad evaporatively cooled (FPV) tunnels.

Time (Months)	Micro-climate	T _{maximum} (±SD)	T _{mean} (±SD)	T _{minimum} (±SD)	RH _{maximum} (±SD)	RH _{mean} (±SD)	RH _{minimum} (±SD)
October	NV	29.9 ±4.8	18.9±2.2	13.3±0.9	96.0±1.5	79.3±5.9	47.6±10.3
	FPV	29.2±2.9	19.2±1.5	14.0±0.8	97.3±0.9	83.5±4.6	53.7±8.8
November	NV	29.4±3.8	19.6±2.0	14.2±1.2	96.7±1.4	80.3±5.3	50.7±9.3
	FPV	30.9±2.3	20.9±1.4	14.8±1.2	98.7±0.5	83.9±4.2	56.8±8.7
December	NV	33.8±2.8	22.9±1.5	16.7±1.0	97.1±0.7	78.6±3.3	45.6±6.1
	FPV	29.0±1.4	22.1±0.7	17.0±0.7	99.1±0.2	83.9±2.0	57.6±4.0
January	NV	33.8±3.9	23.0±1.8	17.0±0.8	96.9±0.9	78.6±5.0	46.5±8.6
	FPV	29.3±2.0	22.0±1.1	17.6±0.8	99.5±0.1	88.0±3.1	64.8±6.3

± indicates 99% confidence. T = temperature; RH = relative humidity

Forty randomly-selected fruits per cultivar from each greenhouse (320 fruits in total) were harvested at the mature-green stage. For each cultivar, half of the fruits (20 fruits) were stored under cold storage conditions and the other half under ambient conditions. The fruits were first cleaned, by washing them with tap water, and then stored in clear plastic bags. A climate test chamber (CTS-GmbH[®], Hechingen, Germany) was used for cold storage. Under ambient air storage, the temperature was 23± 2°C and the RH was 52± 4%. In the controlled storage chamber, the temperature was set at 13°C with a RH of 85%.

4.2.1 Quality attributes analysed

The individual tomatoes were assessed for firmness, colour, total soluble solids (TSS) and pH on days 0, 7, 14, 21 and 28 of storage. The colour indicators were determined, using the Hunterlab Colourflex[®] EZ (Hunter Associates Laboratory, Inc., USA) spectrophotometer. Each fruit was measured for L*, a* and b* at three equatorial positions (blossom end, stem-end and mid-way), which were averaged to determine the overall values for L*, a* and b*.

Using a^* and b^* , the hue angle (h°) for each fruit was calculated from Equation 4.1 (Saltveit, 2005).

$$h^\circ = \tan^{-1}\left(\frac{b^*}{a^*}\right) \quad (4.1)$$

where a^* = the ratio of red to green colour.

b^* = the ratio of yellow to blue colour

The tomato firmness was determined by the puncture test, using the Instron® 3345 Universal Testing Machine (Instron, UK) with a 5 kN capacity, according to Sirisomboon *et al.* (2012). Each fruit was placed in the holding part of the machine, and then a 2 mm stainless steel probe, attached to a loading cell, was driven into the fruit at a penetration rate of $10 \text{ mm}\cdot\text{minute}^{-1}$, as shown in Figure 4.2. The peak force required to penetrate the fruit, known as the rupture point, was measured at three equatorial positions (blossom-end, stem-end and mid-way) on the fruit.

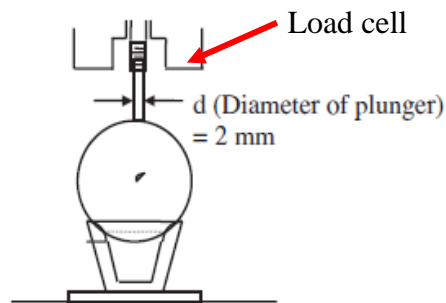


Figure 4.1 Puncture test (after Sirisomboon *et al.*, 2012)

For the pH and the TSS, each tomato fruit was homogenised into a pulp, using a hand-held processor. The pH was then determined, using a Crison® Micro-pH 2000 (Crison Instruments, S.A., Barcelona, Spain) pH meter with a sensitivity of ± 0.01 . The TSS was determined, using a digital Palette® PR101 (Atago Co. Ltd. Japan) hand-held refractometer, measuring from 0.0 to 45°Brix , with a measuring accuracy of $^\circ\text{Brix} \pm 0.2^\circ$, after calibrating it with distilled water.

4.2.2 Data analysis

Data analysis was performed through the analysis of variance (ANOVA), using the MSTAT-C statistical and data management package (Michigan State University, 1993) with evaluations based on a $P=0.05$ significance level. The treatments mean separation was by least significant difference (LSD) using the Duncan's Multiple Range Test (Duncan, 1955).

4.3 Results

The results of the firmness test, colour indexes, TSS content and pH values are presented in this section.

4.3.1 Firmness

The effects of the microclimate conditions, cultivar differences, storage conditions and storage time on the firmness of the tomatoes were significant ($P<0.05$). The tomatoes grown in the NVT were 7.4% more resistant to puncture, with 4.16 N, than those grown in the FPVT, with 3.85 N. Comparison of the firmness between the cultivars showed that the overall average firmness for Star 9009 was 21.5% higher, with 4.50 N, than that of Bona, which had an overall average of 3.53 N, but slightly different to Star 9037 and Zeal, which had overall averages of 4.15 N and 3.84 N, respectively. The overall average showed that the tomatoes stored under cold storage conditions, were 13.6% more resistant to puncture than those kept under ambient air conditions. Furthermore, under cold storage, a firmness texture was maintained for a longer time than under ambient storage.

There were significant ($P<0.05$) effects due to the interaction of microclimate \times cultivar, cultivar \times storage condition, cultivar \times storage time and storage condition \times storage time. Under both NVT and FPVT microclimates, Bona had the lowest overall average firmness, followed by Zeal. Under the NVT microclimate, Star 9009 was significantly firmer (22.7%) than both Bona and Zeal, but not significantly different from Star 9037, while Bona, Star 9037 and Zeal did not differ significantly. In the FPVT, the firmness of the four cultivars did not vary significantly from each other. Similarly, the firmness of fruits grown in the NVT did not vary significantly, when compared to those of the same cultivars from the FPVT.

Under cold storage conditions, cultivar Bona was significantly more resistant (24.1% firmer) to puncture than Bona kept under ambient storage conditions. The firmness for the other cultivars (Star 9037, Star 9009 and Zeal) were not significantly ($P>0.05$) influenced by storage conditions. Under ambient storage, Bona was significantly less firm (22.9% and 29.4%) than the overall average firmness of Star 9037 and Star 9009, respectively. In cold storage, the firmness of the cultivars did not vary significantly. Cultivar Bona resistance to puncture decreased significantly with storage time, especially between Days 14 and 21, when compared to the other cultivars (Figure 4.2). The firmness of Star 9037, Star 9009 and Zeal decreased significantly during the first seven days and were constant over the next 14 days until Day 21, with slight differences between the cultivars. Tomatoes in cold storage maintained higher firmness over the storage period than ambient air stored tomatoes. There were no significant ($P>0.05$) influences on the firmness of the tomatoes, due to the interaction of microclimate \times storage condition and the microclimate \times storage time.

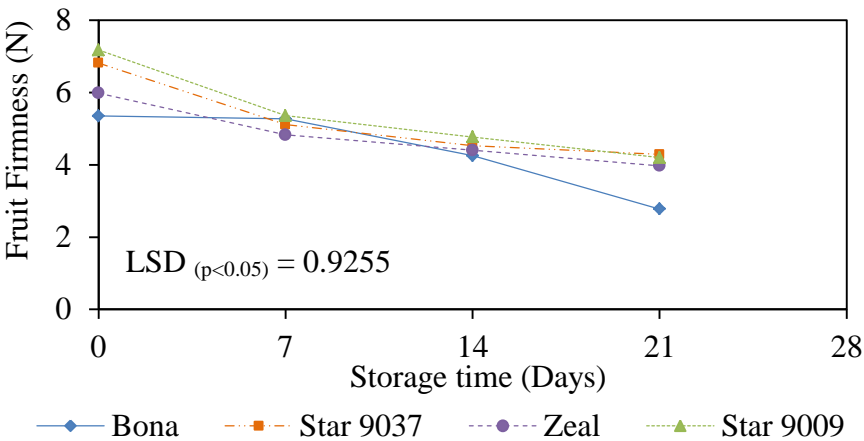


Figure 4.2 The interaction effect of cultivar \times storage period on the firmness of tomatoes over a 28-day storage period.

The interaction of microclimate, cultivar and storage conditions had a significant ($P<0.01$) influence on the firmness of Bona and Zeal (Table 4.2). Bona grown under NVT microclimate conditions and stored under ambient air conditions was 14.9% less resistant to puncture than Bona from the NVT and stored in cold storage. Similarly, NVT Zeal stored under ambient air conditions was 22.7% less resistant to puncture than NVT Zeal in cold storage, particularly between Days seven and 21. FPVT Bona stored at ambient air was 33.9% less firm, when compared to FPVT Bona in cold storage. There were no significant influences on Star 9037 and Star 9009.

Figure 4.3 shows the interaction of microclimate × cultivar × storage time. The firmness of Bona grown in the FPVT decreased faster, in comparison to the other cultivars, starting from Day seven. The firmness of the other cultivars decreased significantly during the first seven days, after which the firmness became constant over the next 14 days. By Day 28, all the cultivars had decayed to such a level that performing the puncture test was impossible.

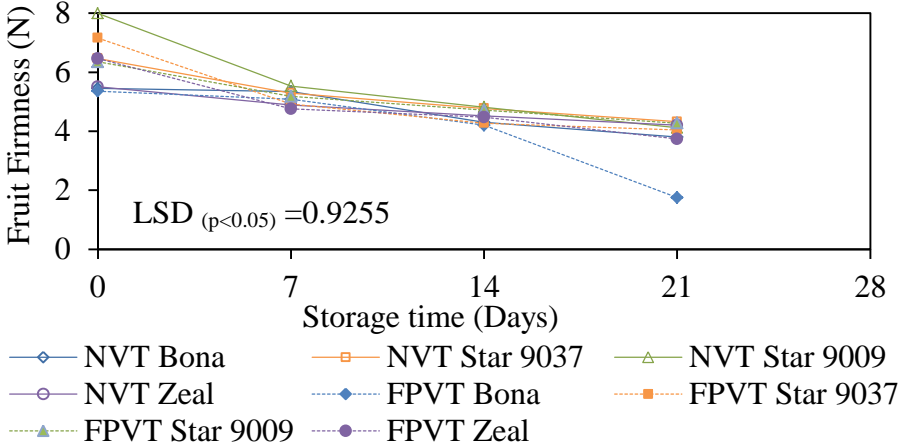


Figure 4.3 The interaction effect of microclimate × cultivar × storage time on the firmness of tomatoes over a 28-day storage period. NVT = natural ventilated tunnel; FPVT = fan-pad evaporatively cooled tunnel

Figure 4.4 shows the interaction of microclimate × storage condition × storage time over 28 days of postharvest storage. The firmness of tomatoes harvested from the FPVT and NVT and stored under ambient air conditions decreased rapidly, when compared to those grown in the FPVT and NVT and stored under cold storage conditions. Under cold storage conditions, the firmness of the NVT-grown tomatoes was significantly higher than that of those grown in the FPVT, during the first 14 days, with no significant difference between Days 14 and 21.

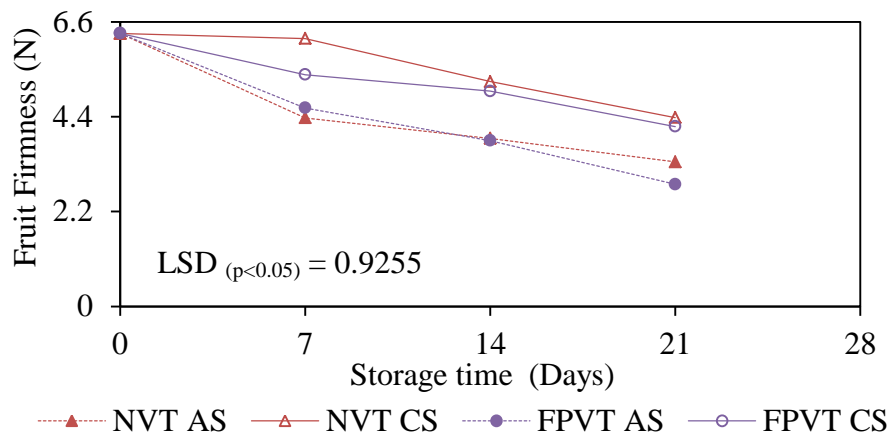


Figure 4.4 The interaction effect of microclimate \times storage condition \times storage time on the firmness of the tomatoes. NVT = natural ventilated tunnel; FPVT = fan-pad evaporatively cooled tunnel; AC = ambient air storage; CS = cold storage

The interaction between cultivar \times storage condition \times storage time had a significant ($P < 0.01$) effect on the firmness of all the cultivars (Figure 4.5). The firmness of cultivar Bona, stored under ambient air conditions, decreased more rapidly, almost linearly, throughout the storage period. Similarly, the firmness of Star 9009 stored under ambient air conditions decreased the most during the first seven days in storage and then was constant between Days seven and 21. Under cold storage conditions, Star 9009 had the highest the firmness, especially during the first 14 days of storage.

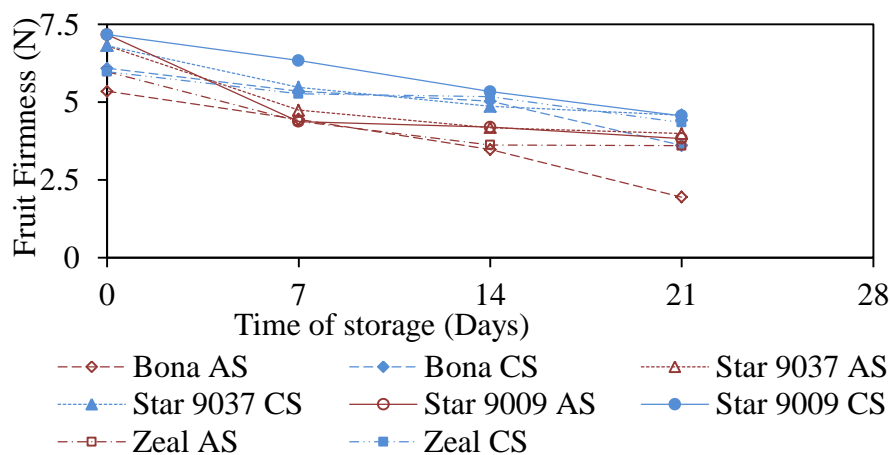


Figure 4.5 The interaction effect of cultivar \times storage condition \times storage time on the firmness of the tomatoes. NV = natural ventilation; FPV = fan-pad evaporative cooling; AS = ambient air storage; CS = cold storage

Table 4.2 The firmness (N) for tomatoes raised under FPVT and NVT and stored under ambient and cold conditions

Ventilation	Cultivar	Ambient storage period (Days)					Cold storage period (Days)				
		0	7	14	21	28	0	7	14	21	28
FPVT	Bona	5.36 ^{d-j}	4.19 ^{k-t}	3.56 st	3.50 st	D	5.36 ^{d-j}	5.98 ^{c-g}	4.91 ^{g-p}	3.50 st	D
	Star 9037	7.16 ^{ab}	4.60 ^{h-t}	3.97 ^{n-t}	3.80 ^{o-t}	D	7.16 ^{ab}	5.25 ^{e-l}	4.70 ^{h-r}	4.58 ^{h-t}	D
	Star 9009	6.35 ^{b-e}	4.72 ^{h-r}	4.30 ^{j-t}	3.81 ^{o-t}	D	6.35 ^{b-e}	5.64 ^{d-h}	5.14 ^{f-m}	4.74 ^{h-r}	D
	Zeal	6.46 ^{b-d}	4.89 ^{g-p}	3.72 ^{q-t}	3.61 ^{r-t}	D	6.46 ^{b-d}	5.35 ^{d-k}	4.63 ^{h-s}	3.75 ^{p-t}	D
NVT	Bona	6.20 ^{b-f}	4.70 ^{h-r}	3.89 ^{n-t}	3.45 st	D	6.20 ^{b-f}	5.35 ^{d-k}	5.15 ^{f-m}	3.72 ^{q-t}	D
	Star 9037	6.47 ^{b-d}	4.88 ^{g-q}	4.40 ^{i-t}	4.18 ^{k-t}	D	6.47 ^{b-d}	5.71 ^{d-h}	5.15 ^{f-m}	4.47 ^{i-t}	D
	Star 9009	7.99 ^a	4.10 ^{l-t}	4.03 ^{m-t}	3.85 ^{n-t}	D	7.99 ^a	7.04 ^{a-c}	5.55 ^{d-i}	4.39 ^{i-t}	D
	Zeal	5.51 ^{d-i}	3.88 ^{n-t}	3.64 ^{r-t}	3.48 st	D	5.91 ^{d-g}	5.51 ^{d-i}	5.01 ^{g-m}	4.93 ^{g-o}	D

LSD ($p \leq 0.05$) = 0.9255; CV = 16.60%

Mean values in the same column with the same superscript letters indicates no significant differences ($P > 0.05$). The letter D represents “decayed”.

4.3.2 Change in colour

The changes in the colour of tomatoes were measured in terms of the L^* value and the hue angle (h°), as shown in Table 4.3. Both the h° and L^* value were significantly ($P \leq 0.05$) influenced by the microclimate, cultivar, storage condition and the storage time. The tomatoes grown in the FPVT had an overall 7.2% higher L^* value, representing the four cultivars for the 28 days of storage, compared to those from the NVT. Similarly, the h° for the FPVT grown tomatoes was 8% higher than that of the NVT-grown tomatoes. In general, the overall average L^* and h° , over the 28 day observation period, for cultivar Bona were 13.4-17.5% and 15.9-20.9% lower than those of the other three cultivars (Star 9009, Star 9037 and Zeal), respectively. There were no significant ($P > 0.05$) differences between Star 9037, Star 9009 and Zeal L^* and h° values. Tomatoes stored under cold storage had an overall average L^* value and an h° that were 6.4% and 8.8% higher, respectively, than those at ambient air storage, for the 28 day observation period. In addition, the h° and L^* values decreased progressively over the time of storage and the minimum values were reached on the last day (Day 28) of measurement.

There were also significant ($P < 0.01$) effects on the h° and the L^* values of the tomatoes, due to the interaction of microclimate \times cultivar, microclimate \times storage conditions, over the 28 day storage period, cultivar \times storage time for both the NVT- and the FPVT-grown tomatoes for the 28 day storage period, as well as storage conditions \times storage time for both NVT- and FPVT-grown tomatoes representative of the four cultivars. The L^* and h° of Star 9037 were 14.5% and 11.7% higher, respectively, for tomatoes from the FPVT than the ones grown in the NVT. Similarly, Zeal grown under FPVT conditions had L^* and h° values that were found to be 14.5% and 12.5% higher, respectively, when compared to those grown in the NVT. Under FPVT microclimate conditions, the L^* and h° values of Bona were 21% and 23% lower, respectively, than those of the other three cultivars. On the other hand, under the NVT conditions, the overall mean L^* and h° were 12.4-13.2% and 12-14.6% lower, respectively, than those of Star 9037 and Star 9009, for the entire 28 day storage period. Tomatoes raised in the FPVT and stored under ambient air conditions, had a 10.4% higher L^* and h° that was 12.7% greater than the values obtained for those produced under the NVT microclimate and stored under ambient conditions. Tomatoes grown in the FPVT and stored under refrigerated conditions had L^* and h° values that were 13.4% and 16.5% higher than those grown in the

Table 4.3 The hue angle and L* values for four tomato cultivars harvested from an FPVT and a NVT stored under ambient and cold storage

		L*									
Ventilation	Cultivar	Ambient storage period (Days)					Cold storage period (Day)				
		0	7	14	21	28	0	7	14	21	28
FPVT	Bona	64.21 ^{a-h}	58.86 ^{e-l}	46.09 ^{v-y}	47.74 ^{t-x}	D	64.21 ^{a-h}	61.54 ^{a-k}	48.24 ^{s-x}	44.51 ^{w-y}	45.99 ^{w-y}
	Star9037	67.46 ^{ab}	66.34 ^{a-d}	55.52 ^{j-r}	58.58 ^{e-l}	58.13 ^{f-m}	67.21 ^{ab}	65.74 ^{a-e}	55.24 ^{j-r}	62.88 ^{a-i}	57.09 ^{h-o}
	Star9009	66.80 ^{ab}	66.11 ^{a-d}	61.73 ^{a-k}	59.24 ^{d-l}	58.86 ^{e-l}	66.81 ^{ab}	63.24 ^{a-h}	66.95 ^{ab}	55.59 ^{j-r}	47.27 ^{u-x}
	Zeal	67.69 ^a	67.21 ^{ab}	59.23 ^{d-l}	53.52 ^{l-u}	54.79 ^{k-t}	67.69 ^a	66.46 ^{a-c}	62.84 ^{a-i}	56.51 ^{i-p}	51.53 ^{m-w}
NVT	Bona	66.99 ^{ab}	59.63 ^{c-l}	49.97 ^{p-w}	49.54 ^{p-x}	D	66.95 ^{ab}	61.71 ^{a-k}	49.24 ^{q-x}	40.41 ^y	50.21 ^{o-w}
	Star9037	65.27 ^{a-f}	64.29 ^{a-g}	50.31 ^{o-w}	50.35 ^{o-w}	53.15 ^{l-v}	65.27 ^{a-f}	61.72 ^{a-k}	57.63 ^{g-n}	56.25 ^{i-q}	45.89 ^{w-y}
	Star9009	68.30 ^a	62.14 ^{a-j}	54.83 ^{k-t}	50.36 ^{o-w}	49.55 ^{p-x}	68.49 ^a	63.23 ^{a-h}	50.34 ^{o-w}	48.39 ^{s-x}	48.99 ^{r-x}
	Zeal	67.94 ^a	59.44 ^{c-l}	47.25 ^{u-x}	50.71 ^{n-w}	D	67.94 ^a	64.48 ^{a-g}	60.24 ^{b-l}	58.29 ^{f-m}	42.92 ^{xy}
LSD ($p \leq 0.05$) = 5.727; CV = 7.36%											
		Hue Angle(°)									
Ventilation	Cultivar	Ambient storage period (Days)					Cold storage period (Days)				
		0	7	14	21	28	0	7	14	21	28
FPVT	Bona	77.6 ^{a-g}	64.7 ^{h-r}	48.5 ^{w-z}	48.7 ^{w-z}	D	77.6 ^{a-g}	78.0 ^{a-g}	50.1 ^{u-z}	44.3 ^z	43.0 ^z
	Star9037	79.2 ^{a-f}	82.5 ^{a-c}	61.4 ^{k-v}	66.7 ^{f-p}	63.9 ^{i-s}	79.2 ^{a-f}	81.9 ^{a-c}	64.0 ^{i-s}	81.1 ^{a-d}	61.0 ^{k-w}
	Star9009	78.9 ^{a-f}	83.8 ^{ab}	70.5 ^{c-l}	68.3 ^{e-n}	65.6 ^{g-q}	78.9 ^{a-f}	82.2 ^{a-c}	82.0 ^{a-c}	68.5 ^{d-m}	47.7 ^{yz}
	Zeal	77.9 ^{a-g}	85.3 ^a	63.1 ^{i-u}	60.4 ^{k-x}	60.3 ^{k-x}	77.9 ^{a-g}	81.0 ^{a-e}	77.0 ^{a-h}	62.0 ^{j-v}	48.6 ^{w-z}
NVT	Bona	78.1 ^{a-g}	70.2 ^{c-l}	51.2 ^{t-z}	52.0 ^{s-z}	D	78.1 ^{a-g}	81.7 ^{a-c}	58.1 ^{l-z}	40.4 ^z	50.7 ^{u-z}
	Star9037	81.4 ^{a-c}	74.6 ^{a-i}	58.7 ^{l-z}	52.7 ^{r-z}	53.2 ^{q-z}	81.4 ^{a-c}	82.8 ^{a-c}	54.3 ^{p-z}	49.6 ^{v-z}	47.9 ^{x-z}
	Star9009	80.5 ^{a-e}	74.8 ^{a-i}	53.7 ^{q-z}	54.8 ^{o-z}	57.1 ^{m-z}	80.5 ^{a-e}	74.9 ^{a-i}	71.5 ^{b-k}	63.7 ^{i-t}	44.2 ^z
	Zeal	79.1 ^{a-g}	66.9 ^{f-o}	46.6 ^z	55.9 ^{n-z}	D	79.1 ^{a-f}	83.4 ^{ab}	81.3 ^{a-d}	73.9 ^{a-j}	40.4 ^z
(LSD ($p \leq 0.05$) = 10.15; CV = 11.35%)											

NVT and stored under ambient conditions, respectively. The decline of the L^* and the h° values was more rapid under ambient than cold storage conditions. Under ambient storage conditions, the L^* and h° values decreased by 51.3% and 52.6%, respectively, throughout the storage period, compared to 27.1% and 39.4%, respectively, in cold storage.

Figures 4.6 and 4.7 show that the L^* and h° values of cultivar Bona differed significantly ($P < 0.05$) from and decreased more rapidly, when compared to Star 9037, Star 9009 and Zeal. Bona L^* and h° fell from 65.6 to 24.1 and from 77.8 to 23.4°, respectively, whereas Star 9037 fell from 67.9 to 53.4 and from 80.3 to 56.5°, respectively. During the last seven days of storage, the L^* and h° of Zeal fell rapidly from 54.8 to 37.3 and from 63.1 to 37.3°, respectively, compared to those of Star 9009 (from 55.3 to 51.3 and from 63.8 to 53.7°) and Star 9037 (from 55.1 to 53.4 and from 62.6 to 56.5°), respectively. The cultivars Star 9009 and Star 9037 maintained higher L^* and h° values throughout the storage period.

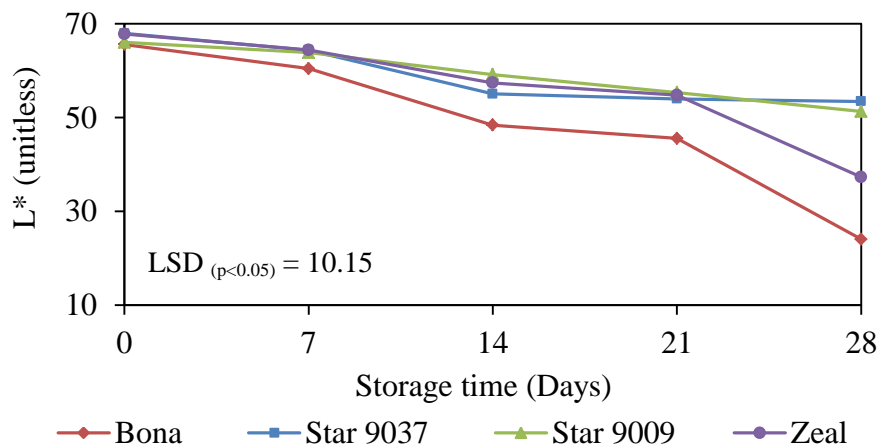


Figure 4.6 Interaction effect of cultivar and storage time on L^* (a) and h° (b) of tomatoes

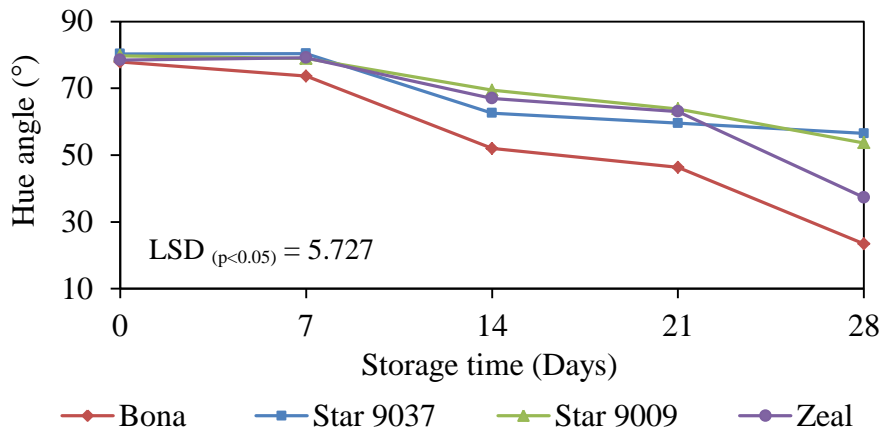


Figure 4.7 Interaction effect of cultivar and storage time on h° of tomatoes

The interaction between microclimate, cultivar and storage conditions significantly ($P < 0.001$) influenced the L^* and the h° values of the tomatoes. Cultivar Bona, grown under FPVT conditions and kept under cold storage conditions had L^* and h° values that were 18% and 18.3% higher, respectively, than NVT-grown Bona stored in cold storage. Cultivar Zeal, stored under cold storage, had L^* and h° values that were found to be 23.5% and 30.6% higher, respectively, than those stored under ambient conditions. Similarly, Bona tomatoes grown in the FPVT and stored under refrigerated conditions had L^* and h° values that were found to be 16.9% and 18.6% higher, respectively, than those stored under ambient conditions.

As shown by Figures 4.8 and 4.9, the overall average L^* and h° values of tomatoes grown in the NVT and stored under ambient air conditions, decreased significantly ($P < 0.001$) faster than those grown in the NVT and stored under cold conditions, starting from Day 7 of storage. The L^* and h° of tomatoes grown in the NVT and stored under cold conditions, decreased at the same rate as those from the FPVT and stored under ambient air and cold storage conditions.

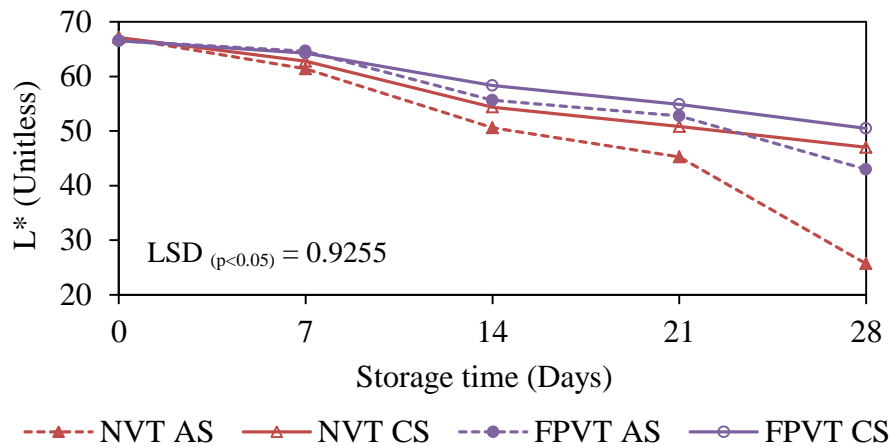


Figure 4.8 Interaction of microclimate, storage condition and time of storage on the L*value of the tomatoes

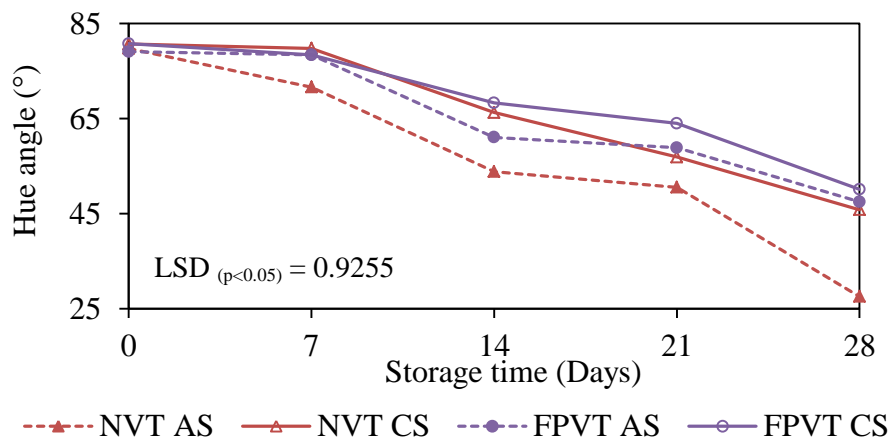


Figure 4.9 Interaction of microclimate, storage condition and storage period on the h° of the tomatoes

4.3.3 Total soluble solids

Table 4.4 shows the effects of microclimate conditions, cultivar differences and storage conditions on the total soluble solids (TSS) of the tomatoes, stored over a 28 day period. Significant ($P < 0.05$) differences resulting from the effect of microclimate, cultivar, storage condition and storage time were observed on the TSS content of tomatoes. In general, the NVT-grown tomatoes had an overall TSS content that was 10.3% higher than that of the FPVT-grown tomatoes. Cultivar Bona tomatoes had a significantly ($P < 0.05$) higher TSS content than Star 9037 tomatoes, but not significantly ($P > 0.05$) different to those of Zeal and Star 9009. The overall average TSS content of Bona tomatoes was 8.3% higher, when

compared to that of the cultivar Star 9037. Generally, tomatoes stored under ambient air conditions had an overall average TSS content that was 17.7% higher than that of the tomatoes in cold storage. With regards to the effect of the storage period, the overall average TSS content of the tomatoes increased by 15.2% between Days 0 and 7, but did not differ significantly between Days 7 and 21. During the last seven days of storage, the TSS content of the tomatoes fell by 59%.

Significant ($P<0.001$) differences arising from the interaction of microclimate with storage conditions were observed on the TSS content of tomatoes grown in the NVT. In general, the tomatoes stored under refrigerated conditions had an overall 22.3% lower TSS content than those under ambient air storage. Similarly, the interaction between cultivar and storage time significantly ($P<0.001$) influenced the TSS content of cultivars Bona and Zeal for both NVT- and FPVT-grown tomatoes stored under both cold and ambient storage condition. The TSS content of Bona and Zeal increased by 27.2% and 18.3% over the first seven days of storage, respectively, but the changes that occurred between Days 7 and 21 were not significant at $P=0.05$. The TSS content of cultivars Star 9037 and Star 9009 were not significantly influenced by storage time during the first 21 days of storage. During the last seven days of storage, the TSS content of all the tomatoes fell by $>50\%$. In the same manner, the interaction between storage condition and storage time had a significant ($P<0.001$) influence on the TSS content of all the tomatoes, particularly during the last seven days of storage. During the first 21 days of storage, the TSS content of the tomatoes kept under cold storage conditions and those under ambient air storage did not differ significantly. Significant differences were observed between Days 21 and 28, where the tomatoes under ambient air conditions had rotted and TSS could not be determined. Tomatoes in cold storage had a TSS content of 4.7°Brix on Day 28 of storage.

Table 4.4 The total soluble solids (°Brix) of the tomatoes grown in the FPVT and the NVT and stored under ambient and cold storage conditions

Ventilation	Cultivar	Ambient storage period (Days)					Cold storage period (Days)				
		0	7	14	21	28	0	7	14	21	28
FPVT	Bona	5.2 ^{i-p}	7.3 ^a	5.8 ^{c-m}	6.7 ^{a-e}	D	5.2 ^{i-p}	6.4 ^{a-i}	7.0 ^{a-c}	5.2 ^{h-p}	D
	Star9037	4.5 ^{n-p}	4.4 ^{o-p}	4.9 ^{j-p}	4.8 ^{l-p}	D	4.5 ^{n-p}	5.0 ^{j-p}	5.2 ^{i-p}	4.9 ^{k-p}	5.2 ^{h-p}
	Star9009	5.0 ^{j-p}	4.9 ^{j-p}	6.2 ^{a-j}	5.5 ^{d-p}	D	5.0 ^{j-p}	5.0 ^{j-p}	5.1 ^{i-p}	4.9 ^{j-p}	5.0 ^{j-p}
	Zeal	4.3 ^p	5.2 ^{i-p}	4.8 ^{l-p}	6.4 ^{a-i}	D	4.3 ^p	4.9 ^{j-p}	5.1 ^{i-p}	4.8 ^{l-p}	5.2 ^{h-p}
NVT	Bona	4.6 ^{m-p}	6.6 ^{a-f}	5.1 ^{i-p}	6.1 ^{b-l}	D	4.6 ^{m-p}	6.5 ^{a-g}	6.8 ^{a-d}	7.3 ^a	5.2 ^{i-p}
	Star9037	5.2 ^{i-p}	5.7 ^{c-n}	5.6 ^{d-o}	5.2 ^{i-p}	D	5.2 ^{h-p}	5.5 ^{d-p}	5.3 ^{g-p}	5.8 ^{c-n}	6.1 ^{a-k}
	Star9009	5.0 ^{j-p}	5.6 ^{d-o}	5.4 ^{f-p}	5.8 ^{c-m}	D	5.0 ^{j-p}	5.7 ^{c-n}	5.9 ^{c-l}	5.8 ^{c-n}	5.1 ^{i-p}
	Zeal	5.0 ^{j-p}	6.7 ^{a-e}	5.8 ^{c-n}	6.1 ^{a-k}	D	5.0 ^{j-p}	5.9 ^{c-l}	6.5 ^{a-g}	6.5 ^{a-g}	5.5 ^{e-p}

LSD ($p \leq 0.05$) = 1.006; CV = 14.91%

Mean values in the same column with the same superscript letters indicates no significant differences ($P > 0.05$). The letter D represents “decayed”.

The three-way interaction of microclimate × cultivar × storage conditions had a significant ($P < 0.001$) effect on the TSS content of the tomatoes, as well as microclimate × cultivar × storage condition ($P < 0.001$). As shown in Figure 4.10, all tomatoes from the NVT, for all the cultivars, had TSS contents that were 20.0-26.2% higher under ambient conditions, compared to cold storage conditions. From the FPVT, only cultivar Star 9037 tomatoes had a TSS content that was 25.2% higher under ambient conditions, compared to cold storage conditions.

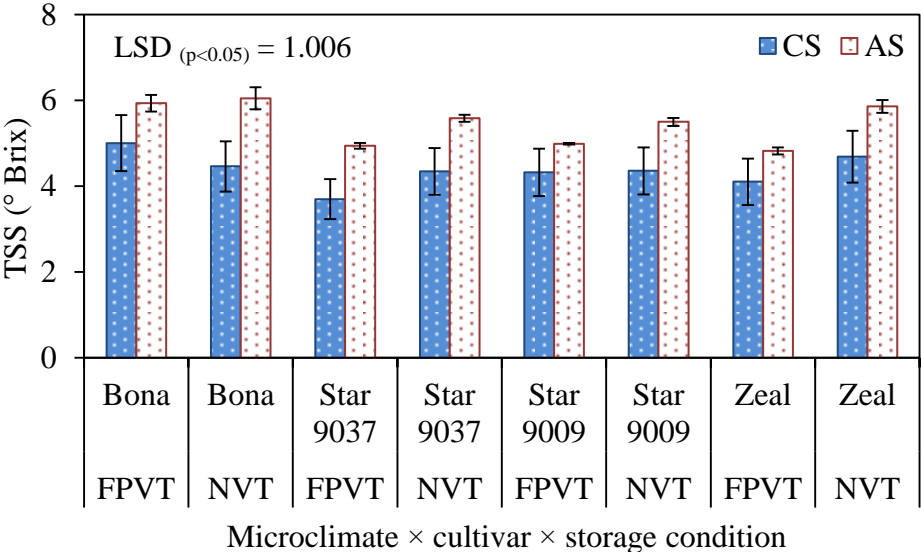


Figure 4.10 The interaction effect of microclimate, cultivar and storage condition interaction on the TSS content of the tomatoes. FPVT = fan-pad evaporatively cooled tunnel microclimate, NVT= naturally-ventilated tunnel microclimate; AS= ambient storage conditions; CS = cold storage conditions.

Figure 4.11 shows that the interaction effects of microclimate with cultivar and storage time significantly ($P < 0.001$) influenced the TSS content of the tomatoes. The TSS contents of Bona tomatoes grown under the FPVT and NVT microclimates were observed to increase the most over the storage period, particularly during the first seven days, when compared to the other cultivars. Between Days 21 and 28, the TSS of cultivar Bona could not be measured due to extreme decay. For cultivars Star 9037, Star 9009 and Zeal grown in the FPVT, the TSS content increased the least over the first 21 days of storage. Between Days 21 and 28, the TSS content of all cultivars, except Bona grown in the FPVT, decreased substantially by 44.2 to 60.3%. Under cold storage conditions, Star 9037 tomatoes grown in the FPVT had a TSS content that was 25.2% higher than those under ambient air storage conditions.

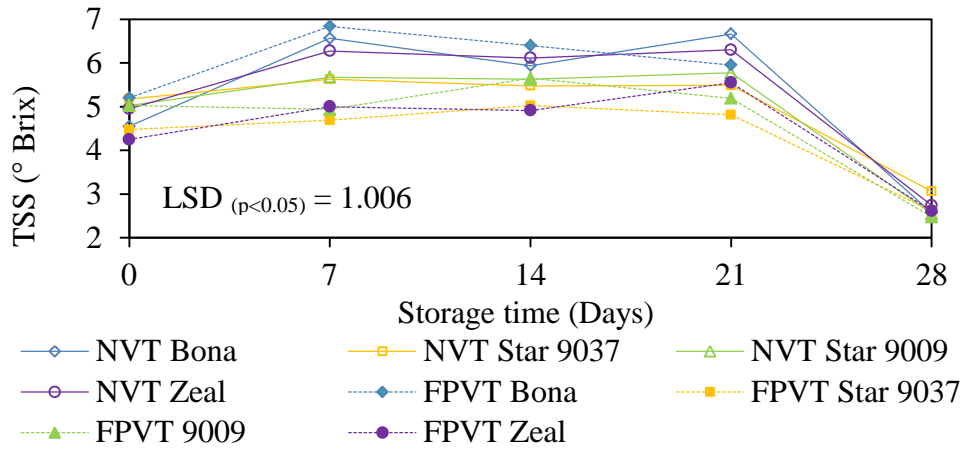


Figure 4.11 The interaction effects of microclimate with cultivar over the 28-day storage period

The interaction between microclimate, storage condition and storage period had a significant ($P < 0.001$) effect on the TSS content of the tomatoes (Figure 4.12). During the first seven days of storage, the TSS content of tomatoes grown in the NVT increased by 19.9% under ambient air storage conditions and by 16.8% in cold storage. Significant differences ($P < 0.05$) also occurred in all tomatoes, except those harvested from the NVT and stored in cold storage, during the last seven days. This was because all the tomatoes, with the exception mentioned above, had decayed by Day 28. There were variations in the TSS content of the tomatoes from both the NVT and the FPVT during the storage time, but these were not significant at $P = 0.05$.

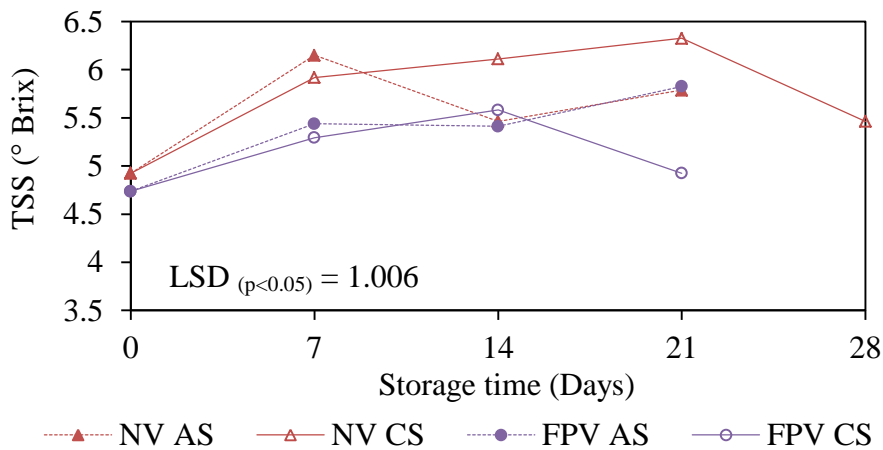


Figure 4.12 The interaction effects of microclimate with storage condition over the 28-day storage period.

Significant differences were also observed in the TSS content with respect to the interaction effects of cultivar with storage condition and storage period. Cultivars Bona and Zeal tomatoes, stored under ambient conditions, had a 30% and 22% increase in the TSS content during the first seven days of storage, respectively. Significant differences ($P < 0.05$) were also observed on all tomatoes from the four cultivars, during the last seven days in storage, primarily because the tomatoes had decayed and testing could not be performed. Similarly, under cold storage conditions, the TSS content of Bona tomatoes increased by 24.2% between Days 0 and 7. Conversely, under cold storage conditions, cultivars Star 9037, Star 9009 and Zeal tomatoes were not influenced by the interaction throughout the 28 days of storage.

4.3.4 pH values

Significant ($P < 0.001$) cultivar effects were observed on the pH of the tomatoes. In general, cultivar Zeal had the highest overall pH value of 3.84, followed by Star 9037 with 3.82, then Star 9009 with 3.74, and lastly, Bona with 3.64 for the entire storage period. The pH of cultivar Bona was significantly lower than that of Star 9037 (by 4.6%) and Zeal (by 5.0%), but not significantly different to that of Star 9009. The storage conditions significantly ($P < 0.001$) influenced the pH value of the tomatoes. Under cold storage conditions, the pH level was 18.8% higher than that of the tomatoes stored under ambient air conditions. Similarly, the storage period had a significant ($P < 0.001$) influence on the pH value of the tomatoes. The pH values of the tomatoes decrease significantly by 6.4%, during the first seven days of storage, and by a further 56.5% between Days 21 and 28. Between Days 7 and 21, there were no significant differences in the pH values. The microclimate conditions were found to have a non-significant ($P > 0.05$) effect on the pH values of the tomatoes.

As shown in Table 4.5, there were significant ($P < 0.01$) interaction effects from: (a) microclimate \times cultivar; (b) microclimate \times storage condition; (c) microclimate \times storage time; (d) cultivar \times storage condition; (e) cultivar \times storage time, and (f) storage condition \times storage time. Under the NVT microclimate, the pH of cultivar Bona tomatoes was 10.3% higher than that of Bona tomatoes from the FPVT. There were no significant differences in the pH value of the other cultivars grown in the NVT and tomatoes of the same cultivar in the FPVT.

Table 4.5 The pH values of tomatoes grown in FPVT and NVT and stored under ambient and cold storage conditions

Ventilation	Cultivar	Ambient storage period (Days)					Cold storage period (Days)				
		0	7	14	21	28	0	7	14	21	28
FPVT	Bona	4.67 ^a	4.06 ^{p-u}	4.07 ^{o-u}	4.29 ^{e-m}	D	4.67 ^a	4.14 ^{m-u}	4.18 ^{i-s}	4.14 ^{m-u}	D
	Star 9037	4.42 ^{c-e}	4.18 ^{i-s}	4.20 ^{h-r}	4.39 ^{c-g}	D	4.42 ^{c-e}	4.29 ^{e-m}	4.34 ^{c-j}	4.47 ^{b-d}	4.35 ^{c-i}
	Star 9009	4.32 ^{d-l}	4.16 ^{k-t}	3.89 ^v	4.37 ^{c-h}	D	4.32 ^{d-l}	4.14 ^{m-u}	4.16 ^{k-t}	4.23 ^{f-p}	4.16 ^{k-t}
	Zeal	4.60 ^{ab}	3.97 ^{u-v}	4.01 ^{s-v}	4.24 ^{f-p}	D	4.60 ^{ab}	4.21 ^{h-q}	4.34 ^{c-i}	4.16 ^{k-t}	4.21 ^{h-q}
NVT	Bona	4.50 ^{bc}	4.03 ^{r-v}	4.24 ^{f-o}	4.29 ^{e-m}	D	4.50 ^{bc}	4.33 ^{c-k}	4.11 ^{n-u}	4.11 ^{n-u}	4.32 ^{d-l}
	Star 9037	4.20 ^{c-e}	4.06 ^{p-u}	4.13 ^{m-u}	4.40 ^{c-f}	D	4.20 ^{c-e}	4.19 ^{i-r}	4.09 ^{n-u}	4.18 ^{i-s}	4.22 ^{g-p}
	Star 9009	4.26 ^{e-n}	3.89 ^v	4.13 ^{m-u}	4.37 ^{c-h}	D	4.26 ^{e-n}	3.99 ^{t-v}	4.11 ^{n-u}	4.11 ^{n-u}	4.04 ^{q-v}
	Zeal	4.61 ^{ab}	3.98 ^{u-v}	4.15 ^{l-t}	4.39 ^{c-g}	D	4.61 ^{ab}	4.22 ^{g-q}	4.16 ^{k-t}	4.16 ^{k-t}	4.10 ^{n-u}

LSD ($p \leq 0.05$) = 0.1394; CV = 2.60%

Mean values in the same column with the same superscript letters indicates no significant differences ($P > 0.05$). The letter D represents “decayed”.

With regards to the interaction of microclimate with storage condition, the pH of tomatoes grown under NVT conditions and stored under cold conditions was 19.8% higher than that of the tomatoes from the NVT, but stored under ambient air conditions. Similarly, the pH of tomatoes from the FPVT and stored in cold storage, was 17.8% higher than those from the FPVT and stored under ambient air conditions. With regards to the effect of the microclimate × storage time, the pH value of tomatoes grown in the NVT decreased significantly by 6.9% during the first seven days. During the last seven days of storage, the pH content of the tomatoes decreased by 50.1%. Similarly, the pH of tomatoes from the FPVT decreased significantly by 6.0% during the first seven days and also significantly by 8.7% during the last seven days. Between Days 7 and 21, the pH level of the tomatoes from the NVT and the FPVT did not vary significantly, but increased slightly.

Under cold storage conditions, the pH values of tomatoes from all the cultivars were found to be significantly higher than under ambient air storage. The pH value of cultivar Bona tomatoes was found to be 10.6% higher under cold storage conditions, with a pH of 3.85, than those under ambient air storage, which had a pH value of 3.49. Similarly, Star 9037 tomatoes in cold storage had a pH of 4.28, which was 21.3% higher, when compared to that of tomatoes of the same cultivar, but under ambient storage. The pH value of Star 9009 tomatoes was 19.8% higher when stored in refrigerated conditions, compared to a pH value of 3.33 without refrigeration. For cultivar Zeal, the pH value of the tomatoes was 4.33 in cold storage, 22.6% higher than those stored under ambient air conditions. With regards to the effect of the interaction of cultivar with storage time, the pH values decreased significantly by 6.5 to 9.0% for all cultivars, except Star 9009 between Days 0 and 7. The pH values of all the cultivars also decreased substantially by 49 to 74% during the last seven days of storage (Figure 4.13). The effect of the interaction of storage condition with storage period was found to decrease the pH of the tomatoes stored under ambient air conditions by 7.6% over the first seven days of storage. The pH values of the tomatoes increased significantly by 5.5% between Days 14 and 21, under conditions of ambient air storage, but the tomatoes had decayed by Day 28. Conversely, under cold storage conditions, the pH value of the tomatoes fell significantly by 5.3% over the first seven days and by a further 11.7% between Days 21 and 28.

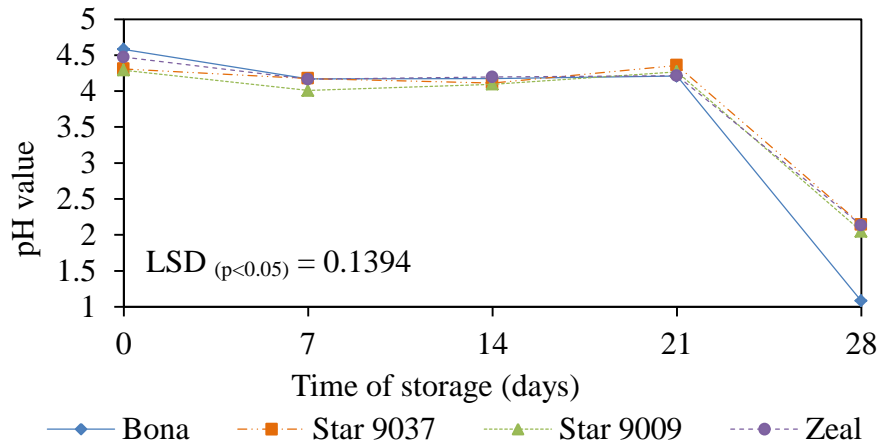


Figure 4.13 The change in pH of tomatoes during 28 days of storage

The three-way interaction effects of the treatments on the pH of the tomatoes were also observed. The microclimate \times cultivar \times storage condition interaction significantly ($P < 0.001$) influenced the pH of the tomatoes, as did microclimate \times cultivar \times storage time ($P < 0.001$). Among the tomatoes grown in the NVT, the pH values of the tomatoes for all the cultivars were higher (18.9 to 20.5%) under cold storage conditions, when compared to those under ambient air storage. Similarly, for FPVT-grown tomatoes, the pH values of cultivars Star 9037, Star 9009 and Zeal were 20.8 to 24.5% higher under cold storage than ambient air storage conditions. With regards to the interaction of microclimate \times cultivar \times storage time, the pH values for cultivars Bona, Star 9009 and Zeal raised under the NVT microclimate, decreased by 7.1-10.6% during the first seven days of storage. During the last seven days of storage, the pH decreased substantially by 48.5 to 52.3% for all the cultivars grown in the NVT. Similarly, for the tomatoes grown in the FPVT, the pH values of the cultivars Bona, Star 9037 and Star 9009 tomatoes in cold storage, fell by 10.8%, 4.3% and 5.6%, respectively, during the first seven days of storage.

The pH values of the tomatoes were further influenced by the three-way interactions of: (a) microclimate \times storage condition \times storage time ($P < 0.001$), and (b) cultivar \times storage condition \times storage time ($P < 0.001$). The pH values of sample tomatoes grown in the NVT decreased significantly by 4.1%, when stored in the climate chamber, as opposed to an 8.9% decrease under ambient air storage. The pH values of the tomatoes then increased by 4.1% under ambient storage, between Days 14 and 21. Conversely, the pH values of the tomatoes grown in the FPVT and stored under ambient air conditions, decreased significantly by 6.9% between Days 14 and 21. By Day 28, the tomatoes stored under ambient air conditions had

decayed to such an extent that the pH could not be determined. Under cold storage, the pH values of the tomatoes from the FPVT decreased significantly by 25.1% between Days 21 and 28. In addition, the change in the pH over the storage period did not vary significantly for tomatoes of the same cultivar grown in the FPVT and the NVT. For example, Bona tomatoes from the NVT were not significantly different to those grown in the NVT with regards to their pH values.

4.4 Discussion

4.4.1 Firmness

Tomato fruit texture is a physical characteristic that describes the deformation of the tomato under the application of a force (Sams, 1999). It is an important parameter used by both producers and consumers to determine the ripeness and storability of fruit and vegetables. It is also important to producers, since it determines the handling and shipping ability of tomatoes (Kader, 1984; Kader, 2008). The firmness of tomatoes grown under the FPVT microclimate was 7.4% lower than that of the tomatoes grown in the NVT (Table 4.2). A lower firmness indicates a weaker skin, which is often associated with ripe, soft and mealy fruit (Sirisomboon *et al.*, 2012) and is indicative of some deterioration in the quality of tomatoes. The skin and tissue of the tomatoes grown in the FPVT were more pliable than those which had been exposed to higher temperatures and low RH in the NVT. This can be attributed to the mechanical properties, in particular, the elasticity of the cuticular membranes of the tomato fruits. According to Matas *et al.* (2005), tomato skin exhibits a more plastic behaviour at low RH, which was attributed to the combined effect of temperature and RH on the cutin matrix that forms the skin tissue of tomatoes. These results agree with Kang *et al.* (2002), who found that the firmness of cucumber fruits produced at higher temperature was higher, and Khanal *et al.* (2013), who reported higher firmness in tomato fruit raised at a day-night temperature regime of 27/14°C, compared to 24/17°C and 30/11°C. This behaviour was attributed to the dependence of the enzymatic activity on the proteins and carbohydrates constituting the cell wall of tomatoes on temperature (Meli *et al.*, 2010) and could be the reason for the differences in the texture of tomatoes grown in the NVT and the FPVT. Further, in the FPVT, the tomatoes were grown under a relatively higher air moisture content, when compared to those grown in the NVT. At high RH levels, water is diverted from the vegetative organs of the

plant and more water is supplied to the fruit, increasing the internal turgor pressure and stretching the fruit skin. When the RH is low, the water supply is diverted back to the vegetative organs, the internal turgor pressure is reduced and the cells contract (Dorais *et al.*, 2004). This repeated stretching and contraction of the tomato fruit skin and tissue could be responsible for the easily deformed skin and tissue of the tomatoes under the application of a constant force.

Significant ($P < 0.05$) differences were observed in the firmness of Bona and Star 9009. The genotypic characteristics of different tomato genotypes are the primary definitive factor of fruit texture and environmental factors can only modify the predetermined response of the fruit to the application of a force (Sams, 1999). This would explain why the firmness of Bona tomatoes was 78.5% that of Star 9009. The firmness of Star 9009, Star 9037 and Zeal tomatoes were higher, and did not differ significantly ($P > 0.05$), suggesting that they are some of the firmer genotypes of the fresh market tomatoes available to farmers in South Africa. The NVT microclimate could have influenced the texture of Star 9009 tomatoes, which, together with Star 9037, had a firmer texture than Bona and Zeal under the NVT environment (Figure 4.3). Bona might not have been affected by the environmental conditions, since under both NVT and FPVT microclimates, its fruits were still the softest. Genotypic differences have also been attributed to differences in the shelf-life of tomatoes. Frascina *et al.* (1998) stated that the loss of texture in hybrids with a shorter shelf-life was due to higher enzyme activity and the degradation of cell wall and middle lamella polysaccharides, compared to the long shelf-life hybrids. This could explain the differences in the firmness of the cultivars with time, particularly Bona, the texture of which deteriorated faster, especially after Day 14, when compared to the other cultivars (Figure 4.2).

Under conditions of higher maximum temperatures and low RH in the NVT (Table 4.1), the firmness of Star 9009 was 22% higher than those of Bona and Zeal. According to Carli *et al.* (2011), a clear understanding of the interaction between cultivar and environment is impeded by the complex nature of the underlying factors that determine physical traits such as texture. They further reported that the textural characteristics of tomatoes seemed to be more affected by genotypic differences than climatic conditions. As a result, variations in the response of tomato firmness to the interaction of the genotype with climate could be due to different

adaptations of each cultivar to a particular environment. This could also explain the rapid reduction in texture for the cultivar Bona, shown in Figure 4.3.

Postharvest storage conditions are important for the maintenance of acceptable texture for tomatoes grown under both NVT and FPVT microclimates. In cold storage, where the storage temperature and RH were maintained at 13°C and 85%, respectively, the tomatoes were 13.6% firmer than those stored under ambient air conditions (23 ±2°C and 52 ±4% RH). In addition, cultivar Bona tomatoes had a firmer texture under cold storage than under ambient air conditions. The metabolic processes of tomatoes, such as transpiration and respiration, continue, even after detachment from the parent plant and in postharvest storage. In particular, respiratory climacteric is responsible for the majority of the changes that occur during the ripening process (Wills *et al.*, 2007). Transpiration leads to moisture loss through the skin of the tomato fruit and a decrease in the turgor pressure of the cells (Požrl *et al.*, 2010). Shackel *et al.* (1991) showed that a reduction in the cell turgor pressure of the pericarp cells preceded the ripening of tomato tissues. According to Požrl *et al.* (2010), the softening of the pericarp has been found to be an important contributing factor to the loss of texture. The optimum storage temperature for tomatoes harvested at the mature-green stage is between 10-15°C and the RH is between 85 and 95% (Moneruzzaman *et al.*, 2009). Under these conditions, plant metabolic processes, such as respiration and transpiration, are reduced (de Castro *et al.*, 2005) and the integrity of the tomato pericarp, tissues and cell walls are maintained. In addition, the transpiration process is driven by the vapour pressure gradient between the surface of the fruit and its immediate environment. A low relative humidity in the surrounding air creates mass transfer induced transpiration from the surface of the tomatoes (Tano *et al.*, 2005). In cold storage, the RH of the storage chamber was maintained at 85%, whereas under ambient air storage conditions, the RH fluctuated around 52%. The higher vapour pressure difference under ambient air conditions could have resulted in higher transpiration rates. The genotype with a lower firmness (Bona) had its texture maintained by the reduced transpiration rates in cold storage.

In areas where cooling equipment is not available to farmers, the selection of cultivars that have a firmer texture and that maintain the firmness for an extended period after harvesting, could reduce economic losses associated with loss of firmness. Cultivars Star 9037, Star 9009 and Zeal preserved their firmer texture for a longer period, although under cold storage, the

firmness was higher for up to 21 days of storage. Conversely, Bona lost the tissue firmness and became soft relatively quicker under ambient conditions. In cold storage, Star 9009 had the firmest skin and tissue and these were preserved for 21 days before decay set in. This has been attributed to the ripening process and loss of moisture from the surface of the tomatoes due to transpiration, which is higher under ambient air storage temperatures (Žnidarčič *et al.*, 2010). However, in cold storage, transpiration rates are reduced, cell turgor pressure is maintained and genotypes with lower resistances to the application of a mechanical force, such as Bona and Zeal, remain firmer for a longer period (Figure 4.5). For situations where cold storage is not available, Bona cultivar would soften and lose economic quality too quickly, whereas Star 9009, Star 9037 and Zeal would perform under both cold and ambient air conditions.

4.4.2 Change of colour

In addition to textural and firmness, colour is the most obvious post-harvest quality attribute used by consumers to gauge the ripeness and readiness for consumption of the tomato fruits (Gorini and Testoni, 1990; Genanew, 2013). Tomatoes grown in the NVT had lower L^* and h° than those grown under the FPVT microclimate (Table 4.3). The h° and L^* values have been found to be good colour indicators of when the ripening process has been initiated and its progress during postharvest storage (Camelo and Gomez, 2004). A decrease in these two parameters shows the progression of colour from green to red and the lowest values are reached when the tomatoes have attained a deep red colour (Saltveit, 2005). During the ripening process, chlorophyll, which is responsible for the green colour of tomatoes, starts to decrease, accompanied by a simultaneous increase in lycopene (Camelo and Gómez, 2004). Lycopene is responsible for the red pigment of tomatoes and its synthesis is favoured by growth temperatures between 18 and 32°C (Dumas *et al.*, 2003). Production of lycopene is repressed completely when tomatoes are exposed to temperatures exceeding 32°C for an extended period (Bradlt *et al.*, 2006). Tomatoes grown in the NVT were exposed to maximum temperatures above 32°C in December and January, although the mean and minimum temperatures were below 32°C. This discrepancy could be attributed to the effect of the lower mean and minimum temperatures that were observed in the NVT. As stated by Gruda (2005), the effect of high temperatures on lycopene synthesis can be compensated for by lower air temperatures, such as those occurring at night. Similarly, the lower temperatures were within

the optimum ranges, which did not affect the change in colour of the tomatoes, from mature-green to red-ripe.

Among the four cultivars, Bona had the lowest h° and L^* , indicative of more tomato redness in this cultivar than the other cultivars. In addition, the colour change of Bona tomatoes, from mature-green to red-ripe was faster, when compared to the other cultivars (Figures 4.6 and 4.7). Tomato colour pigmentation is controlled by many genes (Stommel and Haynes, 1994) and genotypes with high concentrations of the pigment genes have a richer colour than those with less (Jarret *et al.*, 1984; Sacks and Francis, 2001). This could explain the differences in colour among the tomato cultivars used in this study. The results agree with Sacks and Francis (2001), Brandt *et al.* (2006) and Radzevičius *et al.* (2009), who reported appreciable colour variations between cultivars. The faster change in colour observed in the cultivar Bona, coupled with a faster loss of firmness, suggests that Bona had a shorter shelf-life, compared to the other cultivars.

Under both NVT and FPVT microclimatic conditions, cultivar Bona tomatoes were redder and their progression from the mature-green stage colour to the red-ripe colour was more rapid than for the other cultivars (Figures 4.6 and 4.7). Conversely, cultivars Star 9037, Star 9009 and Zeal were found to be redder when produced under the NVT microclimate than under the FPVT conditions. Environmental conditions can modify the response (Sams, 1999) and obscure genetic differences (Sacks and Francis, 2001) between different tomato genotypes. The lower L^* and h° of cultivar Bona, under both microclimate conditions, suggests that its colour development was not subject to environmental conditions.

Under the higher air temperatures of around 23°C under ambient storage conditions, the tomatoes were redder and progressed faster from the mature-green stage to the red-ripe stage, than under cold storage conditions. The ripening of tomatoes is an ongoing process, which, once initiated, cannot be reversed (Bapat *et al.*, 2010). However, cold storage conditions can slow down the ripening process and colour change in tomatoes, by inhibiting the degradation of chlorophyll and the simultaneous synthesis of the red pigment colour lycopene (Vihna *et al.*, 2013), as well as the production of ethylene gas. In addition, cold storage temperatures lower the response of tomato fruit tissues to ethylene, the plant hormone which stimulates, controls and regulates the ripening process of climacteric products, such as tomatoes

(Martínez-Romero *et al.*, 2007). Conversely, the synthesis of lycopene is favoured by temperatures between 16 and 25°C (Camelo *et al.*, 2003). This could explain why the tomatoes stored at 13°C developed the red ripe tomato colour relatively slower than those under ambient air storage

Further, cold storage delayed the changes in colour of the NVT-grown tomatoes (Figures 4.8 and 4.9), improving their storability and overall quality. In addition, the interaction of microclimate with cultivar and storage conditions improved the storability of cultivars Bona and Zeal grown under FPVT conditions (Table 4.2). Without cold storage, the tomatoes from these cultivars were redder and the progression of colour change from mature-green to red improved under cold storage. Fruit ripening is a genetic trait, which controls physiological and biochemical processes that occur within the plant tissues (Klee and Giovannoni, 2011), culminating in the visual presentation of the colour attributes. However, these attributes are modified by external factors, including growth environment (Carli *et al.*, 2011) and most probably postharvest storage conditions. The exact nature of these interaction effects on the inherent genetic traits driving the physio- and bio-chemical processes is complex and not well understood (Grattan and Grieve, 1998; Suarez *et al.*, 2011). Still, the interaction of growth environment, cultivar and storage condition showed that cold storage conditions were required to extend the shelf-life, in terms of colour, for cultivar Bona, regardless of the environment under which the tomatoes were grown. For cultivar Zeal tomatoes produced in the NVT, cold storage was required to delay the metabolic activities that enhance colour change during ripening. For cultivars Star 9037 and Star 9009, whether produced under NVT or FPVT conditions, cold storage conditions were not necessary for delaying the reddening process. However, for Star 9037 and Star 9009, pre-harvest cooling in the FPVT was more beneficial in slowing the progression from mature-green to red in postharvest storage. Postharvest storage slowed the colour changes only slightly.

4.4.3 Total soluble solids

The tomatoes grown in the NVT were found to have a total soluble solids (TSS) content that was 10.3% higher than that of the ones grown in the FPVT (Table 4.4), which is in agreement with Gautier *et al.* (2008), who reported a higher TSS content in cherry tomatoes, corresponding to higher growth temperatures. Higher temperatures between 26 and 30°C

(Walker and Ho, 1977) and increased transpiration rates (Gautier *et al.*, 2008) have been shown to increase the biosynthetic enzymatic activity of carbohydrates, which could have resulted in the higher TSS values of tomatoes. In addition, the sink strength and the distribution of carbohydrates to the fruits have been found to be favoured by high growth temperatures (Beckles, 2012; Khanal *et al.*, 2013).

In addition to environmental conditions, genetic factors are responsible for variations in the TSS of tomatoes (Mattheis and Fellman, 1999). The 8.3% TSS difference between Bona and Star 9037 could be attributed to cultivar differences (Table 4.4). Flavour attributes, such as sweetness, may be affected when the tomatoes are harvested too early, or if a particular genotype has a limited capacity to develop desirable flavour (Beckles, 2012). Since all the tomatoes were harvested at the mature-green stage and confirmed by the objective determination of colour, using a colorimeter, it can be concluded that Star 9037 may have a limited capacity to develop flavour. This suggests that cultivar Bona, which had the highest TSS content with 5.1°Brix, would be tastier than the other three cultivars, particularly Star 9037, with 4.6°Brix. For all the cultivars, the TSS content was between 4.6 and 5.1°Brix, all were above the 3°Brix suggested by Kader (1984) as the minimum for good quality tomatoes. In addition, the TSS contents for Bona and Zeal tomatoes increased significantly by 27.2% and 18.3% during the first was faster days of storage. On the other hand, Star 9037 and Star 9009 did not exhibit significant changes in TSS content after harvest. This could most probably be due to different rates at which the metabolism of complex sugars into simple sugars occurs, during the ripening stages of tomatoes (Luengwilai *et al.*, 2010). According to Saltveit (2003), once the climacteric peak is reached, the respiration rate decreases, presumably due to the exhaustion of the substrate material, including starch and other polysaccharides, which could explain the 55% drop of the TSS observed during the last seven days of storage (Figure 4.11). For cultivar Bona, the substantial increase of the TSS content was accompanied by a rapid change in colour and loss of texture, as discussed in the preceding sections. Star 9037 and Star 9009, on the other hand, although they had low TSS values that did not change much during the study period, maintained higher firmness and exhibited slower colour changes. Thus, Star 9037 and Star 9009 had a better keeping quality than Bona and Zeal.

Under cold storage, the TSS of the tomatoes was 17.7% lower than under ambient storage (Table 4.4), in agreement with Gharezi *et al.* (2012), who reported higher TSS values in tomatoes stored at 25°C than those stored at 10°C. It has been found that the increase of the TSS content during postharvest storage is due to the breakdown of complex sugars, such as starch, cellulose and other polysaccharides, into simple sugars (Beckles, 2012). The normal degradation of the complex sugars into simple sugars is inhibited under cold storage conditions (Beckles, 2012), due to repressed transpiration and respiration rates.

The TSS content of NVT-grown tomatoes that were stored under cold storage conditions was 22.3% higher than that of the NVT-grown tomatoes stored under ambient air conditions (Figure 4.12). According to Hewett (2006), postharvest interventions can only maintain the product's quality that developed during the growth stages. NVT tomatoes were grown under higher temperatures and low relative humidity conditions. The lower TSS values in tomatoes stored under cold storage conditions could have been due to repressed biochemical activities from the lower temperatures. Tomatoes grown in the FPVT were not significantly ($P>0.05$) influenced by the storage temperatures and maintained lower TSS values. The reason for this trend is not well understood, due to limited literature available on the causal effects.

The multi-factorial interaction of the factors affecting postharvest quality in tomatoes, are not well-explained in literature. Linke and Klaring (2004) attributed this to the complex and expensive nature of multi-factorial experiments. As a result, the main reasons for the differences observed in this study remain unclear. However, several interaction effects on the firmness, colour change and the TSS content of the tomatoes were observed, including the microclimate \times cultivar \times storage condition interaction (Figure 4.10). As observed by Beckles *et al.* (2012), crops that have been bred to withstand postharvest handling and to have long shelf-lives, often have poor flavour qualities. Kader (2008) recommended the selection of genotypes that have both good keeping qualities (firmer texture), as well as acceptable flavour.

4.4.4 pH values

As with the other quality factors of tomatoes, the acidity of tomatoes is determined by genotype and great variations exist among different genotypes (Mahakun, 1979; Stevens and

Rick, 1986; Caliman *et al.*, 2010). This could explain the 4.6% difference between Bona and Star 9037 and 5% between Bona and Zeal. The pH values for these four cultivars were 3.64 to 3.84, which were below the 4.35 to 4.56 range, which was reported by Caliman *et al.* (2010) in different cultivars of processing tomatoes. Under FPVT conditions, Bona tomatoes were more acidic than the other three cultivars, as well as more acidic than Bona tomatoes grown in the NVT (Table 4.4). According to Caliman *et al.* (2010), the effect of environmental conditions on the acidity of tomato fruits is intricate. Sakiyama and Stevens (1976) suggested that organic acids responsible for the acidity of tomatoes are synthesized from stored carbohydrates in the fruits, whereas Bertin *et al.* (2000) suggested that some of the organic acids are translocated from the roots and leaves. Thus, the higher acidity of cultivar Bona tomatoes could have been due to the response of the particular cultivar to the environmental conditions in the tunnels. During storage, the pH values of tomatoes decreased by 6.4% during the first week of storage, becoming more acidic. The acidity then reduced by Day 21, as the pH increased slightly by 3.1% (Figure 4.9). The results are in agreement with Davies and Hobson (1981), Žnidarčič and Požrl (2006) and Caliman *et al.* (2010), who reported that, during the ripening of tomatoes, acidity increases until it peaks at the breaker stage, and then it decreases as the fruits reach the mature red stage. Acidity is measured by the concentration of the organic acids, namely, citric, malic and tartaric, among others (Kader, 2008) and tends to reduce after the peak of the ripening is reached. This is because organic acids are substrates for the respiration process (Wills *et al.* 1981; Žnidarčič and Požrl, 2006) and the substantial reduction in the pH values after Day 21 (Figure 4.13) could be due to the exhaustion of the organic acid. Under cold storage (13°C and 85% RH), the tomatoes were 18.8% more acidic than those under ambient air conditions (Table 4.4). This could be due to the consumption of the organic acids under higher respiration rates associated with storage at higher temperatures (Saltveit, 2003). The same effect may be used to explain the differences observed for tomatoes grown in the NVT and the FPVT, where the tomatoes stored at 13°C were more acidic (19.8% and 17.8%) than those stored at room temperature (23 ± 2°C). Under ambient air conditions, temperature was higher, leading to higher respiration rates. As organic acids, the main determinants of tomato pH, are broken-down during respiration, this would increase the pH values of the tomatoes kept under ambient air conditions. The same developments were observed in all interactions that involved storage period, including cultivar × storage conditions.

Bona tomatoes were found to be slightly more acidic when grown in the FPVT than in the NVT (Table 4.4). The effect of microclimate on the organic acids of tomato fruit is complex (Caliman *et al.*, 2010). Sakiyama and Stevens (1976) suggested that organic acids are synthesized in the fruit, while Bertin *et al.* (2000) suggested that some may be translocated from the leaves and roots.

As with the TSS content, the pH was significantly influenced by all the three-way interactions. In general, the pH of the tomatoes was higher for cultivar Bona when stored under cold storage conditions, at 13°C and during the first seven days of storage. The interaction of sugars and acidity determines the taste and flavour of tomatoes (de Bruyn *et al.*, 1971; Kader, 2008). According to Kader (1984), the best tomato flavour is achieved by an interaction of high sugar content and relatively high acidity level. Cultivar Bona had the highest acidity and the highest TSS content and would thus, have a superior flavour in comparison to the other three cultivars.

4.5 Conclusion

This study was undertaken to determine the combined effects of greenhouse microclimate, postharvest storage environment, as well as cultivar and storage period on the postharvest quality of four fresh market tomatoes available on the South African markets. The tomatoes grown under the better conditions in the more costly FPVT were less firm and lost firmness more rapidly than those raised in the NVT. However, the colour change was more rapid for tomatoes grown in the NVT. In addition, cultivar Bona had the lowest firmness and lost firmness more rapidly under both NVT and FPVT microclimates. Cold storage conditions at 13°C and 85% RH helped FPVT-grown tomatoes, as well as cultivars Bona and Zeal tomatoes, to maintain a firmer texture for an extended period than when the tomatoes were stored under ambient conditions. The cultivars Star 9009 and Star 9037 had the firmest texture, especially when grown under the NVT microclimate, but did not benefit from cold storage conditions. In addition, these two cultivars had the slowest colour change from mature-green to red-ripe and the colour change was not halted by cold storage conditions, as with Bona and Zeal. Cold storage conditions were beneficial in reducing the ripening, in terms of colour change, of the NVT-grown tomatoes, as well as of cultivar Bona tomatoes. NVT-grown tomatoes stored under ambient air conditions for all the cultivars had the highest

TSS content. In addition, cultivar Bona grown in the NVT had the highest TSS content, whereas the TSS contents for Star 9037, Star 9009 and Zeal grown in the FPVT were low. The microclimate was not influential on the pH value of the tomatoes, but cultivars Bona and Star 9009 were the most acidic. In addition, at a storage temperature of 13°C and RH of 85%, the NVT-grown tomatoes were more acidic than those stored at $\pm 23^{\circ}\text{C}$ and 52% RH.

This research has shown that naturally-ventilated and fan-pad evaporatively-cooled greenhouse microclimates have a significant effect on the postharvest quality and storability of tomatoes. The study has also provided an understanding of how integrated agro-technologies affect postharvest quality of fresh produce. The less costly, naturally-ventilated greenhouse produced tomatoes that were firmer, with a higher TSS content than the more expensive fan-pad evaporatively cooled tunnel. Under the FPVT microclimate, ripening (in terms of colour change) was slower. Cold storage helped the FPVT-grown tomatoes to maintain a firmer texture and the NVT-grown tomatoes to ripen relatively slower than under ambient conditions. The study has also shown that there is a need for further research on integrated agro-technologies to address the information gap of the multi-factorial interactions of greenhouse microclimate, cultivar and storage conditions, to provide the scientific background on the exact nature of the influence.

4.6 References

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5. WINTER GREENHOUSE MICROCLIMATE AND ITS EFFECT ON BUTTERHEAD LETTUCE

Abstract

Greenhouse microclimate depends on the type of cover, ventilation type and prevailing microclimate. The winter microclimate in greenhouses and its effect on plant growth, yield and quality in the Pietermaritzburg area of KwaZulu-Natal is not documented. A study was undertaken to investigate the temperature and relative humidity in a fan-pad evaporatively cooled (FPVT) and an open-ended naturally ventilated (NVT) polyethylene-covered tunnel greenhouses during winter, using Hoboware sensors and data loggers. Two butterhead lettuce cultivars, Ballerina and Nadine, were used to determine the effect of the microclimates on crop growth, yield and quality. The results indicated that daytime temperatures were 4-10°C higher in the tunnels than outside. The air temperature in the NVT was 4-6°C higher than in the FPVT. Relative humidity was extremely low in the NVT, but was within the crop optima for most crops, including lettuce, in the FPVT. The high temperatures in the NVT did not negatively influence the growth of the lettuce. Ballerina growth was faster than that of Nadine under both microclimates. The yield of Ballerina was enhanced by the optimum environmental conditions provided by the FPVT, but the cultivar was more susceptible to leaf tip-burn. Leaf tip-burn was more prevalent under the FPVT conditions, compared to the NVT conditions. These findings indicate that there is a need for extensive research, to establish the most cost-effective greenhouse design that will provide the optimum microclimate for the Pietermaritzburg conditions. With the right choice of cultivar, the NVT can be used during winter for lettuce production.

5.1 Introduction

Winter-time in cool subtropical areas such as Pietermaritzburg is characterised by cold nights and warm days. The absolute daily minimum temperatures can be as low as -8°C and the absolute maximum as high as 25.6°C (Schulze and Maharaj 2007). The solar radiation flux at noon can exceed $600 \text{ W}\cdot\text{m}^{-2}$ on cloudless winter days (Mills *et al.*, 1990). These weather variables are some of the factors that influence the microclimate of greenhouse facilities in Pietermaritzburg during the winter months. The type of ventilation system used to control microclimate is another factor which can influence the internal microclimate.

Although the total number and the distribution of greenhouse structures in South Africa has not been quantified, the most common types are the naturally-ventilated and the fan-pad evaporatively cooled tunnel greenhouses (Maboko *et al.*, 2010). These structures are used to protect crops against rain and hail (Mills *et al.*, 1990), as well as to increase the humidity. The winter microclimate in these structures under the various South African climates is very limited. Mills *et al.* (1990) conducted experiments in a side-ventilated polyethylene-covered naturally-ventilated tunnel and reported air temperatures exceeding 35°C on a clear winter day, whereas night-time temperatures were as low as 5°C . Temperatures below 12°C and above 30°C negatively affect the production of greenhouse crops, such as tomatoes and green peppers. In other sub-tropical areas, such as under Mediterranean climates, the year-round utilisation of greenhouse facilities is often limited by low temperatures in winter (Jensen, 2002; Castilla and Hernandez, 2007). Without additional heating, production is severely limited by the greenhouse microclimate. However, greenhouse heating can constitute up to 40% of the total production costs (Tadj *et al.*, 2010). In addition to rising energy costs, there is a need to reduce the carbon footprint of the greenhouse industry, which renders the greenhouse a non-viable option (Bartzanas *et al.*, 2005).

Meyer (2011) identified the implementation of effective cropping systems as one of the methods that can be used to reduce the energy input of greenhouse facilities. Cultivating winter crops, the yield of which would not be adversely affected by cool winter temperatures, could extend the growing season. Of the two greenhouse ventilation systems common in South Africa, fan-pad evaporatively-cooled tunnels are costly to install, operate and maintain. However, they offer better control of the temperature, especially during the hot summer

months, as shown in Chapter 3. Naturally-ventilated structures are simple to install and maintain, with minimal operating costs. Kassier (1979) stated that sophisticated heating and cooling systems were not a profitable investment in greenhouses in Southern Africa. While this statement may be out-dated, the basic assumption may still hold true. Because of limited research in greenhouse technology, the most cost-effective ventilation design for optimum microclimate control for the South African climatic conditions has not been established. The limited research on these structures further suggests that there is an information gap, which could be used to advise the decision-making process regarding their use. Thus, a research project was undertaken to study the microclimate of two types of greenhouse. The specific objectives were to:

- Analyse and compare the microclimate of an open-ended naturally-ventilated tunnel and a fan-pad evaporatively cooled tunnel in winter,
- To establish the effect of the microclimate on crop growth, yield and quality of a winter crop, using lettuce during the winter period.

5.1 Materials and Methods

The experiments were conducted in two identical greenhouse tunnels with floor areas of 144 m^2 and ridge heights of 3.5 m. Both greenhouses were 18 m in length with a floor width of 8 m. They had an east-west orientation and were 4.4 m apart. The tunnels were made of galvanized steel frames covered with a $200 \mu\text{m}$ ultra-violet treated low density polyethylene film. The naturally-ventilated tunnel was open-ended and the open ends were covered with black and white Knittex[®] 40 insect screen netting. The other tunnel was fan-pad evaporatively-cooled with a $0.1 \text{ m} \times 5.3 \text{ m} \times 1.15 \text{ m}$ Celdek[®] wet-wall on the east side at 0.95 m from the ground. On the west side, the tunnel had a 1.13 m, 1100 W single speed fan, placed 0.95 m from the floor as shown in Figure 5.1.

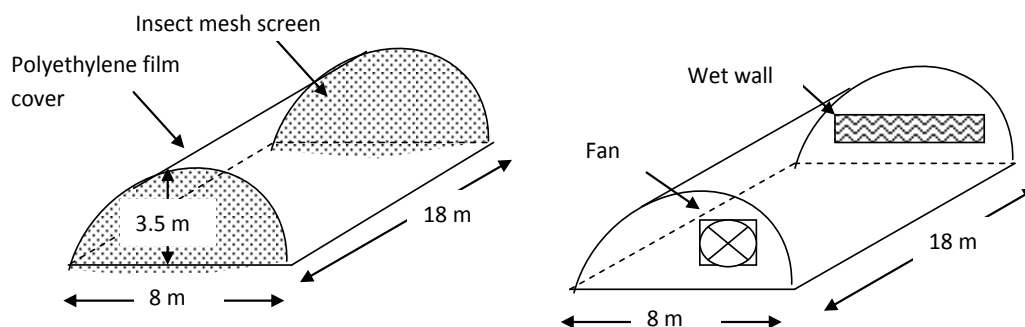


Figure 5.1 Schematic diagrams of the greenhouse tunnels

5.1.1 Experimental design

The experiment consisted of two greenhouse ventilation system treatments, one being a fan-pad evaporative cooling and open-ended natural ventilation, without replications. The fan-pad evaporative cooling system was set to switch on when the internal temperature exceeded 23°C and when RH fell below 60%, and off when the minimum temperature reached 15°C, or when the RH exceeded 80%. Internal temperature and RH were measured using six sensors/data loggers placed in a grid pattern along the centre of each greenhouse. On the horizontal plane, two data logger were placed 3 m from each end and along the main axis of the greenhouse and the other two at the centre of the greenhouse, 6 m from the other two sets of data loggers. On the vertical plane, the lower sensors were 1.15 m from the greenhouse floor and the upper level ones were placed 1.15 m from the roof, with one sensor at each position.

5.1.2 Crop production

Two lettuce cultivars seedlings (Ballerina and Nadine) were transplanted into 10 L plastic pots filled with potting soil. The lettuce plants were irrigated, using one arrow dripper per plant connected to spaghetti tubing and supplying 2.1 L.hr⁻¹. The plants were irrigated ten times a day hourly for one minute per irrigation event, with the first irrigation at 7.00 am and supplying 0.1 L.plant⁻¹.day⁻¹. Fertilizers were applied through the bulk tank system using Hygroponic[®] and Solu-cal[®] supplied by Hygrotech PTY. Ltd, South Africa, delivering N (68 mg.kg⁻¹), P (42 mg.kg⁻¹), K (208 mg.kg⁻¹), Mg (30 mg.kg⁻¹), S (64 mg.kg⁻¹), Fe (1254 mg.kg⁻¹), Cu (22 mg.kg⁻¹), Zn (149 mg.kg⁻¹), Mn (299 mg.kg⁻¹), B (373 mg.kg⁻¹), Mo (37 mg.kg⁻¹), N (117 mg.kg⁻¹) and Ca (166 mg.kg⁻¹).

5.1.3 Data collection

Vegetative plant growth data (number of leaves and dry matter) was collected starting from the second week after transplanting. Ten plants per cultivar were randomly selected from each greenhouse and their leaf numbers were counted weekly. Dry matter was determined through destructive sampling of six plants per cultivar per tunnel on a fortnightly basis. The plants, minus the roots, were dried in an oven at 60°C, until a constant weight was reached. At harvest, 10 plants were used to determine the yield in terms of number of leaves, dry matter

and head diameter of the lettuce heads. The quality of the lettuce was also determined in terms of the number of leaves per head affected by leaf tip-burn.

5.1.4 Analysis

Statistical analysis of temperature and RH was done, using Microsoft Excel computer package. Plant growth yield and quality data were analysed, using MSTAT-C statistical and data management package (MSTAT-C, 1993). Comparison between treatment means was performed with the Duncan Multiple Range Test (Duncan, 1955).

5.2 Results

5.2.1 Microclimate

Figures 5.2 shows the mean hourly air temperature and humidity in the open-ended naturally-ventilated tunnel (NVT) and the fan-pad evaporatively-cooled tunnel (FPVT) for the months of May and June. The air temperature and relative humidity show similar trends for both May and June, although the mean temperatures and relative humidity levels were higher in May than in June. The temperatures were high during the day and low at night, whereas the relative humidity was low during the day and high at night.

There were significant ($P \leq 0.01$) differences in daytime air temperature (Figures 5.2A and 5.2E) and relative humidity (Figures 5.2B and 5.2F) between the NVT, the FPVT and the outside air. The hourly mean air temperature was up to 11°C higher in the NVT, when compared to the outside. A comparison between the FPVT air temperature and outside air conditions showed that the FPVT air was up to 6°C higher than outside.

There was a higher air temperature increase inside the NVT than in the FPVT during the daytime, with a maximum of up to 39°C, compared to a 33.5°C maximum in the FPVT (Figure 5.3). The mean air temperature was up to 6°C higher in the NVT than in the FPVT. The highest temperature differences occurred between 9:00 am and 14:00 pm. There was also a significant ($P < 0.01$) difference in hourly temperature as the air temperature increased progressively from night-time levels. The tunnel temperatures peaked between 11:00 am and

13:00 pm, whereas the external temperature peaked between 14:00 pm and 16:00 pm. Thereafter, the temperature decreased progressively and fell below the outside levels in the middle of the afternoon. The tunnels' peak air temperatures coincided with the global solar radiation, whereas the peak external temperature lagged by three hours.

With regards to air humidity, the mean hourly daytime relative humidity decreased significantly ($P < 0.01$), coinciding with the increasing temperature, both inside the tunnels and outside. The air humidity was highest in the FPVT, followed by the outside air and lowest in the NVT. The NVT air humidity was up to 27% lower in the middle of the day, when compared to the FPVT air humidity. The external air relative humidity was up to 20% higher than in the NVT and up to 40% lower than in the FPVT. The minimum air humidity in the NVT was as low as 10.4%, whereas in the FPVT it was 25.5%.

At night, there were significant ($P \leq 0.01$) differences between the internal tunnel air temperatures and the outside air in both May and June. The outside air temperature was significantly ($P \leq 0.01$) higher than the internal air tunnel temperature for both tunnels. There was no significant difference ($P > 0.05$) between internal air temperature inside the NVT and the FPVT, although the NVT temperature was higher than the FPVT temperature. There were significant ($P \leq 0.01$) differences in night-time relative humidity inside the FPVT, NVT and outside. The relative humidity was highest in the FPVT, followed by the NVT and lowest outside. The highest RH in the FPVT was 99% in both May and June, 97% in the NVT in both May and June, and 96% and 74% outside in May and June, respectively.

Significant ($P \leq 0.01$) differences were observed in the hourly night-time temperature. The air temperatures were highest in the evenings and decreased progressively, to reach the lowest levels at dawn. The temperature decrease was more rapid outside than inside the tunnels. There was also a significant ($P \leq 0.01$) difference in internal air temperature, due to the effect of the ventilation over time in both May and June. Inside the tunnels, air temperature decreased significantly with time, with the highest levels during the early evening and the lowest levels at dawn. There was no significant ($P > 0.05$) difference in the change of relative humidity over time, inside and outside the tunnels. Similarly, there was no significant difference ($P \leq 0.05$) on the RH, as a result of the interaction of ventilation type and night-time.

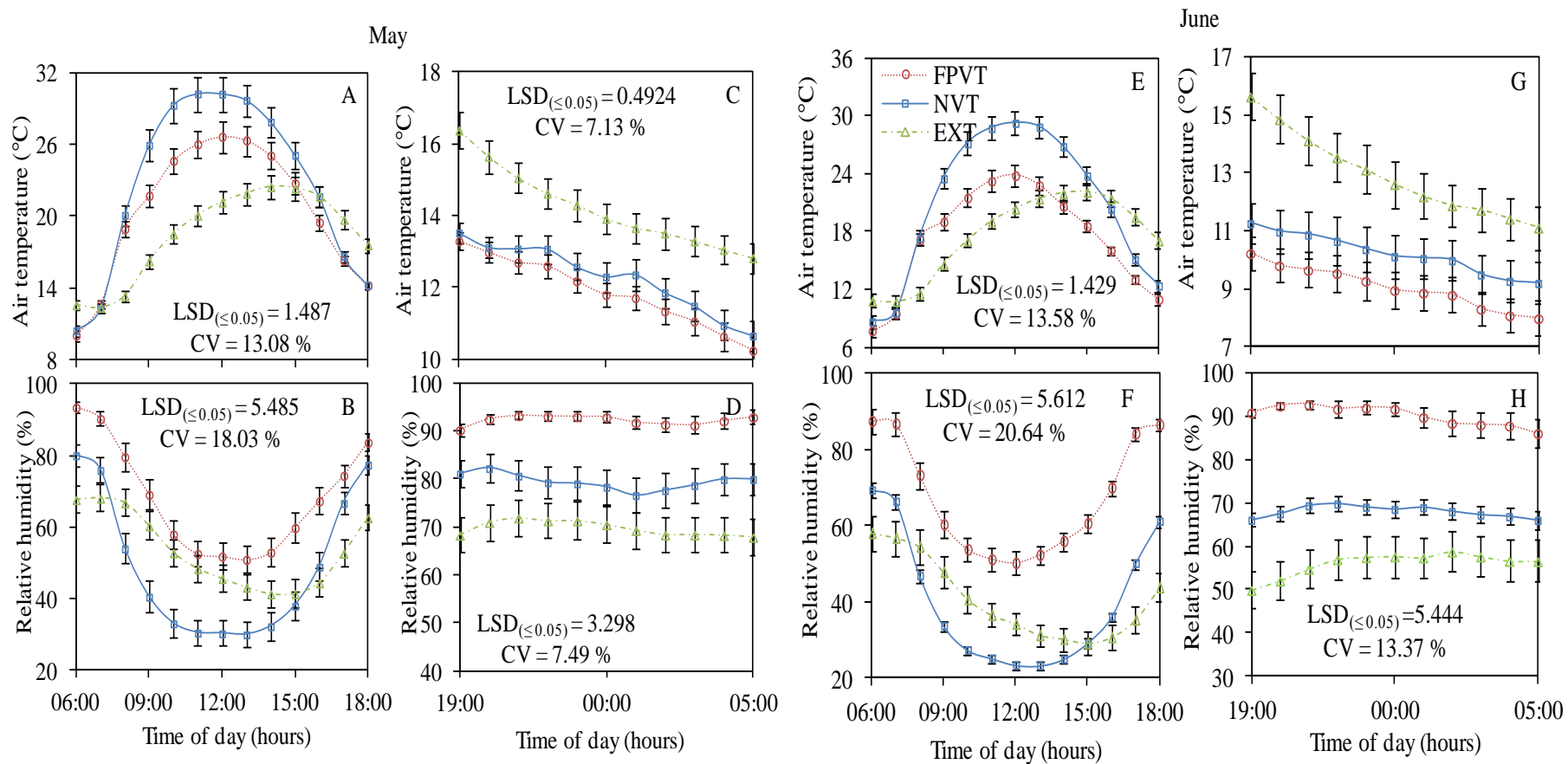


Figure 5.2 Daytime and night-time temperature and relative humidity during May and June. Diagrams A and E represent daytime air temperature; B and F represent daytime relative humidity; C and G represent night-time air temperature; D and H represent night time relative humidity. ● = FPVT= fan-pad evaporative cooled tunnel, ■ =NVT = naturally-ventilated tunnel, △ = EXT= outside.

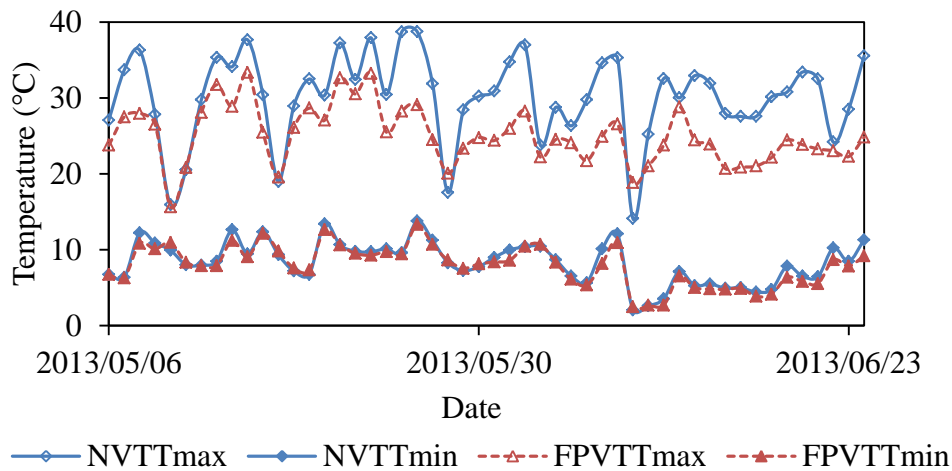


Figure 5.3 Daily maximum and minimum mean temperatures inside the FPVT and the NVT in May and June 2013. Tmax = maximum temperature; Tmin = minimum temperature

5.2.2 Plant growth

Plant growth, yield and the quality of two lettuce cultivars (Ballerina and Nadine) grown in the two tunnels during the winter period of 2013 was analysed, to establish the effect of the microclimate on these parameters. Figure 5.4 shows the growth of lettuce over seven weeks, beginning with the second week after transplanting the seedlings. Cultivar Ballerina had a significantly ($P < 0.01$) higher number of leaves than Nadine, with 12.6% more leaves than Nadine in both tunnels. Starting from the third week, Ballerina accumulated a significantly ($P < 0.01$) higher number of leaves than Nadine every week until the end. The three-way interaction between the ventilation type, cultivar and growth period had a significant ($P < 0.01$) effect on the weekly accumulation of leaves by Ballerina and Nadine. Ballerina accumulated between 8 and 16% more leaves than Nadine throughout, beginning from the third week after transplanting. The tunnels microclimate did not have a significant ($P > 0.05$) effect on the accumulation of leaves by both cultivars in both tunnels. Similarly, the two-way interaction between microclimate and cultivar did not have a significant ($P > 0.05$) effect on the accumulation of leaves by Nadine and Ballerina.

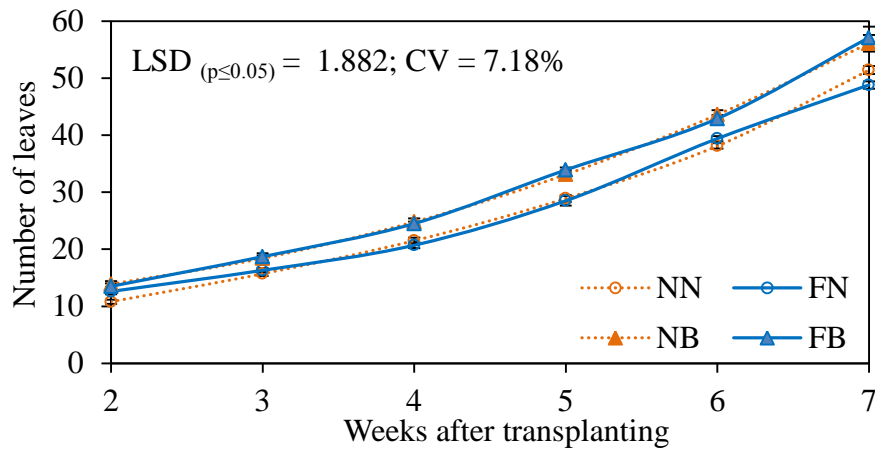


Figure 5.4 Weekly growth of lettuce in the fan-pad evaporative cooled and the open-ended naturally-ventilated tunnels. NN = Nadine grown in the NVT; FN = Nadine grown in the FPVT; NB = Ballerina grown in the NVT; FB = Ballerina grown in the FPVT

There were no significant ($P > 0.05$) effects from the microclimate, cultivar, or due to the microclimate \times cultivar interaction, on the dry matter accumulated by Ballerina and Nadine under both NVT and FPVT microclimates. As shown by Figure 5.5, the growth period was the only influence on dry matter accumulation, while the plants were growing in both tunnels.

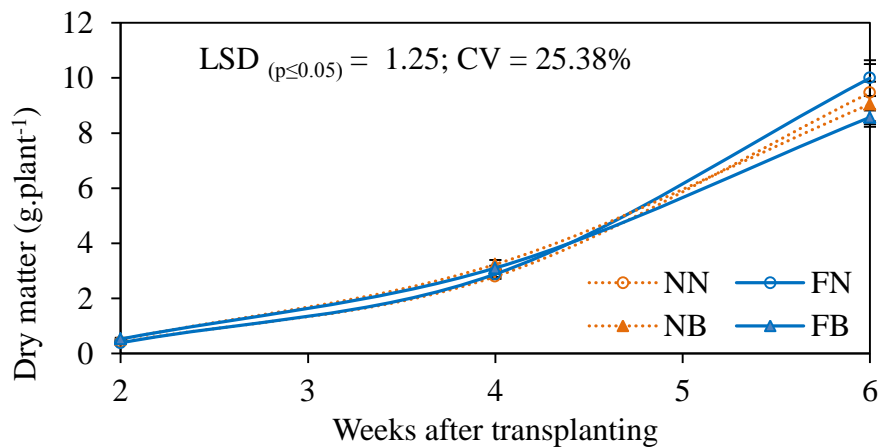


Figure 5.5 Fortnightly accumulation of the lettuce dry matter in the fan-pad evaporative cooled and the open ended tunnels. NN = Nadine grown in the NVT; FN = Nadine grown in the FPVT; NB = Ballerina grown in the NVT; FB = Ballerina grown in the FPVT

5.2.3 Yield and quality

Figure 5.6 shows that there was a significant ($P \leq 0.01$) difference between the number of leaves yielded by Ballerina and Nadine. Ballerina yielded 11.5% more leaves than Nadine. There was no significant ($P > 0.05$) effect due to the interaction between microclimate and cultivar. However, Ballerina grown under the FPVT environment, yielded 14.5% more leaves than Nadine. Under NVT conditions, Ballerina yielded 8.4% more leaves than Nadine.

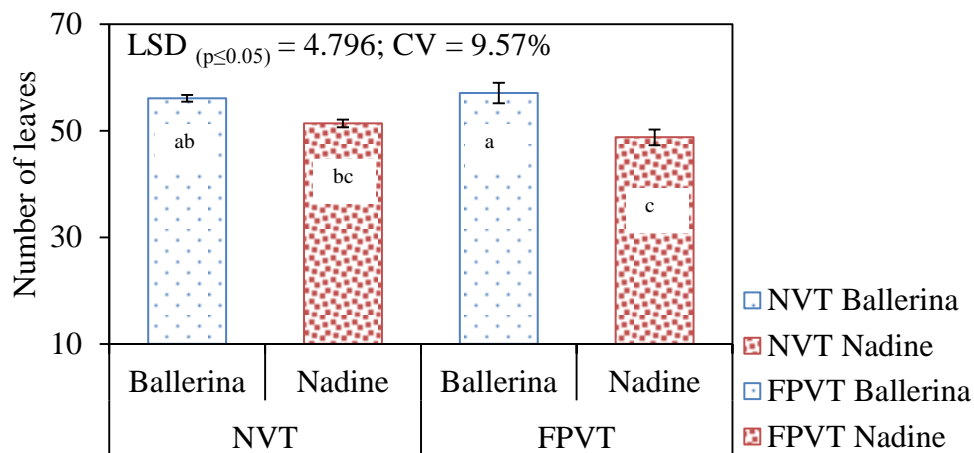


Figure 5.6 Number of leaves harvested from the lettuce grown in the fan-pad and the open-ended tunnels. Similar letters indicate no significant difference at $P = 0.05$.

The interaction between microclimatic conditions and cultivar type had a significant ($P \leq 0.05$) effect on the dry matter yield from Ballerina and Nadine. Figure 5.7 shows that, under FPVT environmental conditions, Ballerina yielded 17.4% more dry matter than Nadine. Conversely, under NVT microclimate conditions, the dry matter yield from the two cultivars did not differ significantly ($P > 0.05$). The microclimate environment and the cultivar effects did not significantly ($P > 0.05$) influence the dry matter yield of Ballerina and Nadine.

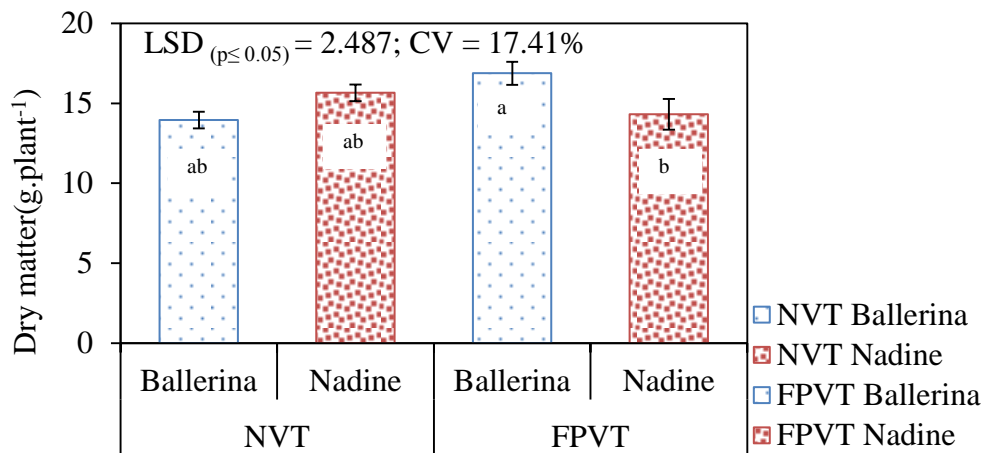


Figure 5.7 Dry matter yield of the lettuce raised in the NVT and FPVT. Similar letters indicate no significant difference at P=0.05.

Figure 5.8 shows that the ventilation type and cultivar type had no significant influence at $P > 0.05$ on the head diameter of the two cultivars. Similarly, the two-way interaction between microclimate condition and cultivar did not significantly influence the head diameter. In addition, there was no clear trend, since under NVT conditions, Nadine head diameter was 4.2% larger than Ballerina head diameter, whereas under FPVT conditions, Ballerina heads were 2% larger than Nadine heads.

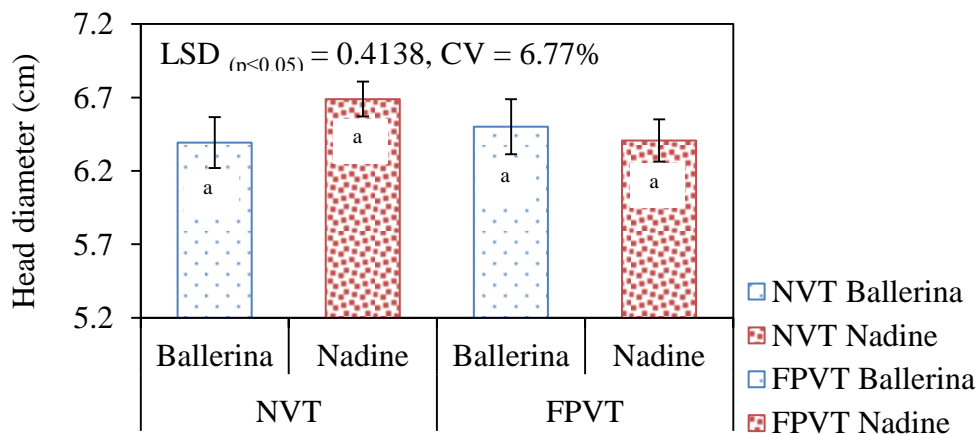


Figure 5.8 Head size of Ballerina and Nadine grown in the FPVT and NVT at harvest

Figure 5.9 shows that the number of leaves affected by leaf tip burn was significantly ($P \leq 0.05$) influenced by the environmental conditions. Under FPVT conditions, 26.9% more leaves were affected by leaf tip-burn than under the NVT environment. Under the NVT environment, Ballerina had 24% more leaves affected by leaf tip-burn than Nadine. Under the

FPVT microclimate, Ballerina had 29.6% more leaf tip-burnt leaves than Nadine. There was a high variability among the lettuce heads affected by leaf tip-burn, as shown by the coefficient of variation.

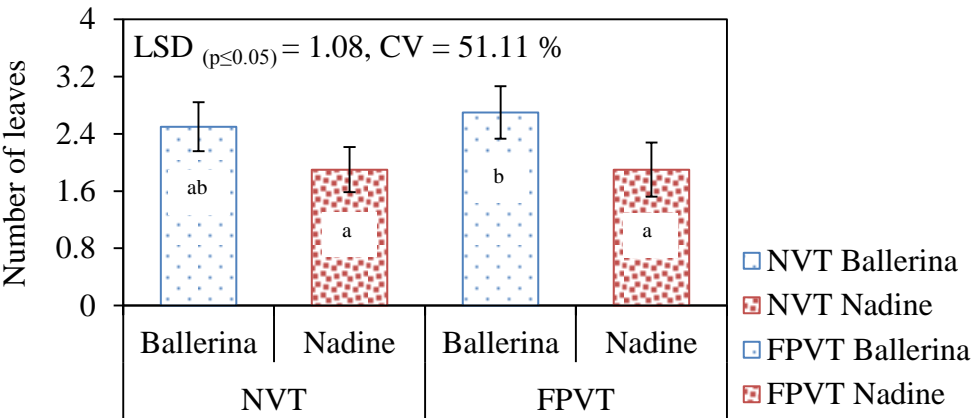


Figure 5.9 Number of leaves affected by tip burn inside the FPVT and the NVT

5.3 Discussion

5.3.1 Microclimate

According to Connellan (2002), if the internal air temperature of a greenhouse is 5-6°C greater than the external air temperature, then its ventilation performance is unsatisfactory. The NVT performance can be termed unsatisfactory, since its air temperature was 11°C higher, when compared to the outside air. Conversely, the FPVT performance can be considered marginal, since the air temperature was 6°C higher than the outside air. The substantial heat gain by the tunnels, when compared to external conditions, can be attributed to the radiation transmission characteristics of the polyethylene cover. According to Kittas and Baille (1999), low density polyethylene transmits 85-89% of the near-infrared wavelengths of the global solar radiation. The near infrared red spectrum of the solar radiation has been found to be responsible for the increase in temperature in greenhouses (Kempkes *et al.*, 2009). In addition, the lack of facilities for controlling the microclimate in the NVT results in the excessive increase in temperature during the daytime hours (Martinez, 1994). The lower temperature observed in the fan-pad evaporatively tunnel can be attributed to the evaporative cooling process. The high heat gain in the FPVT meant that the cooling load required to reduce the internal air temperature through the evaporative cooling during the daytime in the FPVT could lead to high energy use during the winter period. In the NVT, on

the other hand, the high internal temperatures were comparable to those reported by Mills *et al.* (1990) for a polyethylene-covered side-ventilated tunnel during winter in Pietermaritzburg. They observed that in a side-roll door naturally-ventilated tunnel, internal air temperatures reached a high of $> 35^{\circ}\text{C}$ on a clear winter day.

With regards to the daytime relative humidity in the tunnels (Figures 5.2B and 5.2F), the substantial dehumidification in the naturally-ventilated tunnel during the middle of the day had the potential to subject the crops to water stress. When relative humidity is below 60%, crop transpiration increases, to satisfy the atmospheric demand for moisture. The low relative humidity could be attributed to the low external relative humidity and high internal air temperature inside the NVT, as shown in Figures 5.2A, 5.2B, 5.2E and 5.2F. These results are contrary to those reported for greenhouses found in the Mediterranean region. According to Kittas and Bartzanas (2007), high internal greenhouse air humidity is often observed during the winter period. In the FPVT, the higher relative humidity was due to an addition of moisture to the incoming air stream as it passed through the wet pad. This maintained the relative humidity at levels that are optimum for lettuce growth for most of the day.

During the night, the air temperature in the tunnels could have been influenced by the external air temperature, as well as the thermic radiometric properties of low density polyethylene plastic films. Polyethylene transmits 63-65% of the thermal long-wave radiation (Papadakis *et al.*, 2000). High radiative cooling through the polyethylene cover could have been responsible for the low temperatures inside the tunnels (Boulard *et al.*, 2004). The night-time temperature trend compares with that reported from a polyethylene-covered tunnel in Pietermaritzburg during the winter by Mills *et al.* (1990).

The low temperatures in the tunnels suggest that heating may be required, if the cultivation of cold sensitive crops, such as tomatoes and peppers, is desired. However, greenhouse heating leads to up to a 40% increase in total production costs (Tadj *et al.*, 2010), which might result in this option being less attractive. The rising energy costs may make it unattractive, especially to small and resource-poor farmers in developing countries such as South Africa. On the other hand, since the winter period is the off-season for crops such as tomatoes and sweet peppers, the extra costs may be compensated for by the higher prices that farmers are likely to get during this period.

The provision of heating of the open-ended tunnel, on the other hand, would not be possible, since the tunnel is not closed at night. In this tunnel, farmers can extend their growing season by growing winter crops, which can withstand the low night-time temperatures. Crops, such as lettuce, cauliflower and broccoli, are high value crops, which can be used by small-scale and resource-poor farmers to increase their returns from their greenhouse investments.

The night-time relative humidity approached saturation levels in the FPVT at 99% (Figures 5.2D and 5.2H). This could be due to the fact that the FPVT was kept closed at night, whereas in the NVT, there could have been an exchange of moisture with the outside through the open ends of the tunnel. Compared to the summer conditions reported by Thiye (2014) in Chapter 3 of this document, the NVT and external relative humidity levels were lower in winter.

5.3.2 Crop growth

The most suitable daytime air temperatures for optimum lettuce growth and development are between 17 and 27°C and night-time temperatures between 2 and 12°C. Temperature is one of the factors that have an impact on successful lettuce production (DAFF, 2013), influencing yield and quality. The high daytime temperatures and low daytime relative humidity in the NVT did not negatively affect the growth of the lettuce. According to the breeders' 2012-2013 catalogue, cultivars *Ballerina* and *Nadine* are most suitable for growing in autumn, spring and summer. This would explain why the higher daytime temperatures in the NVT were tolerated by both cultivars. In addition, according to Maboko and du Plooy (2003), high temperatures above 27°C encourage vegetative growth in lettuce, especially during the early stages of growth (Kanaan and Economakis, 1992), which explains why the generation of new leaves was not inhibited by the higher NVT air temperatures.

The main effect on the growth was due to cultivar differences (Figure 5.4). *Ballerina* vegetative growth was more rapid, when compared to *Nadine*, although the dry matter accumulation rate was not different. The results suggest that *Ballerina* is a faster-growing cultivar, when compared to *Nadine* and could reach maturity earlier.

5.3.3 Yield and quality

The performance of Ballerina was better than that of Nadine. Under the cooler daytime air conditions in the FPVT, Ballerina yield, both in terms of number of leaves, as well as dry matter, out-performed Nadine. This suggests that Ballerina is more sensitive to the environmental conditions under which it is grown, but may have the potential to produce higher yields under optimum microclimatic conditions. Methods that can reduce the solar heat gain of the NVT and enhance the microclimatic conditions of the NVT should be investigated. Since the NVT requires no power input and constant water supply like the FPVT, reducing the solar heat input into the NVT may improve the microclimatic conditions. This could improve the Ballerina yield, even in the NVT. These results agree with those reported by Wallace *et al.* (2012), who reported significant differences in the total yields, due to cultivar differences in lettuce grown in high tunnels, with varying maximum and minimum temperatures.

Butterhead lettuce forms soft solid or loose heads, with overlapping leaves. Temperatures exceeding 27°C lead to poor head development, although heat tolerant cultivars exhibit better head formation even at high temperatures (Grubben, 2004). This could be the reason why there were no significant differences in the head size of the two cultivars under the two microclimates. The expectation would be that since the daytime temperatures were up to 4°C higher in the NVT (Figures 5.2A and 5.2E), the lettuce grown under this microclimate would be inferior and smaller in size. However, the night-time temperatures, under both FPVT and NVT microclimates, were within the optimum range for successful lettuce production (Figures 5.2C, 5.2G and 5.3), and could have compensated for the high daytime temperatures in the NVT.

High temperatures have been found to induce bolting and lead to high incidences of leaf tip-burn in lettuce. Bolting was not observed on the two cultivars and thus was not analysed. Butterhead lettuce is particularly susceptible to leaf tip burn (Wien, 1997). Leaf tip-burn lowers the quality of lettuce and can result in non-marketable yield. Under extreme high production air temperatures, leaf tip-burn has been found to lead to complete crop failure of crisp head lettuce (Misaghi *et al.*, 1992). It is a calcium deficiency physiological disorder, which is worsened by high temperatures and high relative humidity (Wien, 1997). The

microclimate in the FPVT showed lower temperatures, but higher relative humidity, when compared to the NVT. The high relative humidity in the FPVT could have been the cause of the 26.9% more leaves affected by leaf tip-burn. The movement of calcium within lettuce tissues is driven primarily by transpiration (Barta and Tibbits, 1986). Under low air humidity environmental conditions, high plant transpiration enhances water and nutrient transport to the transpiring tissues (Wien, 1997). Low air humidity has been shown to induce high transpiration rates and vice versa for high relative humidity. The relatively high air humidity in the FPVT, particularly in the morning and late afternoon, could have repressed transpiration and the transport of plant nutrients to the actively growing leaves. On the other hand, the very low relative humidity in the NVT could have induced high transpiration in the lettuce and enhanced the transport of calcium to the growing leaves. Although there were no significant cultivar influences on the incidence of leaf tip-burn, Ballerina was the most susceptible, with 24% and 29.6% more leaves affected by leaf tip-burn than Nadine.

5.4 Conclusion

The “greenhouse effect”, created by greenhouse structures, was of little benefit in the Pietermaritzburg area of KwaZulu-Natal during the winter period, resulting in an unsatisfactory performance of the NVT and marginal performance of the FPVT. The daily temperatures in the NVT fluctuated between extremely high daytime temperatures of up to 39°C, and low night-time temperatures, as low as 2°C. The daytime temperatures in the NVT, especially in the middle of the day, exceeded the optimum maximum of 28°C for most greenhouse crops, including lettuce. In addition, the relative humidity in the NVT was extremely low, reaching the lowest minimum of 10% during the daytime, conditions that could potentially induce water stress and negatively impact plant growth. In the FPVT, the evaporative cooling process kept the daytime temperature below 28°C, whereas the night-time temperature was as low as 2°C. The evaporative cooling also helped to maintain higher levels (>50%) of relative humidity. The frequent need for evaporative cooling during the winter period implies that the costs of operation of the FPVT over winter would be high.

Although the microclimate in the NVT was unfavourable for lettuce growth, the growth, yield and quality of the lettuce cultivars selected, were not disadvantaged by the environmental conditions. There were no significant ($P>0.05$) differences in the number of leaves and dry

matter accumulated by the lettuce plants in both tunnels. However, the yield of cultivar Ballerina was better, in terms of the number of leaves harvested (14.5% higher) and dry matter yield (17.4% higher), when grown under the FPVT conditions. Conversely, leaf tip-burn was also 29.6% higher for Ballerina, grown under the FPVT microclimate. This research has shown that, in the Pietermaritzburg area of South Africa, both the NVT and the FPVT can be used for cultivation of winter crops such as lettuce, although cultivar selection is important. If cultivation of cold-sensitive, crops such as tomatoes is to be carried out, provision for night-time heating would be essential.

5.5 References

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6. CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

Small-scale commercially-oriented agriculture and technology transfer have been identified as some of the options that can be used for income generation and to combat food insecurity in South Africa (Altman *et al.*, 2009). Greenhouse technology, as one of the fastest growing food production systems in the world (van Straten, 2011), has the potential for small-scale crop production in developing countries. In spite of this potential for poverty alleviation, the mitigation of unemployment and the prevention of malnutrition, research on greenhouse facilities for crop production in Southern Africa is lacking.

This study was undertaken with the aim of comparatively analysing the microclimate of two of the most common greenhouse types available in South Africa, as well as their effect on crop growth, yield and quality, during the summer and winter periods. The research was carried out at the University of KwaZulu-Natal Ukulinga Research Farm, in Pietermaritzburg, South Africa in 2012-2013. A fan-pad evaporatively-cooled tunnel (FPVT) and a naturally-ventilated open-ended tunnel (NVT) were used in the study. Four tomato cultivars (Bona, Star 9037, Star 9009 and Zeal) were used to study the effect of the microclimates during the summer and two lettuce cultivars (Ballerina and Nadine) were used in winter. Integrated agro-technologies, involving pre- and postharvest treatments that included the microclimate and postharvest storage environmental conditions on the texture, colour, TSS and pH of the four tomato cultivars, were also studied.

The findings of the study showed that, during summer, the daytime FPVT temperature was up to 4°C lower and the relative humidity was up to 20% higher than in the NVT. The evaporative cooling process in the FPVT maintained the temperature within the 21 to 28°C range, as suggested by Snyder (2003), as well as the RH above the 60% minimum level, as suggested by von Zabeltitz (2011), as the optimums for cultivation of most greenhouse crops, including tomatoes. In the NVT, the daytime temperatures were up to 32°C and the RH levels were as low as 49%, conditions that are not optimum for tomatoes. There were no significant ($P>0.05$) differences in the night-time temperatures in both tunnels, and both were above the minimum 12°C threshold for greenhouse tomato cultivation (Castilla and Hernandez, 2007).

However, the saturated air conditions prevalent in the FPVT at night-time, resulted in condensation on the inside of the polyethylene cover, a situation which had the potential for increasing the incidence of fungal disease attacks on the crops (Piscia *et al.*, 2012).

During winter, the daytime temperatures in the NVT were up to 6°C higher and the RH was 20 to 30% lower than in the FPVT. The need for evaporative cooling in the FPVT, during the winter period meant that the FPVT energy requirements are consistently high throughout the year. The high temperatures in the NVT created conditions that were not optimum for lettuce cultivation, which grows best at 17 to 27°C. During the night-time, the temperatures inside both tunnels decreased substantially, reaching a minimum level of 2°C. Although this temperature was acceptable for winter crops, including lettuce, if cultivation of cold-sensitive crops such as tomatoes, peppers and cucumbers is desired, heating would be required.

There was also a marked vertical and horizontal variation of both temperature and relative humidity in both tunnels. Greenhouse facilities are known for their non-uniform microclimates, with the potential to induce non-uniform crop growths and yields (Kittas *et al.*, 2003; Teitel *et al.*, 2008). In the FPVT, the temperature was lowest at the wet-wall section and highest at the fan section, with a temperature gradient between 4.3 and 8.0°C between the wet-wall and the fan. In both tunnels, the temperature was highest close to the cover and lowest within the crop canopy, with a temperature difference of up to 5.8°C in the NVT and 7.4°C in the FPVT.

Results on the effect of the microclimate on crop growth and yield showed that, in summer, the optimum microclimate in the FPVT encouraged faster vegetative growth for three of the four tomato cultivars. In the NVT, the high temperatures and low RH restricted the vegetative growth for all the cultivars, except Zeal, the vegetative growth of which was not significantly ($P>0.05$) influenced by microclimatic conditions. Further, the FPVT microclimate resulted in better qualities of the tomatoes produced, as shown by lower unmarketable yields. The total unmarketable yields in the FPVT were half of the unmarketable yields in the NVT. In addition, the higher temperatures in the NVT resulted in high temperature-related defects, such as the 54.4% more undersized fruit mass than in the FPVT. The NVT was also prone to insect attack, which reduced the quality of the tomato fruits by 29.5%, as opposed to 5% in

the FPVT. The vulnerability of the NVT to invasion by insect/pests could raise the production costs, through measures employed to control insect attacks in this tunnel.

Comparison between the tomato cultivars showed that cultivar Bona performed the best, with the fastest vegetative growth, 42 to 69% more total yields and 43 to 79% more marketable yields than the other three cultivars, when grown under the FPVT microclimate. Although the differences in the total yield among the four cultivars in the NVT were not statistically significant ($P>0.05$), cultivars Star 9037 and Star 9009 performed the best, with 35 to 38% more total yields than when grown under the FPVT microclimate. However, these high yields in the NVT were substantially reduced by 25 to 35%, by the effect of high temperatures, low RH and insect/pest attack.

In winter, there were no significant ($P>0.05$) differences in terms of growth and yield of the lettuce crops, resulting from the effect of the microclimate. Significant ($P<0.01$) cultivar differences were observed on the growth, yield and quality of the lettuce crop. Ballerina had the fastest vegetative growth and higher yields with 11.5% more leaves than Nadine. In addition, Ballerina benefitted from the lower temperatures in the FPVT, as shown by the 17.4% higher dry matter yields than Nadine, compared to the NVT microclimate, where there were no significant ($P>0.05$) differences in the dry matter yields of the two cultivars. The FPVT microclimate lowered the quality of the lettuce, where the incidence of leaf tip-burn was 26.9% higher than in the NVT. Leaf tip-burn, a calcium deficiency disorder, is worsened by high RH levels, which reduce transpiration and limit the supply of nutrients to the leaves (Barta and Tibbits, 1986; Wien, 1997). Comparison between the cultivars showed that Ballerina was more susceptible to leaf tip-burn, especially under the FPVT microclimate, where 29.6% more leaves than Nadine had tip-burn, compared to 24% more under the NVT microclimate.

The postharvest evaluation on the combined effects of the microclimate and postharvest storage environment on the texture, colour changes, TSS and the pH of the tomatoes showed that there were significant ($P\leq 0.05$) influences. Tomatoes grown under the NVT microclimate had and retained a firmer texture (by 7.4%) and had a TSS content that was 10.3% higher than those grown in the FPVT. The lower growth temperatures in the FPVT were influential in slowing down the change of colour (by 7.2 to 8.0%) from mature-green to red-ripe, and in

slowing down the ripening process of the tomatoes. Among the four cultivars, Bona had the shortest shelf-life, whereas Star 9009 and Star 9037 had the longest. Bona was the least firm (by up to 78.5%) and lost firmness and changed colour from mature-green to red-ripe the fastest, when compared to the other cultivars. In addition, Bona had the highest TSS content (up to 8.3% higher than the other cultivars) and the lowest pH values. Star 9009 had the firmest texture (up to 21.5% firmer than other cultivars, particularly Bona) and retained a firmer texture for a longer period, whereas Star 9037 had the lowest TSS content. This showed the genetic variations that exist among the tomato cultivars available in South Africa, with regards to the postharvest qualities.

Significant ($P < 0.05$) effects due to the interaction of microclimate, postharvest storage condition and cultivar were also observed. Cold storage conditions at 13°C and 85% RH, helped the FPVT-grown tomatoes and cultivar Bona tomatoes to retain a firmer texture for an extended period of time. However, for Star 9037 and Star 9009, the cold storage conditions were not beneficial, since there were no significant ($P > 0.05$) differences in the texture and colour changes from the tomatoes stored under ambient air conditions ($\pm 23^\circ\text{C}$ and $\pm 52\%$ RH). The cold storage condition also extended the shelf-life on the NVT-grown tomatoes, by reducing the colour changes and maintaining a firmer texture for longer, than under ambient air storage. In addition, cold storage conditions repressed the TSS content of tomatoes, which was 17.7% higher under ambient air storage conditions. Star 9009, Star 9037 and Zeal had significantly ($P < 0.05$) higher TSS values, when grown in the NVT and stored under ambient air conditions.

These results exhibited the effect of multi-factorial treatments that combined pre- and postharvest treatments on the postharvest quality of tomatoes. However, a clear understanding of the interaction effects of the microclimate with cultivar and storage conditions on the physical traits of tomatoes is impeded by the complex nature of the underlying factors which determine physical traits, such as such texture and colour (Carli *et al.*, 2011). Furthermore, the exact nature of the effects of multi-factorial treatments that involve more than two treatments is restricted by the costly and complex nature typical of such studies (Linke and Klaring, 2004). In addition, environmental conditions can modify and obscure genetic differences that determine traits, such as colour (Sacks and Francis, 2001).

The study has shown that, although the naturally-ventilated structures are cheaper and simpler to construct and operate (Ould Khaoua *et al.*, 2006), they create non-optimum environmental conditions, which affect the quality of tomato fruit. These structures are also vulnerable to invasion by insect/pests, which, in addition to further reducing the quality of the produce, could increase the production costs, through the use of insect/pests control measures. In the FPVT, although the microclimate was better than in the NVT, there was little benefit from the optimum conditions in terms of higher total yields.

However, the study has also shown that the utilisation of greenhouse facilities may be extended by cultivating summer crops in summer and cold-tolerant crops in winter. Under Pietermaritzburg conditions, Star 9009 and Star 9037 would be the best cultivars for summer cultivation in the NVT, since these had the highest total and marketable yields under the NVT environment. Further, these two cultivars did not require cold storage conditions to maintain acceptable quality levels, in terms of colour and firmness. In the FPVT, cultivar Bona, which had the highest total and marketable yields when grown in this tunnel, would be the best cultivar for this tunnel in summer. However, cold storage is essential for retaining high quality attributes, particularly texture and colour, and for extending the shelf-life for this cultivar. In winter, Ballerina, which had the higher yields under the FPVT microclimate, would be best-suited for cultivation in the FPVT, although leaf tip-burn could lower the quality of the produce. Nadine would be the best suitable for cultivation in the NVT, since its growth and yield were not influenced by the microclimatic conditions.

6.2 Recommendations

Based on the outcomes of this study, the following research needs and recommendations were identified:

- A cost-benefit analysis for both tunnels to establish the cost of production for the higher marketable yields in the FPVT and the opportunity cost of the higher unmarketable yields in the NVT,
- Alternative cost-effective methods for reducing the solar heat gain in the tunnels, such as whitewashing and the use of near-infrared reflective screens,
- Alternative methods for increasing the RH in the NVT, such as fogging and misting, although this will likely increase the production costs of the NVT,

- Further research with other greenhouse crops, such as sweet-peppers and cucumbers to establish their performance under both microclimates,
- Extensive research of the various ventilation and cooling methods, including roof- and/or side-ventilation, and
- Further research in other agro-climatic regions of South Africa to extend the information base about greenhouse microclimate and its effect on crops in South Africa.

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7. APPENDICES

7.1 Appendix 3.1 ANOVA Tables for Plant Growth Parameters

Variable: Leaf number

K value	Source	Degrees of freedom	Sum of squares	Mean square	F value	Probability
1	Replication	9	77.045	8.561	2.1265	0.1382
2	Factor A	1	3.564	3.564	0.8852	
-3	Error	9	36.232	4.026		
4	Factor B	3	5625.505	1875.168	656.6966	0.0000
6	AB	3	200.745	66.915	23.4341	0.0000
8	Factor C	10	28869.507	2886.951	1011.0297	0.0000
10	AC	10	197.061	19.706	6.9012	0.0000
12	BC	30	1320.220	44.007	15.4117	0.0000
14	ABC	30	74.430	2.481	0.8689	
-15	Error	774	2210.123	2.855		
Total		879	38614.432			

Factor A= Microclimate; Factor B= Cultivar; Factor C= Growth period

Variable: Plant height

K value	Source	Degrees of freedom	Sum of squares	Mean square	F value	Probability
1	Replication	9	4482.336	498.037	1.5138	0.2733
2	Factor A	1	11549.255	11549.255	35.1052	0.0002
-3	Error	9	2960.905	328.989		
4	Factor B	3	539071.368	179690.456	3856.8140	0.0000
6	AB	3	12501.318	4167.106	89.4413	0.0000
8	Factor C	10	1501217.670	150121.767	3222.1619	0.0000
10	AC	10	4143.270	414.327	8.8930	0.0000
12	BC	30	120744.457	4024.815	86.3872	0.0000
14	ABC	30	5706.457	190.215	4.0827	0.0000
-15	Error	774	36060.959	46.590		
Total		879	2238437.995			

Variable: Leaf area

K value	Source	Degrees of freedom	Sum of squares	Mean square	F value	Probability
1	Replication	3	0.016	0.005	0.2231	
2	Factor A	1	0.012	0.012	0.5096	
-3	Error	3	0.071	0.024		
4	Factor B	3	3.793	1.264	47.0036	0.0000
6	AB	3	0.076	0.025	0.9470	
8	Factor C	4	25.788	6.447	239.6436	0.0000
10	AC	4	0.014	0.003	0.1290	
12	BC	12	1.389	0.116	4.3031	0.0000
14	ABC	12				
-15	Error	114				
Total		159	34.467			

Variable: Vegetative biomass

K value	Source	Degrees of freedom	Sum of squares	Mean square	F value	Probability
1	Replication	3	250.335	83.445	0.2746	
2	Factor A	1	624.930	624.930	2.0565	0.2470
-3	Error	3	911.635	303.878		
4	Factor B	3	27575.741	9191.914	37.1065	0.0000
6	AB	3	341.887	113.962	0.4601	
8	Factor C	4	340676.030	85169.007	343.8158	0.0000
10	AC	4	684.704	171.176	0.6910	
12	BC	12	14768.652	1230.721	4.9683	0.0000
14	ABC	12	3194.483	266.207	1.0746	0.3880
-15	Error	114	28239.738	247.717		
Total		159	417268.135			

7.2 Appendix 3.2 ANOVA Tables for Tomato Yield and Quality Parameters

Variable: Total Yield (TY)

K value	Source	Degrees of freedom	Sum of squares	Mean square	F value	Probability
1	Replication	9	40.489	4.499	1.4997	0.2778
2	Factor A	1	14.801	14.801	4.9339	0.0535
-3	Error (a)	9	26.998	3.000		
4	Factor B	3	40.751	13.584	5.4439	0.0046
-5	Error (b)	27	67.371	2.495		
6	AB	3	19.344	6.448	2.9760	0.0492
-7	Error (c)	27	58.501	2.167		
Total		79	268.264			

Factor A = Microclimate; Factor B = Cultivar

Variable: Under-sized (US)

K value	Source	Degrees of freedom	Sum of squares	Mean square	F value	Probability
1	Replication	9	0.428	0.048	2.7381	0.0748
2	Factor A	1	0.830	0.830	47.7841	0.0001
-3	Error (a)	9	0.156	0.017		
4	Factor B	3	0.787	0.262	15.5429	0.0000
-5	Error (b)	27	0.456	0.017		
6	AB	3	0.135	0.045	2.8968	0.0534
-7	Error (c)	27	0.421	0.016		
Total		79	3.214			

Factor A = Microclimate; Factor B = Cultivar

Variable: Blossom-end rot (BER)

K value	Source	Degrees of freedom	Sum of squares	Mean square	F value	Probability
1	Replication	9	0.169	0.019	0.8069	
2	Factor A	1	0.020	0.020	0.8524	
-3	Error (a)	9	0.210	0.023		
4	Factor B	3	0.358	0.119	5.9598	0.0030
-5	Error (b)	27	0.542	0.020		
6	AB	3	0.069	0.023	1.1905	0.3320
-7	Error (c)	27	0.521	0.019		
Total		79	1.888			

Factor A = Microclimate; Factor B = Cultivar

Variable: Insect damage (ID)

K value	Source	Degrees of freedom	Sum of squares	Mean square	F value	Probability
1	Replication	9	0.387	0.043	1.0591	0.4666
2	Factor A	1	1.815	1.815	44.7565	0.0001
-3	Error (a)	9	0.365	0.041		
4	Factor B	3	0.429	0.143	4.9643	0.0072
-5	Error (b)	27	0.779	0.029		
6	AB	3	0.451	0.150	5.2563	0.0055
-7	Error (c)	27	0.773	0.029		
Total		79	4.999			

Factor A = Microclimate; Factor B = Cultivar

Variable: Cracks (CR)

K value	Source	Degrees of freedom	Sum of squares	Mean square	F value	Probability
1	Replication	9	0.229	0.025	0.6185	
2	Factor A	1	0.007	0.007	0.1664	
-3	Error (a)	9	0.370	0.041		
4	Factor B	3	0.226	0.075	6.1035	0.0026
-5	Error (b)	27	0.333	0.012		
6	AB	3	0.019	0.006	0.2242	
-7	Error (c)	27	0.743	0.028		
Total		79	1.926			

Factor A = Microclimate; Factor B = Cultivar

Variable: Deformed (DF)

K value	Source	Degrees of freedom	Sum of squares	Mean square	F value	Probability
1	Replication	9	0.376	0.042	0.9679	
2	Factor A	1	0.198	0.198	4.5876	0.0608
-3	Error (a)	9	0.388	0.043		
4	Factor B	3	0.443	0.148	3.4440	0.0306
-5	Error (b)	27	1.157	0.043		
6	AB	3	0.097	0.032	0.7844	
-7	Error (c)	27	1.117	0.041		
Total		79	3.776			

Factor A = Microclimate; Factor B = Cultivar

Variable: Total unmarketable yield (TUY)

K value	Source	Degrees of freedom	Sum of squares	Mean square	F value	Probability
1	Replication	9	2.157	0.240	2.8579	0.0668
2	Factor A	1	8.528	8.528	101.7116	0.0000
-3	Error (a)	9	0.755	0.084		
4	Factor B	3	1.463	0.488	3.3984	0.0320
-5	Error (b)	27	3.876	0.144		
6	AB	3	0.976	0.325	2.9808	0.0490
-7	Error (c)	27	2.948	0.109		
Total		79	20.703			

Factor A = Microclimate; Factor B = Cultivar

Variable: Total marketable yield (TMY)

K value	Source	Degrees of freedom	Sum of squares	Mean square	F value	Probability
1	Replication	9	27.354	3.039	1.0948	0.4474
2	Factor A	1	0.855	0.855	0.3080	
-3	Error (a)	9	24.985	2.776		
4	Factor B	3	50.924	16.975	8.2262	0.0005
-5	Error (b)	27	55.714	2.063		
6	AB	3	12.866	4.289	2.0804	0.1263
-7	Error (c)	27	55.658	2.061		
Total		79	228.356			

Factor A = Microclimate; Factor B = Cultivar

7.3 Appendix 4.1: ANOVA Tables for Tomato Postharvest Storage Quality Parameters

Variable: Fruit firmness

K value	Source	Degrees of freedom	Sum of squares	Mean square	F value	Probability
1	Replication	3	2.271	0.757	3.1263	0.1871
2	Factor A	1	7.657	7.657	31.6210	0.0111
-3	Error	3	0.726	0.242		
4	Factor B	3	41.363	13.788	18.5498	0.0000
6	AB	3	10.032	3.344	4.4990	0.0159
-7	Error	18	13.379	0.743		
8	Factor C	1	28.358	28.358	64.2508	0.0000
10	AC	1	0.259	0.259	0.5863	
12	BC	3	4.634	1.545	3.4995	0.0164
14	ABC	3	5.234	1.745	3.9531	0.0090
16	Factor D	4	1348.919	337.230	764.0702	0.0000
18	AD	4	4.075	1.019	2.3081	0.0591
20	BD	12	31.259	2.605	5.9021	0.0000
22	ABD	12	31.123	2.594	5.8764	0.0000
24	CD	4	41.201	10.300	23.3377	0.0000
26	ACD	4	10.987	2.747	6.2237	0.0001
28	BCD	12	16.420	1.368	3.1002	0.0005
30	ABCD	12	25.616	2.135	4.8367	0.0000
-31	Error	216	95.334	0.441		
	Total	319	1718.849			

Variable: L*

K value	Source	Degrees of freedom	Sum of squares	Mean square	F value	Probability
1	Replication	3	41.298	13.766	0.3186	
2	Factor A	1	1398.670	1398.670	32.3684	0.0108
-3	Error	3	129.633	43.211		
4	Factor B	3	5625.134	1875.045	66.3602	0.0000
6	AB	3	1051.882	350.627	12.4091	0.0001
-7	Error	18	508.600	28.256		
8	Factor C	1	1099.014	1099.014	65.0901	0.0000
10	AC	1	237.516	237.516	14.0671	0.0002
12	BC	3	1553.231	517.744	30.6638	0.0000
14	ABC	3	703.292	234.431	13.8844	0.0000
16	Factor D	4	25105.788	6276.447	371.7281	0.0000
18	AD	4	1035.142	258.785	15.3268	0.0000
20	BD	12	5752.769	479.397	28.3927	0.0000
22	ABD	12	2364.134	197.011	11.6682	0.0000
24	CD	4	2403.948	600.987	35.5940	0.0000
26	ACD	4	543.277	135.819	8.0440	0.0000
28	BCD	12	6931.558	577.630	34.2106	0.0000
30	ABCD	12	1026.524	85.544	5.0664	0.0000
-31	Error	216	3647.054	16.885		
Total		319	61158.463			

Variable: Hue angle (h°)

K value	Source	Degrees of freedom	Sum of squares	Mean square	F value	Probability
1	Replication	3	112.463	37.488	0.1887	
2	Factor A	1	2293.386	2293.386	11.5462	0.0425
-3	Error	3	595.881	198.627		
4	Factor B	3	10354.551	3451.517	59.1636	0.0000
6	AB	3	1785.523	595.174	10.2021	0.0004
-7	Error	18	1050.093	58.338		
8	Factor C	1	2768.599	2768.599	52.2109	0.0000
10	AC	1	692.223	692.223	13.0541	0.0004
12	BC	3	2099.302	699.767	13.1964	0.0000
14	ABC	3	1901.095	633.698	11.9504	0.0000
16	Factor D	4	58051.896	14512.974	273.6894	0.0000
18	AD	4	1547.740	386.935	7.2969	0.0000
20	BD	12	7893.311	657.776	12.4045	0.0000
22	ABD	12	4149.169	345.764	6.5205	0.0000
24	CD	4	1377.607	344.402	6.4948	0.0001
26	ACD	4	661.176	165.294	3.1172	0.0161
28	BCD	12	9339.086	778.257	14.6766	0.0000
30	ABCD	12	1330.822	110.902	2.0914	0.0186
-31	Error	216	11453.869	53.027		
Total		319	119457.792			

Variable: Total soluble solids (TSS)

K value	Source	Degrees of freedom	Sum of squares	Mean square	F value	Probability
1	Replication	3	3.172	1.057	2.3720	0.2483
2	Factor A	1	22.208	22.208	49.8270	0.0058
-3	Error	3	1.337	0.446		
4	Factor B	3	7.470	2.490	4.0565	0.0229
6	AB	3	3.571	1.190	1.9390	0.1595
-7	Error	18	11.050	0.614		
8	Factor C	1	70.594	70.594	135.4331	0.0000
10	AC	1	9.488	9.488	18.2016	0.0000
12	BC	3	3.368	1.123	2.1536	0.0945
14	ABC	3	9.558	3.186	6.1120	0.0005
16	Factor D	4	541.399	135.350	259.6654	0.0000
18	AD	4	4.688	1.172	2.2485	0.0649
20	BD	12	60.685	5.057	9.7019	0.0000
22	ABD	12	29.969	2.497	4.7912	0.0000
24	CD	4	280.066	70.017	134.3252	0.0000
26	ACD	4	10.136	2.534	4.8613	0.0009
28	BCD	12	30.580	2.548	4.8890	0.0000
30	ABCD	12	15.160	1.263	2.4236	0.0057
-31	Error	216	112.589	0.521		
	Total	319	1227.086			

Variable: pH

K value	Source	Degrees of freedom	Sum of squares	Mean square	F value	Probability
1	Replication	3	0.007	0.002	0.0570	
2	Factor A	1	0.382	0.382	9.5374	0.0538
-3	Error	3	0.120	0.040		
4	Factor B	3	1.853	0.618	46.1184	0.0000
6	AB	3	3.064	1.021	76.2639	0.0000
-7	Error	18	0.241	0.013		
8	Factor C	1	48.742	48.742	5115.9946	0.0000
10	AC	1	0.224	0.224	23.5311	0.0000
12	BC	3	3.942	1.314	137.9070	0.0000
14	ABC	3	4.336	1.445	151.6965	0.0000
16	Factor D	4	294.761	73.690	7734.5550	0.0000
18	AD	4	4.144	1.036	108.7402	0.0000
20	BD	12	12.491	1.041	109.2524	0.0000
22	ABD	12	12.059	1.005	105.4729	0.0000
24	CD	4	171.615	42.904	4503.1952	0.0000
26	ACD	4	4.629	1.157	121.4562	0.0000
28	BCD	12	9.368	0.781	81.9394	0.0000
30	ABCD	12	10.544	0.879	92.2293	0.0000
-31	Error	216	2.058	0.010		
Total		319	584.580			

Factor A= Microclimate; Factor B= Cultivar; Factor C= Storage Conditions; Factor D= Storage time

7.4 Appendix 5.1 ANOVA Tables for Lettuce Growth and Quality Parameters

Variable: Weekly leaf accumulation

K value	Source	Degrees of freedom	Sum of squares	Mean square	F value	Probability
1	Replication	9	97.233	10.804	0.6518	
2	Factor A	1	0.150	0.150	0.0090	
-3	Error	9	149.183	16.576		
4	Factor B	1	952.017	952.017	208.9831	0.0000
6	AB	1	0.267	0.267	0.0585	
8	Factor C	5	47157.283	9431.457	2070.3580	0.0000
10	AC	5	17.500	3.500	0.7683	
12	BC	5	134.433	26.887	5.9021	0.0000
14	ABC	5	58.683	11.737	2.5764	0.0277
-15	Error	198	901.983	4.555		
Total		239	49468.733			

Factor A= Microclimate; Factor B= Cultivar; Factor C= Growth period

Variable: Fortnightly dry matter accumulation

K value	Source	Degrees of freedom	Sum of squares	Mean square	F value	Probability
1	Replication	5	4.864	0.973	0.8337	
2	Factor A	1	0.000	0.000	0.000	
-3	Error	5	5.834	1.167		
4	Factor B	1	0.428	0.428	0.3685	
6	AB	1	0.722	0.722	0.6220	
8	Factor C	2	986.370	493.185	424.8450	0.0000
10	AC	2	0.008	0.004	0.0033	
12	BC	2	5.383	2.691	2.3184	0.1089
14	ABC	2	0.883	0.442	0.3804	
-15	Error	50	58.043	1.161		
Total		71	1062.534			

Factor A= Microclimate; Factor B= Cultivar; Factor C= growth period

Variable: Number of leaves yield

K value	Source	Degrees of freedom	Sum of squares	Mean square	F value	Probability
1	Replication	9	77.600	8.622	1.3590	0.3275
2	Factor A	1	6.400	6.400	1.0088	0.3414
-3	Error	9	57.100	6.344		
4	Factor B	1	422.500	422.500	16.2119	0.0008
6	AB	1	32.400	32.400	1.2432	0.2795
-7	Error	18	469.100	26.061		
Total		39	1065.100			

Factor A= Microclimate; Factor B= Cultivar

Variable: Head diameter

K value	Source	Degrees of freedom	Sum of squares	Mean square	F value	Probability
1	Replication	9	2.806	0.312	1.0204	0.4882
2	Factor A	1	0.103	0.103	0.3371	
-3	Error	9	2.750	0.306		
4	Factor B	1	0.075	0.075	0.3862	
6	AB	1	0.386	0.386	1.9931	0.1751
-7	Error	18	3.487	0.194		
Total		39	9.607			

Factor A= Microclimate; Factor B= Cultivar

Variable: Dry matter yield

K value	Source	Degrees of freedom	Sum of squares	Mean square	F value	Probability
1	Replication	9	25.751	2.861	0.9640	
2	Factor A	1	1.862	1.862	0.6273	
-3	Error	9	26.713	2.968		
4	Factor B	1	6.281	6.281	0.8961	
6	AB	1	45.775	45.775	6.5307	0.0199
-7	Error	18	126.164	7.009		
Total		39	232.546			

Factor A= Microclimate; Factor B= Cultivar

Variable: Leaf tip-burn

K value	Source	Degrees of freedom	Sum of squares	Mean square	F value	Probability
1	Replication	9	10.500	1.167	1.0396	0.4774
2	Factor A	1	4.900	4.900	4.3663	0.0662
-3	Error	9	10.100	1.122		
4	Factor B	1	0.100	0.100	0.0756	
6	AB	1	0.100	0.100	0.0756	
-7	Error	18	23.800	1.322		
Total		39	49.500			

Factor A= Microclimate; Factor B= Cultivar