EVALUATION AND MODELLING OF DIFFERENT GREENHOUSE MICROCLIMATES UNDER SOUTH AFRICAN AGRO-CLIMATIC CONDITIONS

E du Plessis

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University of KwaZulu-Natal
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Supervisor: Prof TS Workneh
Co-supervisor: Prof M Laing

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As the candidate's supervisors, we have approved this thesis for submission

Supervisor .... Date: ....

Professor TS Workneh

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PREFACE

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ABSTRACT

It is estimated that the South African population will grow by 1.7% per annum and that 35% of the current South African population presently live with inadequate access to food. Conventional agricultural methods show obvious limitations in producing sufficient food for the current population. Africa is also thought to be extremely vulnerable to the impacts of climate change. Controlled environment agriculture such as greenhouse crop production is becoming more popular in South Africa. It is, however, often associated with high capital and operating costs and undesired internal micro-climates. Research of the current literature shows that limited knowledge exists and very limited reviews have been done regarding the performance of different greenhouse structures and designs for local agro-climatic conditions in South Africa. Greenhouse cooling systems and the evaluation thereof are especially relevant to the South African arid climate and for providing a solution to the problems experienced as a result of over-heating inside greenhouses. Due to the lack of available scientific information, it is necessary to predict the performance of different greenhouse structures and cooling systems when it comes to the internal micro-climate for different external agro-climatic conditions in South Africa.

A comparative study was done on microclimatic conditions such as the temperature and relative humidity of three greenhouses with different designs. The three greenhouses used for this study included a naturally ventilated greenhouse fitted with insect nets on the roof vents (NVG), a naturally ventilated greenhouse fitted with fogging (NVFG) and a shadenet tunnel (SNT). The effects of the different greenhouse conditions on a lettuce crop were also studied for one growth cycle.

The day-time temperatures for the naturally ventilated polycarbonate greenhouse (NVG) were significantly ($P<0.05$) higher than external temperature and mostly higher than temperatures in the other two greenhouses. The day-time RH measurements in the NVG were generally lower than the outside as well as when compared to the other two greenhouses on the relevant days. There was a significant ($P<0.05$) difference in terms of RH when compared to the NVFG. The microclimates in the three greenhouses were similar at night times.

Plant yield was generally higher in the fog-cooled greenhouse (NVFG) for lettuce varieties Erasmus RZ and Cook RZ and slightly higher in the naturally ventilated greenhouse for varieties the Gaugin RZ and Xerafin RZ. The colour of the red lettuce was maintained in the shadenet greenhouse due to better light transmission. However, the lowest yield for all varieties was achieved in the shadenet greenhouse.

Experimental data were used in a study to test a selected mathematical model for the ability to predict the internal microclimatic conditions of the three different greenhouse designs, when exposed to different external climatic conditions. It was found that the selected model predicted the difference in external and internal temperature for the shadenet tunnel well ($R^2 = 0.85$). However, the results from the suitability test for the other models for the NVG and NVFG were found to be less accurate ($R^2 = 0.65$ and $R^2 = 0.63$) in the temperature difference prediction. All models did not predict the vapour pressure difference well.

The study has provided information regarding the difference in microclimates achieved in three different greenhouses over a specific period. The temperatures in the NVG were mostly above the optimum levels for lettuce crop production, while the RH values were below optimal. The climate conditions in the NVG were acceptable for the production of typical greenhouse crops, while the climate in the SNT closely followed that of the measured external conditions. The study showed the effect on lettuce varieties grown in these greenhouses over one crop cycle. It provided a mathematical model to predict the internal climate conditions when it comes to the different greenhouses. The model can only accurately predict the internal temperature of the shadenet tunnel for different external climate conditions. The study has shown that further research can be done to improve the accuracy of the model by adding more data points and adjusting coefficients to increase the accuracy. Other, more complex, models can also be developed for the conditions in the same greenhouses.
The costs for installing, operating and maintaining the structures and equipment of the three experimental greenhouses were compared and predicted based on a 1 ha greenhouse design. Although some of the operational costs associated with the greenhouse facilities were evaluated in this study a detailed cost-benefit analysis, incorporating other input costs and market prices, can be done to provide further important information influencing the

decision making process of investing in different greenhouse systems. Research can be extended to include the evaluation of cucumber, tomato and peppers as well as the same lettuce crop production over more than one season in order to better evaluate the benefits of the specific greenhouse designs on quality and yield.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Page

LIST OF PUBLICATIONS

1. Du Plessis, E, Workneh, T, Laing, M. 2015. Chapter 6: Greenhouse Cooling Systems and Models for Arid Climate. *Sustainable Agriculture Reviews*, Vol. 18: 181-215.

1 INTRODUCTION

The world population is expected to grow by a billion more people within the next 13 years (World Hunger Statistics, 2013). South Africa has an estimated population growth rate of 1.7% per annum (du Toit *et al.*, 2011), and it is estimated that 35% of the South African population live with inadequate access to food. The lack of suitable traditional farming conditions, such as large open spaces and good soil conditions contribute to shortages (Venter, 2010). Since a large proportion of Africa's crop production depends on rainfall, a factor that is expected to become a great uncertainty due to possible climate change (Challinor *et al*., 2007), Africa is thought to be vulnerable to the impacts of climate change. Although the lack of access to agricultural resources exists all over the world and is one of the most important causes of food insecurity in the continent, the light and water we have access to are sufficient to help produce enough crops to feed the earth's population (Venter, 2010). Conventional agricultural methods show obvious limitations and are not efficient enough to produce sufficient food for everyone. Controlled environment agriculture (CEA) is where the natural environment is modified or manipulated to optimize plant growth; this leads to economic return and has the potential to contribute towards the reduction of poverty and food insecurity problems.

The main advantage of using greenhouses to produce crops is that it enables the all-year round production of fresh produce crops and is not influenced by adverse climatic conditions, which would be the case if the plants were grown in open fields (Venter, 2010). Greenhouses are expensive and energy-intensive and therefore they need to show a significant increase in crop production to be competitive when compared to open field agriculture (Jensen, 2002), before the decision is made to invest.

Greenhouse production has grown significantly worldwide over the last 30 to 40 years. The estimated total area under the cover of greenhouse in major greenhouse production countries are as follows: China 2 760 000 ha; Korea 57 444 ha; Spain 52 170 ha; Japan 49 049 ha; Turkey 33 515 ha; Italy 26 500ha; Mexico 11 759 ha; the Netherlands 10 370 ha; France 9 620 ha; and the United States 8 425 ha (CEAC, 2012). It is estimated that there are currently 250-350 ha of protected flower cultivation in South Africa (de Visser and Dijkxhoorn, 2012). There is a total area of 136 000 ha of vegetable production in South

Africa, with a very small percentage under protected cultivation (de Visser and Dijkxhoorn, 2012).

The development of greenhouses can have a significant impact on food security in developing countries like South Africa. In terms of contributing to economic development in South Africa, there is a large domestic market and an increasing demand for a constant supply of high quality vegetables. The demand in other Southern African countries is also increasing. If transport costs can be reduced, large markets can be accessed internationally.

South Africa is a warm country with several different agro-climatic zones. In terms of internal greenhouse climate control, problems are generally experienced from overheating in greenhouses during the summer months. Several different cooling system designs exist in South Africa, such as natural ventilation, forced ventilation and different methods of evaporative cooling. The running costs of forced ventilation systems are very high and increase with constantly rising electricity costs (Visser and Dijkxhoorn, 2012; Maboko *et al.*, 2012). This causes investors to move away from using these systems (Olsen 2013; van Niekerk, 2013; Venter, 2013). Little reliable information is available on the performance of the different types of greenhouses and cooling systems in the different regions of South Africa. Even the success of existing greenhouses, in terms of cost-effectiveness and climate control, have not been documented properly and limited studies or experiments on crop production have been formally recorded. There are also limited locally-developed models that can be applied when it comes to designing new greenhouses for a specific area. In order to effectively increase the productivity of agricultural production under protected cultivation in South Africa, the existing local knowledge has to be scientifically expanded by obtaining empirical data on the microclimate of the existing greenhouses and modelling the changes in temperature, vapour pressure and relative humidity inside the greenhouses.

Research has shown that growers in the protected cultivation sector in South Africa do not readily cooperate, and share knowledge and experience with other growers or emerging farmers (de Visser and Dijkxhoorn, 2012). In terms of greenhouse construction and design in this country, greenhouse suppliers regularly take the role of designing the complete greenhouse structure and environmental control systems for a specific investor. Specifically international suppliers rarely take local conditions into account (Venter, 2013). Suppliers use their own design techniques based on models or experience and have their own limited range of products. The resulting greenhouse may not be the most desirable outcome for that particular investor or buyer. All of the above mentioned factors clearly indicate how vital it is to conduct research into the identified information gaps.

The study will evaluate micro-climatic conditions, such as internal air temperature and relative humidity (RH), against external conditions. The performance of different lettuce varieties in three different greenhouse designs will also be investigated. A mathematical model will be developed to predict climate parameters, such as temperature and vapour pressure for further greenhouse applications under South African climate conditions, and will be validated. Certain operational and capital costs associated with the different greenhouse systems will be captured and compared.

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2 LITERATURE REVIEW

Abstract

This review identifies different greenhouse designs and cooling systems available and that are applicable to South African agro-climatic conditions. Certain greenhouse systems often fail in performance to achieve optimal climate conditions when placed in specific climatic regions. Climatic requirements of different greenhouse crops were reviewed. Using mathematical models to predict the performance of a greenhouse in terms of internal microclimatic conditions are cheaper and can be effective in terms of optimizing greenhouse designs for different climatic regions. Different models that have been developed and applied were reviewed. Some economical aspects associated with greenhouses were briefly investigated. The performance of typical greenhouse designs and cooling systems used in South Africa should further be researched. Models to predict performance of different greenhouse designs for South African conditions should be further investigated. Costs associated with operating typical greenhouses, and the performance of crops in specific greenhouses should also be further researched.

2.1 Introduction

Due to the constant increase in the population and the continuous decrease of natural resources and impact of climate change, food security remains a critical focus area in Southern Africa (du Plooy *et al.,* 2012). The development of greenhouses can have a significant impact on improving food security in developing countries such as South Africa (Pack and Mahta, 2012).Also in terms of contributing to economic development in South Africa, there is a large domestic market and an increasing demand for a constant supply of high quality vegetables. The demand for fresh produce in Southern African countries is also increasing. If transport costs can be reduced, large markets can be accessed internationally (de Visser and Dijkxhoorn, 2012).

Greenhouses can enable year-round production and also ensures the efficient use of resources such as water, fertilizers, pesticides and labour (Pardossi *et al*., 2004). It protects the crop from wind and hail damage, birds, weeds, rodents, insects, fungi, viruses and other diseases. It can also lead to higher yields per hectare, compared to open field cultivation, because of the optimal growing conditions and balanced plant nutrient supply (Jensen, 2002). In some instances, tomato yields can reach 500 – 600 tons per hectare per year in controlled greenhouses, in comparison to the 120 – 150 tons per ha per year of open field cultivation (Venter, 2010).Limited scientific data regarding greenhouse system performance and designs for South African conditions are available. This paper reviews different greenhouse designs and cooling systems available as well as the capital costs associated with it. It also reviews the different models that have been developed to predict internal climatic conditions for certain greenhouse designs. It looks at the status of greenhouses in South Africa, the different climatic conditions of South Africa and briefly investigates the climate parameters and thresholds for different greenhouse crops.

2.2 Greenhouse Climate Parameters

Plants require specific factors that enhance growth resulting from photosynthesis. These parameters, namely, temperature, relative humidity, light and carbon dioxide, are described in the sections below.

2.2.1 Temperature

Temperature has a direct impact on the physiological development phases such as flowering, germination and development of the plant, and affects the transpiration rate which impacts on the plant water status during the photosynthesis. Temperature requirements in a greenhouse depend largely on the type of crop to be grown (Peet, 1999).
Each crop and its development process responds differently to temperature. High temperatures generally cause escalation in plant growth rates, with an increase in leaf area. It stimulates a greater transpiration rate in plants, which cools plants, but will result in water loss and an imbalance of the distribution of photosynthates (Tognoni *et al*., 1999). This can, in turn, cause physical disorders and restrict the reproductive development of plants (Peet, 1999).
The difference between day and night temperatures, as well as the mean 24-hour temperatures can also affect plant growth. Low temperatures can have a significant effect on growth rates and can influence fruit and seed production (Peet, 1999). As further described in Section 2.6, South Africa has various regions with different climatic conditions. Temperature in a climate area plays a large role in greenhouse design. When it comes to greenhouse production, South Africa generally has very high temperatures that can limit the success of all-year-round greenhouse crop production. This should be carefully considered when designing greenhouse structures and control systems.

2.2.2 Relative humidity

It is critical that the correct balance of temperature and humidity is kept in the greenhouse. Humidity control remains a challenge and high or low humidity levels affect plant development. Vapour pressure deficit (VPD) is the difference between the air's moisture content and the amount of moisture the air can hold when it is saturated. High VPD is usually caused by high temperatures and low humidity and affects plant growth by causing high stomatal resistance and plant water stress because the plant transpires more water than it can absorb. Low VPD, in turn, causes low levels of plant transpiration and associated physiological disorders (Körner and Challa, 2003).

The main challenge with humidity control is the interaction with temperature. Many greenhouse operations are moving towards controlling the greenhouse according to VPD or moisture deficit, which measure the combined effect, rather than controlling only the relative air humidity (RH) (Peet, 1999). Areas specifically on the South African coastline have very high humidity and the effect of such external conditions can have detrimental implications on greenhouse crops. Designs and control systems have to thus be adjusted for these specific conditions. Moreover, the effectiveness of different greenhouse designs and control systems in terms of maintaining the optimum inside air relative humidity needs to be understood.

2.2.3 Light intensity

The growth of plants is controlled by three light processes, namely photosynthesis, photomorphogenesis and photoperiodism (Venter, 2006b). Every variation in light has a direct effect on these processes. Light is part of the photosynthesis process, by converting carbon dioxide into organic material and then releasing oxygen in the presence of light. Photomorphogenesis is the way plants develop under the influence of different types of light and photoperiodism is how the plant reacts to different day-lengths which determine whether they flower. The most critical process is photosynthesis and light is the primary energy source to enable this process (Venter, 2006b). In South Africa, light levels are generally sufficient for effective plant production and artificial lighting is only required for crops that require longer day lengths (de Visser and Dijkxhoorn, 2012).

2.2.4 Carbon dioxide

Carbon dioxide (CO_2) is the primary substrate for the creation of photosynthates during photosynthesis (Tognoni *et al.*, 1999). It accelerates plant growth by increasing net photosynthesis in plants. A well-ventilated greenhouse in South Africa with healthy gas exchange rates and air circulation should ultimately have CO_2 levels of approximately 300 ppm. By increasing CO_2 levels from the natural level to a concentration of between 700 and 900 $\mu l l^{-1}$ increases plant growth (Panwar *et al.*, 2011). Recent studies have shown that plants do not really benefit much from dosing when CO_2 levels exceed 1000 $\mu l l^{-1}$. CO_2 is absorbed via stomata in the plant and effective absorption of CO_2 in a greenhouse is, therefore, strongly dependent on other climate factors affecting the stomata openings in the plant (Tognoni *et al.,* 1999). The physiological fluxes should be optimized by limiting plant stress caused by unfavourable climate parameters. All of the parameters described above are critical for plant growth and needs to be controlled in a greenhouse environment.

2.3 Climate Control Installations

2.3.1 Cooling systems

A big challenge of greenhouse growing and greenhouse production is cooling of the internal climate. High summer temperatures directly impact the success of year-round greenhouse crop production. Greenhouse designers should consider the economic viability of a cooling system that successfully controls the microclimate of the greenhouse in relation to external climatic conditions (Sethi and Sharma, 2007; Mutwiwa *et al*., 2007; Kumar *et al*., 2009).

2.3.1.1 Greenhouse ventilation systems

As presented in Section 2.4.2, the greenhouse structure should be specifically designed to incorporate the choice of ventilation and cooling. Net solar radiation in a greenhouse can reach values ranging between 500 and 600 $W.m^{-2}$. To maintain the inside temperatures of the greenhouse close to the outside temperatures, about 200-250 $W.m^{-2}$ of sensible heat should be removed (Kittas *et al*., 2005). Ventilation should provide temperature control to prevent the extreme build-up of heat during the summer months, to control excessive humidity in the greenhouse and to ensure sufficient air exchanges occur inside the greenhouse to manage carbon dioxide and oxygen levels in the greenhouse (Venter, 2006a).

Natural ventilation is the result of pressure differences created by wind and temperature gradients between the inside and outside of a greenhouse (Kumar *et al.,* 2009). It occurs through openings in the greenhouse structure. It reduces humidity and temperature build-up within the greenhouse and can ensure sufficient air exchange. It requires less energy, in some cases no energy for fixed ventilation openings, and is, therefore, the cheapest method of cooling greenhouses. Natural ventilation works better than other cooling technologies for greenhouses, especially in humid, tropical and subtropical regions (Kumar *et al*., 2009). Ventilation openings should be optimized in order to attempt to cool the greenhouse, even

in low wind speed conditions. Ventilation areas should at least be 25-30% of the greenhouse floor area for most of our local South African regions (Venter, 2006a). However, limited data is available in South Africa on the various greenhouse designs and ventilation systems that have been proven to be most effective, under local conditions.
Forced ambient air ventilation can also be implemented by installing exhaust fans and blowers. Forced ventilation can reduce the internal air temperature of the greenhouse and improve greenhouse conditions (Kittas *et al*., 2005). However, forced ventilation without evaporative cooling pads can actually increase internal greenhouse temperatures when outside-conditions of low humidity and high temperatures exist (Willits, 2003).

In several instances in South Africa, closed greenhouses have been built, and forced ventilation has been used. However, with the rising electricity costs in the country, developers are moving away from this concept. The cost-effectiveness and performance of each cooling system should be evaluated in detail, prior to deciding on a system. Empirical data and accurate modelling are required to properly evaluate and cost each system.

2.3.1.2 Shading

Direct solar radiation is the primary source of heat gain in greenhouses. This can be controlled by shading or reflection. Shading can be done using several different approaches, such as internal and external shade screens, paints and nets. However, shading can negatively influence plant development and photosynthesis because of the reduction of light and the possible effects on ventilation rates and gas exchange (Gonzalez-Real and Baille, 2006). Hence, care should be taken, when deciding on the type of shading and associated control strategies. Partially reflected internal shade screens can be installed and have been proven to reduce the greenhouse air temperature by up to 6˚C, compared to ambient temperatures. The most effective screens contain highly reflective aluminized materials, usually woven with plastic thread. The screens reflect the unwanted solar radiation from the greenhouse roof, while still allowing some light transmittance (Sethi and Sharma, 2007; Kumar *et al*., 2009).

A cheaper alternative is the use of white paint on the roofs of the greenhouse. It is effective in reducing the VPD, air temperature and canopy-to-air temperature, and has a positive effect on the microclimate of the greenhouse (Sethi and Sharma, 2007; Kumar *et al*., 2009). White paint also transforms a large part of the direct radiation into diffused radiation, which has been proven to increase the absorbed radiation by the crop (Gonzalez-Real and Baille, 2006). Another benefit of this cooling method is that it does not impact the ventilation rate of the greenhouse.

External mobile shade cloths are also used for shading and have been proven to reduce crop transpiration and internal VPD (Medrano *et al*., 2004). They are preferable because it prevents the heat input in the greenhouse. External screens have to withstand all atmospheric conditions and are therefore expensive to install (Castilla, 2013). Internal shade screens are often used in South African greenhouses, but they also have a negative effect on light and ventilation rates, as described above (Venter, 2013).

2.3.1.3 Evaporative cooling

Evaporative cooling decreases the air temperature in greenhouses, and increases the absolute internal humidity and it is therefore often more desirable in certain regions than the other cooling technologies (Abdel-Ghany *et al*., 2006a). Fan-pad systems, fogging systems and roof evaporative cooling systems are generally the most common and effective evaporative cooling installations for greenhouses. Their suitability is restricted to certain regions due to limited evaporation in most humid regions and it seldom suits tropical and subtropical climate regions (Kumar *et al*., 2009). With evaporative cooling, water evaporates and absorbs the heat from the air and, in turn reduces the air temperature. It is seen as the most effective way to control temperature and humidity inside a greenhouse (Sethi and Sharma, 2007).

The fan-pad system consists of a fan on one gable end and a wet pad on the opposite end. A small stream of water is run over the pad continuously and air is drawn through the pad by the fans, absorbing heat and water vapour in the greenhouse which cools the air (Arbel *et al*., 2003). It also increases the humidity of the internal air (Sethi and Sharma, 2007). This technology has been shown to reduce air temperature by up to 12˚C, even under very high ambient temperatures. The length of the greenhouse should be considered, as the efficiency decreases and large temperature gradients can be expected across greenhouses of longer lengths (Sethi and Sharma, 2007). Other disadvantages are that it is an expensive installation with high operation costs, namely, fresh water supply, electricity and the high maintenance costs (Vadiee and Martin, 2012). However, there is little empirical data available on the efficiency of pad and fan systems under South African conditions.

Fogging installations are used to increase relative humidity and cooling inside a greenhouse. Water is pumped through high pressure nozzles and sprayed as extremely fine droplets into the air (Sethi and Sharma. 2007). The decrease in droplet size increases the surface area per unit mass of water, which increases the heat and mass exchange between water and air and, in turn, increases the evaporation rate (Linker *et al*., 2011). The evaporation effect causes cooling, as well as humidification. Nozzles are usually installed just below gutter height and can be distributed throughout the greenhouse to ensure a uniform effect. This technology has proven to be more effective than the fan-pad system in terms of evenness in temperature and humidity across the greenhouse (Linker *et al*., 2011). Although some greenhouses that have been designed and constructed in South Africa depend on fogging systems for cooling and humidification, there is little information on their performance on maintaining optimum temperature and humidity inside the structures.

Roof evaporative cooling involves spraying water onto the external surface of a roof which creates a thin water layer on the surface. This decreases the solar radiation transmissivity into the greenhouse and cools the roof and closely surrounding air under the roof (Sethi and Sharma, 2007). Again, this system will work most effectively in hot, dry climate regions.

2.3.1.4 Solar radiation filtration

Global solar radiation enters a greenhouse as three different types of radiation, namely, ultraviolet radiation (UV), photosynthetic active radiation (PAR) and near infrared radiation (NIR). Most of the UV radiation is absorbed by the earth's atmosphere. The extreme exposure of plants to UV can result in the degradation of the photosynthetic process. PAR is absorbed by the plant and is important for photosynthesis and plant growth. NIR is primarily absorbed by the greenhouse structure and equipment, causing the increase in ambient temperature in the greenhouse (Hemming *et al*., 2006). Cooling the greenhouse by modifying covering materials has been investigated and implemented for many years (Hemming *et al*., 2006; Mutwiwa *et al*., 2007). NIR-filtering is also done by using specific plastic films, glass for greenhouses, moveable screens or NIR filtering paint (Hemming *et al*., 2006).

2.3.2 Internal air circulation system

Internal air velocities of a greenhouse are recommended to be between 0.5 to 0.7 m s^{-1} for optimal plant growth, by facilitating gas, CO_2 and water vapour, exchange (Castilla, 2013). To ensure this, fans are often installed above the crop. The number of fans that have to be installed in the greenhouse are calculated to ensure a flow rate of $0.01m^3.s^{-1}$ per m^2 of floor area and have to be installed in the direction of the ridge. Distances between the fans should not exceed 30 times the diameter of the fans (Castilla, 2013).

2.3.3 Air humidification

Other than using fogging installations for cooling and humidity control, the following systems are also used for humidification:

a) Steam,
b) High pressure humidifiers, and
c) Pulsators.

Steam boilers are often used in colder countries to supply heat or for humidity control in greenhouses (Venter, 2010). Kettle heaters can also be used to create warm saturated vapour that is then pumped into the greenhouse (Vadiee and Martin, 2012). For high pressure humidifiers, compressed air is used to split water into tiny droplets which then propelled through the greenhouse in an air stream. Pulsators are generally used for irrigation, but are sometimes used for overhead irrigation, and they also serve to humidify the greenhouse (Venter, 2010). Pulsator drops are thus much larger than high pressure humidifiers, but can still be as successful and economical.

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2.3.4 Carbon dioxide control

As previously described, carbon dioxide (CO_2) enrichment systems have shown positive effects on plant growth for many years. CO_2 enrichment is usually a source of fuel combustion. A brief description of some CO_2 enrichment systems that are available are given below (Kenig, 2000):

- Liquid CO_2: Pure CO_2 is pumped from containers to the greenhouse and is the purest type of CO_2 enrichment. Like many other systems, it does not create the greenhouse heating effect. The disadvantage of this system is the high cost of supplementing and transporting gas containers.
- Fuel combustion: Burning liquid kerosene, propane-butane gas or natural gas produces CO_2 as part of the gas emissions from the burners. Heat is also produced by this type of operation and is often the primary reason for the installation. The constraint of these systems is that CO_2 can only be dosed when heat is also required in the greenhouse. The choice of the type of fuel is generally based on availability and cost per unit and the purity of the gas emissions.

Dosing should be specifically controlled according to light levels, temperature and ventilation in greenhouses, to ensure the efficiencies are optimized.

2.4 Greenhouse Designs

Not every system is cost-effective in every location. A large range of different requirements have to be incorporated when it comes to greenhouse design. The following factors should be considered when designing greenhouses (Venter, 2010):

a) Sunlight utilization
b) Costs
c) Sufficient ventilation
d) Easily accessible
e) Low maintenance and operational costs
f) Efficient energy use
g) Adaptability for automation

The choice of crop also influences the type of greenhouse and climate required. A favourable economic outcome in the end determines the size of investment and the greenhouse design and control systems. A logical and model-based approach to greenhouse design can be described in Figure 2.1. The diagram illustrates the logic of the eight critical components that should be taken into account during the design process of a greenhouse. It illustrates that if the economic model does not result in positive and maximum financial results, the greenhouse design should be revisited until this is achieved.

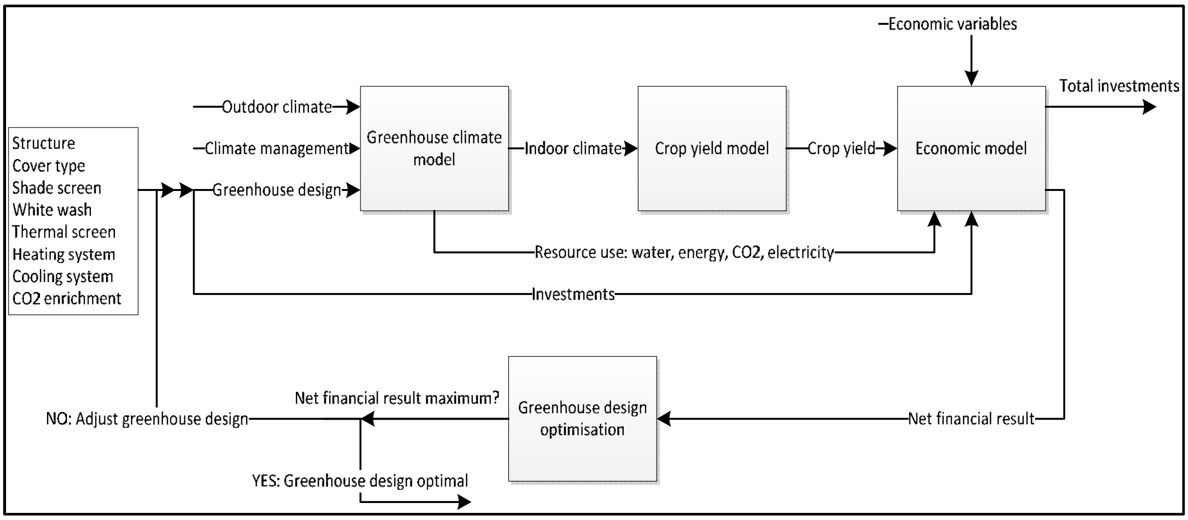

Figure 2.1An overview of a model-based greenhouse design method (Vanthoor *et al.*, 2011a)

2.4.1 Greenhouse shapes and sizes

Greenhouses can be categorized, based on shape and size, amongst other things. The different design form and typical application are listed and described below (Venter, 2010):

a) Span-roofed greenhouses: These greenhouses are mostly used for extensive commercial operations. They have vertical walls and pitched roofs and are generally used with cover materials like glass and polycarbonates.
b) Domestic greenhouses: Domestic greenhouses are generally the shape of span-roof greenhouses, but are usually 1.65 m-2.25 m high, between 1.8 and 3 m wide and 3-6 m long.
c) Mobile greenhouses: Mobile greenhouses were designed in Europe in order to be disassembled and moved around to different locations and to accommodate crops that have to be covered during the night and open during the day.

d) Curvilinear structure: These greenhouses are usually used in very cold countries and the structures are designed so that the different surfaces of the greenhouse can be faced more or less perpendicular to the sun for maximum absorption during certain times of the day.
e) Lean-to types of greenhouses: Lean-to greenhouses are built against another building and utilize the wall of the building as heat storage. They are generally used in colder countries and for small operations.
f) Plastic tunnels: These were only introduced towards the end of the twentieth century. They became popular because of their low cost and ease of construction and are used in large commercial operations. Different qualities and thickness of plastic are available. Tunnels are available in 6, 7, 8, 10 and 12 m widths and in 30 to 60 m lengths and they can be constructed as single span (standalone) or multi-span (joined) structures. The most common shapes of single span greenhouses studied by researchers are even-span, uneven-span, vinery, modified arch and quonset types (Sethi and Sharma, 2007). Double plastic layer tunnels are also often used for better insulation. Air is pumped in between the two layers and serves as extra insulation.
g) Shade netting greenhouses: Crops can also be successfully grown commercially under shade netting, especially in warmer climates. Shade netting has a longer life-span than polyethylene, but is used in less expensive structures. Different colours, such as green, black and white and densities of netting are available and various designs can be used for structures such as tunnels and multi-span designs
h) Height: Recent focus has been on developing greenhouses with higher gutter heights. Glass greenhouses are constructed with a gutter height of 6 m and plastic covered greenhouses can go up to 3.5-4 m. This has been shown to significantly improve the growing environment for greenhouse crops (Connellan, 2002).

The structural design of the greenhouse also influences the energy efficiency of a system. A study done by Djevic and Dimitrijevic (2009) showed that the type of structure can influence energy input per kg of a product, energy efficiency and the productivity of a system and indicates that multi-span greenhouses are more energy efficient than single tunnel greenhouses.

2.4.2 Design for greenhouse cooling

Certain climate factors can influence the structural design of the greenhouse. These factors are normally related to the heating and cooling requirements of the greenhouse. Only greenhouses that are used in commercial operations will be discussed. Different shapes, orientation and vent configurations are used when designing for natural ventilation and these influence the ventilation rate and cooling effectiveness. Greenhouses are constructed in multi-span or single-span with continuous roof, side or roof and side ventilation (Figure 2.2,Figure 2.3, Figure 2.4,Figure 2.5). Greenhouses are also designed with a natural ventilation system in combination with insect netting over the ventilation openings.

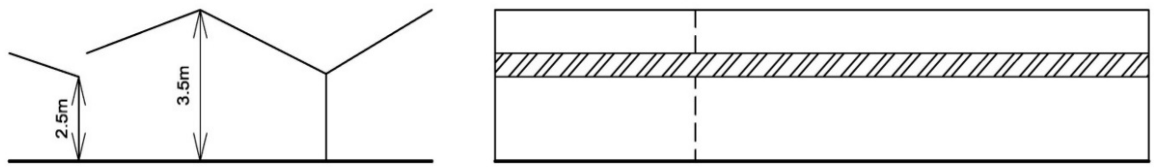

Figure 2.2 Front and side view of a greenhouse with one side continuous roof ventilation greenhouse.

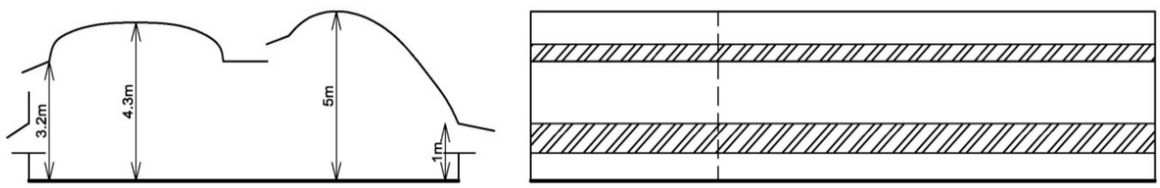

Figure 2.3 Front and side view of a greenhouse with continuous roof and side ventilation greenhouse.

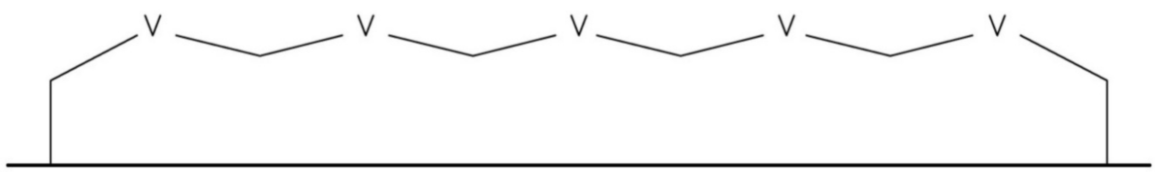

Figure 2.4 Front view of a greenhouse with continuous roof (double) roof ventilation greenhouse

Greenhouses have to be specifically designed for forced ventilation and evaporative cooling. Greenhouses are constructed in multi-span or single-span, with exhaust fans and openings or with evaporative cooling pads and fans (Figure 2.6, Figure 2.7, Figure 2.8).

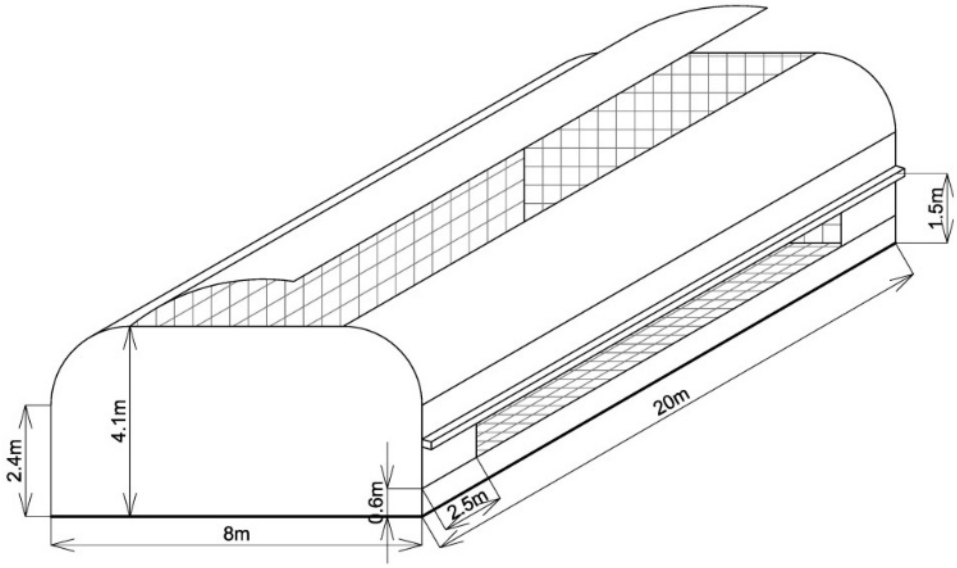

Figure 2.5 Illustration of a naturally ventilated greenhouse with insect netting

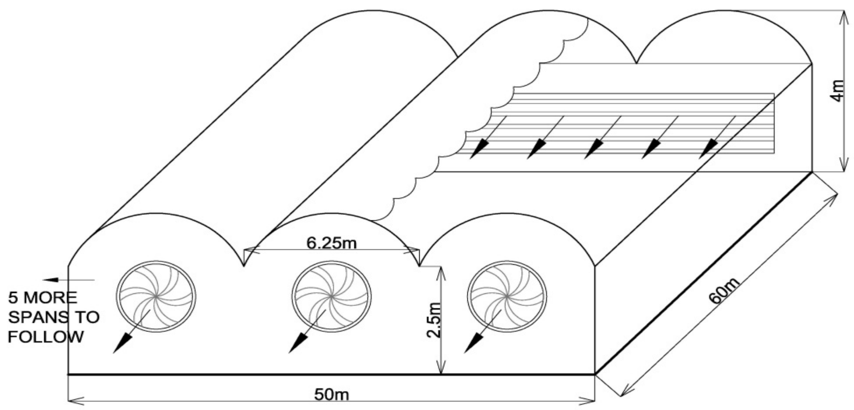

Figure 2.6 A typical greenhouse with exhaust fans and openings

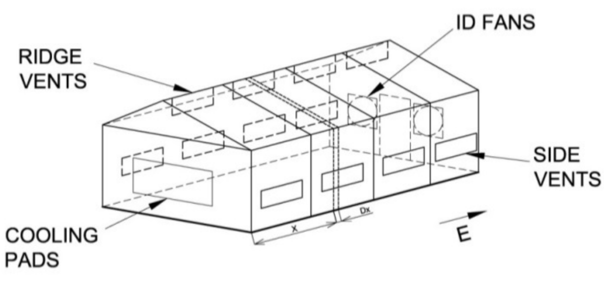

Figure 2.7 Illustration of a greenhouse with forced and natural ventilated combination

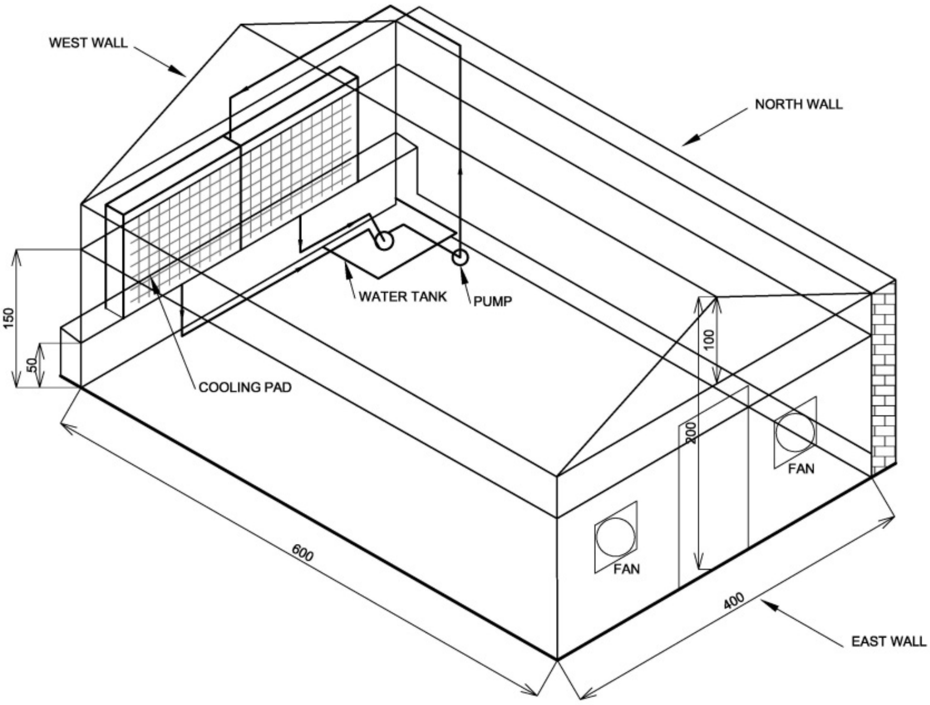

Figure 2.8 Illustration of a pad and fan evaporative cooled greenhouse

It is clear from this analysis that several factors such as costs, outside climate conditions, choice of crop and choice of cooling systems are to be considered when the shape and structure of the greenhouse is designed.

2.5 Greenhouse Micro-climate Modelling

Several different greenhouse climate models have been developed over the years in order to ultimately evaluate or predict the performance of greenhouse designs. Predictions of micro-climatic conditions (temperature, vapour pressure and relative humidity) can be achieved by using experimental data or by simulations, using pure mathematical models (Abdel-Ghany and Kozai, 2006b). Simulations and mathematical models are preferable because they are cheaper, quicker and more flexible (Wang and Boulard, 2000). Ideally, the coefficients of models should be calibrated with experimental work in order to use them in different conditions and situations (Baptista *et al.*, 2010). Certain developed models, based on energy and mass balance equations, can be classified as static, dynamic or homogeneous models (Abbes *et al.*, 2010). Other, more complex, models are combined with crop requirements and include air state variables, which measure the system performance over time or heterogeneous models (Abbes *et al.*, 2010) that are based on computational fluid dynamics (CFD) that can perform two- or three-dimensional numerical analysis of equations (Kittas and Bartzanas, 2007). Some models focus on specific phenomena, for instance, natural ventilation, forced ventilation, evaporative cooling, insect netting and heating. More recent studies on greenhouse climate control have focused on addressing optimizing energy usage, water consumption and CO_2 dosing. Some of the different models are described in the following section.

2.5.1 Computational fluid dynamics

Computational fluid dynamics (CFD) is used more often now for heterogeneous modelling in many horticultural and agricultural applications (Reichrath and Davies, 2002). CFD is a simulation approach that evaluates the behaviour of different types of fluid flow, heat and mass transfer (Pontikakos *et al.*, 2005; de la Torre-Gea *et al.,* 2011; Lee *et al.*, 2013) or chemical reactions (Bartzanas *et al.*, 2013). The domain in which the simulation takes place (for example, the greenhouse and the environment) is divided into small cells and conservation equations are applied to each volume and variables are calculated from there (Pontikakos *et al.*, 2005). This type of modelling approach provides accurate simulations for a wide range of different geometrical and boundary conditions of greenhouses, enabling improvement in greenhouse designs and control for specific applications (Boulard *et al.,* 2002) and they can characterize non-steady ventilation rates, temperature and humidity inside the greenhouse.

The following equation describes the 3-D conservation equations for steady fluid flow characteristics (Kittas and Bartzanas, 2007, OuldKhaoua *et al.*, 2006):

$$\frac{\partial(U\phi)}{\partial x} + \frac{\partial(V\phi)}{\partial y} + \frac{\partial(W\phi)}{\partial z} = \Gamma\Lambda^2\phi + S_\phi \qquad (2\text{-}1)$$

Where: U, V, W = three components of the velocity vector; ϕ = the concentration of the transport quantity of components in either momentum, mass or energy equations; x, y, z = Cartesian space coordinates;Γ= diffusion coefficient; Λ = the velocity gradient; andS_ϕ = the source term.

CFD simulations for natural ventilation in greenhouses have been performed for different reasons. Ventilation rates and air movement have been studied for different roof vent configurations in greenhouses (Bartzanas *et al.,* 2004; Baeza *et al.,* 2006). Insect screens and the effect on greenhouse ventilation and air velocities have been predicted, using CFD modelling (Teitel, 2009; Majdoubi *et al.,* 2009).

Franco *et al.* (2011) developed and validated a CFD model that optimizes pad and fan designs and the geometry of the pads, by evaluating different wind speeds and water flows on pressure drop over the pads. Humidifying and dehumidifying a greenhouse with fogging and refrigerative humidifiers and the humidity distribution in a single-span greenhouse were studied by Kim *et al.* (2008). Forced ventilation (Fidaros *et al.,* 2008) and the effect of solar radiation distribution and climatic behaviour in a greenhouse with a tomato crop have been numerically analysed, using CFD. Moreover, CFD simulations have also been used for describing climate control and buoyancy forces in greenhouses with pipe heating and electric air heaters (Bartzanas *et al.,* 2013).

CFD simulation reduces the cost and increases the quality of complex research involving fluid flows, heat and mass transfer and other reactions and is a well-proven tool (Lee *et al.,* 2013). However, experimental data is vital to validate the accuracy and reliability of CFD models, and to date, no standard for validating CFD models have been developed (Lee *et al.*, 2013). The result is that experimental results often do not correspond with the model. CFD modelling requires large computer memory and specific software that might limit the widespread use of the model (Lee *et al.,* 2013).

2.5.2 Static and dynamic micro-climate models

Homogenous modelling (static and dynamic modelling) are based on energy and mass balance equations and they generally assume steady state conditions and uniform distribution inside a greenhouse. Limitations in these types of models may be because the greenhouse areas cannot always be assumed uniform (Teitel *et al.*, 2008, Bournet and Boulard, 2010).

2.5.2.1 Natural ventilation models

Different natural ventilation models have been developed and calibrated to predict the ventilation rate in a greenhouse. The effect on crop, vent-opening configuration, along with the two major forces (wind and stack forces), are all considered as the model parameters (Boulard *et al*., 1997). A summary of natural ventilation models reviewed in this study is given in Table 2.1below. These equations have been widely used to evaluate the effect of different vent configurations on ventilation and air exchange in a greenhouse.

Table 2.1 Natural ventilation models

Model	**Eq. No**	**Ventilation type**	**Reference**
$G = \frac{S}{2} C_d \left[2g\left(\frac{\Delta T}{T}\right)\left(\frac{H}{2}\right) + C_w U^2\right]^{0.5}$	2-2	Roof or side	Boulard *et al.* (1997)
Where: G= Volumetric flow rate ($m^3.s^{-1}$); S= Vent open area (m^2); C_d= Discharge coefficient (dimensionless); g= Gravity constant; T= Air Temperature (K); ΔT = temperature difference between inside and outside (K); H = Vertical distance separating the openings for air inflow and outflow (m); C_w= Wind effect coefficient (dimensionless); and U = wind speed ($m.s^{-1}$)			
$G = \frac{S_T}{2} C_d \left[2g \in^2 \left(\frac{\Delta T}{T}\right)\left(\frac{H}{2}\right) + C_w U^2\right]^{0.5}$	2-3	Roof and side	Boulard *et al.* (1997)
Where: G, C_d, g, T, ΔT, H, C_w and U is the same as above, and: S_T = Total roof and side ventilation area $\varepsilon = 2\sqrt{2b}/(1+b)(1+b^2)^{05}$; b= $\frac{S_R}{S_S}$;			
$G = \frac{S}{2} C_d C_w^{0.5} u_w$	2-4	Roof or side	Kittas *et al.* (1996)

Model	Eq. No	Ventilation type	Reference
Where: G, C_d, S, $C_w$is the same as above; and U_w = wind speed across openings $m.s^{-1}$			
$$N = \left(\frac{3600}{V}\right) C_d \left[\left(\frac{A_r A_s}{\sqrt{{A_r}^2 + {A_s}^2}}^2 \right) 2gx \left(\frac{T_i - T_e}{T_i} \right) + \left(\frac{A_r + A_s}{2} \right)^2 C_w {u_e}^2 \right]^{05}$$	2-5	Roof and side	Fatnassi *et al.* (2003), Kittas *et al.* (1997); Mashonjowa *et al*. (2013)
Where: N= air renewal rate (h^{-1}); V= Volume of the greenhouse (m^3) T_i, T_e = internal and external temperature (K) x=height (m) S_R or A_R= roof vents area(m^2), S_s or A_S= Side vents area (m^2); and U_e= wind speed ($m.s^{-1}$)			

C_d and C_w(discharge and wind effect coefficient) are descriptive values of each type of greenhouse and can be calculated by using experimental data and fitting it into the models.

These equations have been widely used to evaluate the effect of different vent configurations on ventilation and air exchange in a greenhouse (Ganguly and Ghosh, 2009; Mashonjowa *et al*., 2013). However, these equations and models do not take into account physiological fluxes and solar radiation and cannot predict internal relative humidity, all of which are critical factors for successful greenhouse design and crop production.

2.5.2.2 Other models for temperature and humidity prediction

Table 2.2 below describes more models that were developed to predict air temperature and relative humidity, with basic descriptions of the types of control systems applied to a greenhouse. These models are designed to optimize cover properties and ventilation rates of a greenhouse with side and roof ventilation openings, as well as insect netting (Table 2.2, Eq. 2-7 - 2-9).

Table 2.2 Summary of temperature and humidity models

Model	**Eq. No**	**EP**	**Control system applied**	**Reference**
$m_g C_p \frac{dT_g}{dt} = Q_{available} - UA_{covering}(T_g - T_a) - \dot{m}_v C_p (T_g - T_a)$	2-6	T_g	Natural ventilation, shading	Ganguly and Ghosh, (2009)
where: m_g = greenhouse air mass; T_g= temperature of the greenhouse air (K); T_a= ambient /outdoor temperature (K); Q = total heat flow rate (W); $\dot{m}_v$= air mass flow rate caused by natural ventilation; and C_p = specific heat of air in J.kg^{-1} K^{-1}				
$P_c - h_{csky,LWR}(T_c - T_{sky}) = h_{cg,CON}(T_c - T_g) - \lambda E_{cg}$	2-7	T_c	Natural ventilation, insect screens	Impron *et al.* (2007)
$h_{ga,CON}(T_g - T_a) + h_{ga,VEN}(T_g - T_{out}) = P_g - h_{cg,CON}(T_c - T_g)$	2-8	T_g		Impron *et al.* (2007)
$h_{ga,LAT}(e_g - e_a) = \lambda E_{cg}(S, T_g, T_c, e_g)$	2-9	VP		Impron *et al.* (2007)
Where: P_c= solar radiation absorbed by greenhouse cover; P_g= solar radiation flux to the greenhouse air; T_c and T_{sky}= temperatures of the crop canopy and the sky (K); E_{cg}= crop transpiration (kg.m^{-2}.s^{-1}); λ=latent heat (J.kg^{-1}) $h_{csky,LWR}$= the thermal conductance between greenhouse cover and the sky (W.m^{-2}.K^{-1}); $h_{cg,CON}$= thermal conductance between the crop and greenhouse in W.m^{-2}.K^{-1}, $h_{ga,CON}$ = overall sensible thermal conductance between the greenhouse and outdoor via the plastic cover W.m^{-2}.K^{-1}, $h_{ga,VEN}$= sensible thermal conductance between greenhouse and outdoor air by ventilation in W.m^{-2}.K^{-1}, $h_{ga,LAT}$ = thermal conductance by ventilation in W.m^{-2}.Pa^{-1}, e_g= outdoor air water vapour pressure in Pa; e_a= indoor air water vapour pressure in Pa; and S= outdoor radiation (global) in W.m^{-2}				
$(K_s + K_c)\Delta T + K_L \Delta e = \mu S - Q_m$	2-10	T_g	Natural ventilation,	Kumar *et al.* (2010)

Model	Eq. No	EP	Control system applied	Reference
		VP	shading	
$\left(\delta(T_g) - (T_a)\right)\Delta T + \left[\frac{\gamma(r_s + r_a)}{\rho C_p I_{LA}} K_L + 1\right]\Delta e - \delta(T_g)\Delta T_{fo} = D_o$	2-11	T_c		Kumar *et al.* (2010)
$\frac{\rho C_p I_{LA}}{r_a}\Delta T - K_L \Delta e - \frac{\rho C_p I_{LA}}{r_a}\Delta T_{fo} = -R_n$	2-12			Kumar *et al.* (2010)

Where:
K_s= sensible heat transfer coefficient in (W.m^{-2}.K^{-1});
K_c= overall heat transfer coefficient (W.m^{-2}.K^{-1});
K_L= latent heat transfer coefficient (W.m^{-2}.K^{-1}).
ΔT= the internal-external difference in temperature in Kelvin;
D_o= vapor pressure deficit of the external air;
ΔT_{fo} = the temperature difference between the crop canopy and external air
Δe = vapor pressure difference (VPD) between the greenhouse and outside (Pa);
μ= solar heating efficiency (dimensionless);
Q_m= heat transfer rate of the soil in W.m^{-2};
δ= saturation air water vapour pressure gradient in Pa.K^{-1};
γ = psychometric constant in Pa.K^{-1};
r_s = stomatal resistance in s.m^{-1};
r_a = aerodynamic resistance in s.m^{-1};
ρ= air density in kg.m^{-3};
C_p = specific heat capacity of the air J.kg^{-1}.K^{-1};
I_{LA} = is the leaf area index (dimensionless); and
R_n = net solar radiation inside (W.m^{-2})

$\lambda E_{cg} = \frac{(K_1 K_s + K_2 \delta)\Delta T + K_2 D_o}{1 - K_1 + \frac{K_2}{K_L}}$, where $K_1 = \frac{\delta}{\delta + \gamma(1 + \frac{r_s}{r_a})}$ and $K_2 = \frac{2 I_{LA} \rho \frac{C_p}{r_a}}{\delta + \gamma(1 + \frac{r_s}{r_a})}$	2-13 2-14 2-15	E_{cg}	Natural ventilation, heating and cooling	Boulard and Wang (2000)
Where the parameters are defined in the previous section (Kumar *et al.*2010)and $K_1$and K_2 are constants				

<table>
<tr><th>Model</th><th>Eq. No</th><th>EP</th><th>Control system applied</th><th>Reference</th></tr>
<tr><td>$$A_c(SC+RC)-Q_{c-am}-Q_{c-a}-2QE_c = \left(mC_p\right)_c \frac{dT_c}{dt}$$</td><td>2-16</td><td rowspan="3">T_g, T_c, T_p, ω_a</td><td rowspan="3">Natural ventilation, fogging</td><td rowspan="3">Abdel-Ghany and Kozai (2006)</td></tr>
<tr><td>$$Q_{f-a}+Q_{c-a}+Q_{p-a}+Q_{pot-a}-Q_{vs} - \kappa(\beta\dot{m}_w) = (mCp)_a \frac{dT_g}{dt}$$</td><td>2-17</td></tr>
<tr><td>$$\dot{m}_{ven} = \frac{A_f(G_s\tau_{sc})-UA_c\left(T_g-T_a\right)-A_fD}{I_a-I_{am}}$$</td><td>2-18</td></tr>
<tr><td colspan="5">ω_a= absolute humidity of the internal greenhouse air (kg of vapour per kg of dry air);
T_p = plant temperature ;
SC, RC = solar and thermal radiation respectively absorbed by the cover (W.m^{-2})
Q_{c-am}= convective heat transfer between cover and ambient;
Q_{c-a}= convective heat transfer between cover and internal air
Q_{f-a}= convective heat transfer between the floor and internal air;
Q_{p-a}= convective heat transfer between plants and internal air;
Q_{pot-a}= convective heat transfer between the pot soil surface to the internal air;
Q_{vs}= sensible heat associated with ventilated air during the natural ventilation process;
QE_c= emission from the cover surface;
κ = latent heat due to vaporization of water (J.kg^{-1})
β = fraction of the evaporated fog;
$\dot{m}_w$ = water flow rate of fogging water;
$\dot{m}_{ven}$ = natural ventilation rate of moist air in kg.s^{-1};
A_c= surface area of the greenhouse cover (m^2);
A_f = surface area of the greenhouse floor (m^2);
G_s = solar radiation flux (W.m^{-2});
τ_{sc}= dimensionless transmittance of cover to solar radiation;
U = overall heat transmission coefficient;
D = soil heat flux; and
I_a ,I_{am}= enthalpy of moist air inside and outside the greenhouse respectively</td></tr>
<tr><td>$$\rho_a c_a v_a \frac{\partial T_g}{\partial t} = \alpha_a S + Q_{loss} + Q_{s-a} + Q_{p-a} + Q_{ven} + Q_{heat}$$</td><td>2-19</td><td>T_g</td><td>Hot water heating</td><td>Du et al., (2012)</td></tr>
<tr><td colspan="5">S = net solar radiation entering the greenhouse;
Q_{loss}= heat loss rate from the greenhouse;
Q_{s-a} = heat flux between the soil and greenhouse air;
Q_{p-a}= heat flux between the plants and greenhouse air;
Q_{ven} = heat flux caused by greenhouse ventilation;
Q_{heat} = heat supply rate by the heating system;
T_g, ρ_a, c_a, v_a = air temperature, specific heat, greenhouse air density, specific heat and specific volume, respectively; and
α_a = net solar radiation absorption coefficient by air in the greenhouse</td></tr>
</table>

Model	Eq. No	EP	Control system applied	Reference
$a\alpha\tau G_0 + b\delta(T_0)\Delta T - (b+K_1)\Delta e + bD_0 + \lambda W = 0$	2-20	Energy balance	Natural ventilation and fogging	Boulard and Baille (1993)
$a\alpha\tau G_0 + (b+\beta)\delta(T_0)\Delta T - (b+\beta+K_1)\Delta e + (\beta+b)D_0 = 0$	2-21			
$\Delta T = \dfrac{\left[\left(\frac{b+K_1}{K_1}\eta G_0\right) - bD_0 - a\alpha\tau G_0 - F\right]}{\left[b\delta(T_0) + \frac{(b+K_1)(K_s+K_c)}{K_1}\right]}$	2-22	ΔT		
$\Delta e = \dfrac{[\eta G_0 - \Delta T(K_s+K_c)]}{K_1}$	2-23	VP		
$\lambda E_t = K_1\Delta\mathrm{e} - \mathrm{F}$	2-24	E_t		
$K_c = A + BV$	2-25			
$K_s = \frac{\rho C_p V_g N}{3600 S_g}$	2-26			
$K_1 = \frac{\gamma\rho\lambda V_g N}{3600 S_g}$	2-27			
$N = \left[\varsigma\left(\frac{S_o}{2}\right)C^{05}\ V\right]\left(\frac{3600 S_g}{V_g}\right)$	2-28			

K_s= sensible heat transfer coefficient in (W.m^{-2}.K^{-1});
K_c= overall heat transfer coefficient (W.m^{-2}.K^{-1});
K_1= latent heat transfer coefficient (W.m^{-2}.Pa^{-1});
A and B = coefficients;
F = latent heat of misted water;
ρ= air density in kg.m$^{-3;}$
C_p= specific heat capacity of the air J.kg^{-1}.K^{-1};
V = Wind speed (m.s^{-1});
γ= conversion factor between air and vapour content;
λ=latent heat of vaporization;
ζ= discharge coefficient;
V_g=greenhouse volume (m^3);
N=Greenhouse ventilation rate (h^{-1});
S_g= ground area (m^2);
S_o = surface of the vent area (m^2.m^{-2})
ΔT= the internal-external difference in temperature in Kelvin;
T_o= outside temperature in Kelvin;
D_o= vapor pressure deficit of the external air (kPa);
Δe = vapor pressure difference (VPD) between the greenhouse and outside (Pa);
η= solar heating efficiency (dimensionless);
b and a= functions of the canopy resistances (s.m^{-1});
α= canopy absorption coefficient for solar radiation (dimensionless);

Model	Eq. No	EP	Control system applied	Reference
τ= greenhouse global transmission; δ= saturation air water vapour pressure gradient in Pa.K^{-1}; G_o= Global outside radiation (W.m^{-2}); and F= latent heat of vaporization of sprayed water (W.m^{-2})				

Eq. No = Equation number, EP = estimated parameter, VP = Vapour Pressure

Kumar *et al.* (2010) also developed models to specifically predict air vapour pressure, internal air temperature and crop canopy temperature on three different greenhouses with roof and side ventilation. The model takes into account solar radiation absorbed and transferred by the crop canopy and greenhouse cover and ignores heat transfer of the soil. These models were validated with experimental data and found to be reliable and accurate (Table 2.2, Eq.2-10 - 2-11).

Boulard and Wang (2000) developed a dynamic model that determines greenhouse crop transpiration. The parameters are discussed and different greenhouse types and crops are taken into consideration (Table 2.2, 2-13).

The dynamic model (Eq. 2-16) developed by Abdel-Ghany and Kozai (2006a) determines the air, crop, greenhouse cover and floor temperatures, as well as relative humidity in a fog-cooled and naturally-ventilated greenhouse (Table 2.2). On the other hand, Du *et al.*(2012) developed and validated a simulation model (Eq. 2-19) for greenhouse heating, using heat-pipe system with a thermal storage tank. Air and soil temperatures were predicted (Table 2.2).Another simplified model (Eq. 2-22) to predict inside RH, temperature and crop transpiration and temperature in a greenhouse with natural ventilation fogging was developed by Boulard and Baille (1993) (Table 2.2).

2.5.2.3 Forced ventilation models

The relationship between greenhouse ventilation and greenhouse temperature (V and T) has also been examined within a closed multi-span greenhouse with forced ventilation. The effect of ventilation rate caused by the fans, external wind speed, external air temperature, solar radiation and the transmissivity of the cover material on greenhouse air temperature, has been modelled and validated. The following relation was derived from a greenhouse energy balance equation (Kittas *et al.,* 2005):

$$T_i = T_o + \frac{R_{s,o}\tau(1-\alpha)}{\left(\frac{A_c}{A_g}\right)(K_1+K_2u)+\rho C_p V_a} \quad (2\text{-}29)$$

where T_i/T_o= inside and outside temperatures, respectively (˚C); $R_{s,o}$= outside solar radiation (in Wm^{-2}); τ=greenhouse transmissivity to solar radiation; α = latent heat transfer rate to radiation ratio; A_c is the greenhouse cover surface area (m^2); A_g= greenhouse ground surface area (m^2); $K_1$and K_2 are constants; μ= outside air speed ($m.s^{-1}$); ρ= air density (kg air per m^3 air); C_p = specific heat of air at a constant pressure ($Jkg^{-1}°C^{-1}$);$V_a = \frac{Q}{A_g}$ is the greenhouse ventilation rate for the floor area ($m^3.s^{-1}.m^{-2}$); Q = ventilation flow rate (m^3[air]$.s^{-1}$). The model assumes a regularly transpiring crop. Relative humidity in the greenhouse is not predicted by this model, which is a critical factor to consider.

Ganguly and Gosh (2007) developed and validated a model (Eq.(2-30)) predicting the internal temperature for cooling and ventilation through a pad and fan greenhouse under steady-state conditions. Shading was also applied and the effect of plant heat absorption is taken into account. The Ganguly and Gosh (2007) model is presented as follows:

$$T_x = \left(T_a + \frac{A}{B}\right) + \left(T_{pad} - T_a - \frac{A}{B}\right) e^{-Bx} \quad (2\text{-}30)$$

where:

$$A = \frac{(1-C\alpha)(S_c(I_{tc.N}+I_{tc.S})P+S_{sw}I_d 2H)}{V\rho C_p} \quad (2\text{-}31)$$

and

$$B = \frac{2U(P+H)}{V\rho C_p} \quad (2\text{-}32)$$

Where:

T_x= the internal greenhouse temperature, distance x (in meter) from the cooling pad in Kelvin; T_a= ambient temperature in (K); T_{pad} = air temperature through the cooling pad (K); A = greenhouse solar heat load coefficient; B = heat loss coefficient through greenhouse cover; C= fraction of surface area covered by crop; α = plant absorptivity; S_c

and S_{sw} are shading factors for the canopy and the side walls, respectively (1 for zero shading and 0 for full shading);I_{tcN} and I_{tcS} = total radiation heat transfer rate of the north and south canopy respectively in W.m^{-2}; I_d= dispersed radiation heat transfer rate in W.m^{-2}; H = greenhouse height in m; V = ventilation rate of the fan in m^3.s^{-1}; ρ = air density in kg.m^{-3}; C_p= specific heat capacity of the air; U = the overall heat loss coefficient of the greenhouse in W.m^{-2}.K^{-1} ; P = is the half perimeter distance of the cover in m. The model assumes that the relative humidity remains constant and does not predict it.

Kittas *et al.* (2003) also developed and validated another model (Eq.(2-33)) that predicts the internal air temperature profiles in a greenhouse fitted with evaporative cooling pads, fans and shading in the greenhouse.

$$T_{in}(x) = T_o + \left[-\eta\left(T_o - T_{o,w}\right) - A_1\right]e^{-A_2 x} + A_1 \qquad (2\text{-}33)$$

where

$$A_1 = \frac{\left[\tau(1-\alpha)R_g\right]L}{V_p C_p} \qquad (2\text{-}34)$$

and

$$A_2 = \frac{K_c L}{V_p C_p} \qquad (2\text{-}35)$$

and

$$\eta = \frac{T_o - T_{pad}}{T_o - T_{o,w}} \qquad (2\text{-}36)$$

Where:

$T_{in}(x)$ = internal temperature (in ˚C) at a distance x in the length of the greenhouse in meter; T_o = the outside air temperature in ˚C; η = the cooling efficiency of the system; $T_{o,w}$ = outside wet bulb temperature in ˚C; T_{pad}= dry bulb air temperature leaving the pads in ˚C; $A_1$and A_2= coefficients; R_g= the outside global solar radiation in W.m^{-2}; L = the greenhouse width in meter; V = Ventilation rate in m^3.s^{-1}; C_p= specific air heat in J.kg^{-1}.˚C^{-1}; K_c= the heat loss coefficient of the greenhouse cover; α = coefficient that represents the influence of solar radiation/energy on the plant transpiration.

The coefficients that are critical for accurate prediction in this model are K_c and α and are determined by optimizing experimental data. Soil heat transfer and evaporation are neglected in this model. The response of plant physiology to local physical conditions is not incorporated in this model.

Fuchs *et al.* (2006) developed and validated another model (Eq. (2-37)) that predicts average greenhouse temperature, crop transpiration (Eq.(2-38)) and water vapour pressure (Eq. (2-39)) in an evaporative cooled greenhouse.

$$T_i = T_p + \frac{r_X(R_n - E)}{\rho C_p} \tag{2-37}$$

where

$$E = \frac{\rho C_p e(T_c) - e_p}{\gamma(r_a + r_s)} \tag{2-38}$$

and

$$e_i = e_p + \frac{\gamma r_X E}{\rho C_p} \tag{2-39}$$

Where:

T_i= internal greenhouse temperature in ˚C; T_p = the temperature of air leaving the cooling pads in ˚C;T_c= temperature at crop canopy in ˚C; r_X= ventilation resistance in s.m^{-1}; R_n= the net radiation of the foliage in W.m^{-2}; E= heat transfer rate of the crop in W.m^{-2} ; ρ= the outside air density in kg.m^{-3}; $e(T_c)$= saturated water vapour pressure at the crop in kPa; γ= psychrometric constant ≈ 0.0667 kPa.K^{-1}; r_a and r_s = the total convective resistance and crop foliage resistance to water vapour diffusion respectively, in s.m^{-1}; e_i= internal greenhouse vapour pressure in KPa ;e_p= air vapour pressure of the air leaving the cooling pad in kPa.

These models were not developed for conditions of South Africa. To use these models, the coefficients need to be optimized, using experimental data obtained under South African conditions.

2.6 Agro climatic conditions in South Africa

As mentioned in the previous sections, the choice of greenhouse design depends largely on the location and the associated agro-climatic conditions. Climate conditions range from Mediterranean in the south-west side, moderate in the central plateau and subtropical towards the north-east side of the country. There are four main climatic zones, including the desert zone, or hyper-arid and arid zones; the semi-arid zone; the subtropical wet or humid zone; and the Mediterranean, or dry sub-humid winter rainfall region (Benhin, 2006).

The desert, or arid region, generally borders the Northern Cape Province and north-eastern parts of the Western Cape Province. The average temperatures during the winter and summer in these areas are 10.2˚C and 23.8˚C respectively (Benhin, 2006). The semi-arid zone is comprised of Limpopo, Mpumalanga, the North-West, Free State, the western parts of KwaZulu-Natal (KZN), the Eastern Cape and the northern parts of the Western Cape. The mean long term temperatures during winter and summer in these areas range between 9.5 - 15.4˚C and 18.4 - 22.8˚C, respectively, with minimum and maximum temperatures of 8.9 and 22.8˚C (Benhin, 2006). Within the semi-arid zones, extremely cold winter temperatures are experienced in certain areas in the Free State, with temperatures dropping to 1˚C in winter. Parts of in Limpopo have warmer winters and extremely warm summers that can reach up to 45˚C.

The coastal strip of KZN and the Eastern Cape are classified as sub-tropical wet zones. The average 24-hour temperatures during winter and summer in these areas are 12.3˚C and 19.1˚C, and minimum and maximum temperatures are 9.1˚C and 21.3˚C respectively (Benhin, 2006). The daily temperatures in Durban (KZN) in summer average at 32.0˚C.

The southern coastal strip of the Western Cape with its winter rainfall is classified as a Mediterranean region. The mean temperatures for these areas range between 20.8˚C in summer and 10.8˚C in winter, with minimum temperatures of 9.5˚C in winter and 19.4˚C in summer. Maximum temperatures during summer for these areas reach 21.3˚C (Benhin, 2006).

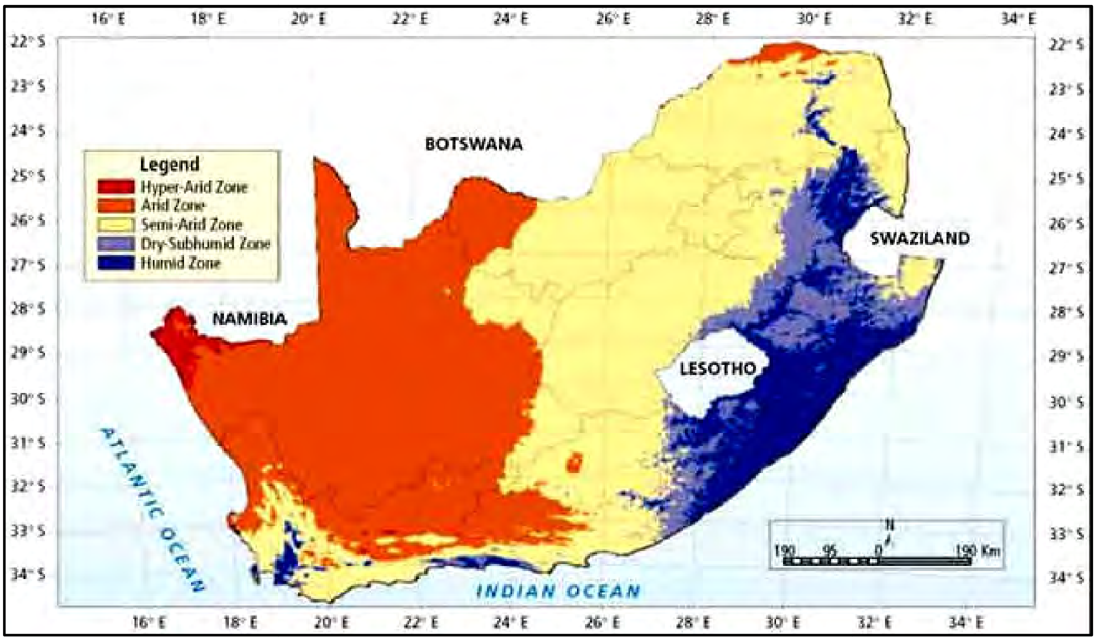

Figure 2.9Agro-climatic areas of South Africa (FOA, 2005)

South Africa generally has ideal outdoor growing conditions and greenhouses were initially only used in South Africa for crop protection against excessive rains and hail. Another big stumbling block for growers in South Africa is the limited availability of water and crop cover. Hydroponic crop production has been implemented to improve the efficiency of water-use. Greenhouse production has also implemented, due to the significant fluctuations in temperature throughout the different regions, to optimize the indoor climatic conditions and therefore optimizes crop production (de Visser and Dijkxhoorn, 2012). Greenhouse designs and choice of crop are related to the differences in climate with respect to temperature, humidity and radiation. South Africa generally has high temperatures and the management of supra-optimal in local temperatures in the greenhouses remains one of the biggest challenges in the engineering of greenhouse systems. Johannesburg, Durban and Cape Town are the main greenhouse production areas in South Africa.

2.7 Greenhouses in South Africa

The first vegetable production in South Africa was started by the Dutch in 1653. The flower industry in South Africa began between the 1920's and 1930's (de Visser and Dijkxhoorn, 2012). The first flower crops were cultivated under protection in South Africa during the 1960's, with vegetables following in the 1970's and 80's.

Farmers in South Africa are, generally, categorized as follows (de Visser and Dijkxhoorn., 2012):

a) Commercial farmers,
b) Emerging (small scale) farmers, and
c) Subsistence farmers – focusing on only supplying food only for their own consumption.

Table 2.3below also describes the general classification of these types of farmers in relation to the type of greenhouse technology and production systems that are being used. It is also compared to the standard quality grown in the United States of America (USA). Each of these types of farmers might at some stage have the opportunity to make a transition towards improved crop productivity. It provides typical size, cover type used, production process, cooling systems and farmers associated with the level of technology used in greenhouses. Choosing the applicable technology for a region then becomes critical.

Table 2.3 Approximate classification of South African protected horticulture (de Visser and Dijkxhoorn, 2012).

	Technology type		
	Low	**Medium**	**High**
Typical size	1-10 ha	2-50 ha	3-20 ha
Cover type	Shadow net	Plastic roof, net walls	Plastic, glass
Production process	Soil	Hydroponics	Hydroponics, climate control
Cooling system	Natural ventilation	Natural ventilation	Pad&Fan
US 1 Quality of produce	40%	60-70%	90%
Farmer	Subsistence Emerging Farmers	Emerging Commercial Farmers	Commercial Farmers

Some of the major greenhouse construction companies in the country were consulted and information was gathered regarding existing greenhouse installations in South Africa (Olsen, 2013; van Niekerk, 2013; Venter, 2013). In hyper-arid areas of South Africa, greenhouses are generally structures of 4 m high and equipped with a combination of natural ventilation, fogging, pad and fan cooling and energy saving screens. Heating is often also installed, based on the type of crop planted, to control the cold nights in these areas. In semi-arid areas, greenhouses are generally constructed 4.5-5 m high and equipped with a combination of natural ventilation (in some places forced ventilation and pad and fan cooling), hot water heating, air circulation fans and screening (shading and thermal screens).

In the subtropical, humid areas of South Africa, greenhouses are generally higher (5-6 m gutter height), to improve ventilation and humidity control. Ventilation is maximized by having side and roof ventilation and shade screens and fans are often installed to control temperature and humidity. Heating is not often installed. In the dryer sub-tropical (Mediterranean) areas, greenhouses are also constructed at a 5 m height, with natural ventilation. Closed greenhouses are often used in these areas equipped with pad and fan.

Problems with pad and fan cooling have been experienced with the rapidly increasing electricity costs, as well as the fact that it is the only method of ventilation, even during cold periods, which has negative effects on plants. Problems have also been experienced regarding ventilation, because natural ventilation is often not sufficient. Many greenhouses are designed by international companies and are often not suitable for many climatic zones in South Africa.

2.8 Crops and Their Requirements

The main crops that are grown in greenhouses in South Africa are tomatoes, cucumbers, sweet peppers, lettuce, aubergine, herbs, strawberries, melons, gem squash, baby marrows and green beans (Venter, 2013). Some of the crops and their climate requirements are provided in Table 2.4 below.

Table 2.4 Different crop temperature requirements

Crop	**Temperature**	**Reference**	
	Optimum night (˚C)	**Optimum day (˚C)**	**Reference**
Tomato	14	18 (no fruit set above 25˚C daily mean)	Peet (1999)
Cucumber	20	30	Hui *et al.*(2003)
Eggplant	18	30	Hui *et al.*(2003)
Sweet pepper	16	21 (maximum 32 ˚C for fruit set)	Manrique (1993)
Lettuce and herbs	12	24	Manrique (1993);Peet (1999)
Spinach	15	20	Peet (1999); Hui *et al.*(2003)
Cabbage	2	15-16	Peet (1999)
Strawberries	12 12	18 (optimum growth for roots and fruits) 25 (growth of the whole plant)	Manrique (1993); Wang and Camp (2000)
Baby marrows	18	30	Hui *et al.*(2003)
Melons (musk melon)	15	32	Nonnecke (1989)

The balance between a vegetative and generative growth should be found, by controlling the internal climate conditions. The vegetative and generative conditions are provided in Table 2.5 below (Fourie, 2015).

Table 2.5 Vegetative and generative growth conditions

Vegetative growth conditions	**Generative growth conditions**
Soft and consistent light	Short and high intensity light
Low electrical conductivity (EC) in irrigation water	High electrical conductivity (EC) in irrigation water

Vegetative growth conditions	Generative growth conditions
Warm nights and days	Cold nights, warm days
High amount of water supply	Low water supply

2.9 Greenhouse Installation Costs

Economical and bankable feasibility is critical for any type of investor, regardless of the classification (low, medium or high technology) and purpose of the greenhouse. Examples of costs for different greenhouse types and components are given in Table 2.6below (Olsen, 2013; van Niekerk, 2013; Venter, 2013).

Table 2.6 Indication of greenhouse installation costs

Multi-span 1 ha greenhouse	
Component	Cost/m^2 (ZAR)
Structure with continuous double sided ridge ventilation	150-200
Screens for shading	60-80
Drip irrigation with fertigation system	40-50
Fogging	30-50
Hot water heating	150-180
Hot air heating	40-50
Computer climate control system (controlling only critical aspects)	15-30
Ground cover (plants grown on ground)	5-10
Gutter growing system	40-50
Pad and fan	40-50
Shade net greenhouse (low cost) – multi-span 1ha structure	
Structure and cover	50-60
Irrigation	40-50
Ground cover	5-10

The costs are generally based on a 1ha multi-span greenhouse. Costs per m^2 will increase, if the size of the greenhouse is reduced, and decrease for larger sizes.

2.10 Discussion and Conclusion

Greenhouses have been designed by suppliers in South Africa, who often provide specific technologies and greenhouse designs (van Niekerk, 2013; Venter, 2013). Particular climatic conditions are rarely taken into account when designs are prepared and this can lead to high operating and maintenance costs, as well as the sub-optimal performance of greenhouses with regards to climate control (Venter, 2013). There is also limited expertise in the field of greenhouse technologies and design requirements in Africa, including South Africa, and not many investors consult others for input into design/technology selection.

Microclimate conditions that have to be controlled to optimize crop growth include temperature, RH, solar radiation, CO_2 and internal air velocity. Light intensity, or solar radiation, and CO_2 are the primary factors that enhance photosynthesis and plant growth. Temperature and RH are the critical factors to control (Bournet and Boulard, 2010), to optimize plant photosynthesis under optimal light and CO_2 conditions, but also the most difficult factors to successfully control in greenhouses, especially in South Africa, where extremely high temperatures are experienced at certain times of the year and therefore greenhouse cooling remains a challenge (Kumar *et al*., 2009).

Greenhouse structures are designed to control and optimize the internal micro-climate inside the structure. Types of greenhouse structures and the performance in terms of internal temperature and ventilation rates have been evaluated by some authors (Boulard *et al*., 1997; Sethi and Sharma, 2007). Different shapes, sizes, orientations and greenhouse covers have been used in combination with various cooling systems, to attempt to provide the optimal control of the internal climate. Various cooling systems across the globe and their performance in controlling these factors have been reviewed by several researchers (Sethi and Sharma, 2007; Kumar *et al*., 2009). Experimental and numerical studies have been done, as described in the literature, on the performance of different cooling systems under specific conditions. Natural ventilation, pad-fan evaporative cooling, screening and fogging systems are commonly-used cooling systems in South Africa. Each system will perform differently, depending on the area.

Limited literature is available on cooling system performance for the variable agro-climatic conditions in Southern Africa. However, Maboko *et al*. (2012) indicated that evaporative cooling systems like the use of a wet pad and fan are not often used in South Africa, because of high operating and maintenance costs. Researchers have also stated that natural ventilation might not effectively manage the extreme high temperatures experienced inside greenhouses (Maboko *et al*., 2012; Mashonjowa *et al*., 2013). System performance in similar agro-climatic conditions, other than South Africa, has been researched and shows that for tropical and subtropical regions, greenhouses should be fitted with a ventilation area of 15-30% of the floor area. Fogging systems and pad and fan systems during summer seasons, with shading for areas with lower average humidity, are also often used (Kumar et al., 2009). In Mediterranean regions, natural ventilation with cover whitening and shading was proven to be the preferred option (Gonzalez and Baille, 2006; Castilla, 2008). Evaporative cooling and forced ventilation systems are proven to be more effective in dry (arid) areas (Jensen, 2002). The lowest cost greenhouse is, however, shade-net greenhouse. To predict the performance of different greenhouse structures and climate control (cooling) systems under certain conditions, several models are being developed (Boulard *et al*., 1997; Fatnassi *et al*., 2003; Abdel-Ghany and Kozai, 2006a). More complex or heterogeneous models are used to characterize the non-uniform situation of the internal climate of a greenhouse. Recently, Computational Fluid Dynamics (CFD) modelling has been used for these purposes. Homogenous (static or dynamic) models assume steady-state conditions in a greenhouse and are based on the energy balance of the internal system. It also assumes a uniform distribution. Homogenous models that can predict greenhouse temperature and humidity are more complex, and have more input parameters and can only predict the overall averages of the climate parameters. Models for predicting the ventilation rate and greenhouse temperatures for different structures and vent configurations have been developed extensively, but do not have the capability to predict RH (Ganguly and Ghosh, 2009; Mashonjowa *et al*., 2013).

In conclusion, there is a large knowledge gap in published data to assist local South African investors/farmers to select the optimum greenhouse designs and the associated systems. There is limited peer-reviewed literature available in South Africa that compares the performance of different natural and evaporative cooling systems. To be able to develop models for predicting this performance for different designs and climatic conditions, the calibration and optimization of models are required. The selection of greenhouses cannot be done without taking into account capital expenditure and operating and maintenance costs.

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3 PERFORMANCE EVALUATION OF DIFFERENT GREENHOUSE DESIGNS AND COOLING SYSTEMS

3.1 Abstract

Greenhouse cooling systems, and the evaluation of these systems, are relevant to the South African arid climate and for providing a solution to the problems experienced as a result of over-heating inside greenhouses. Natural ventilation, pad and fan evaporative cooling, screening and fogging systems are commonly-used cooling systems in South Africa.

Due to the lack of scientific data available on the performance of greenhouses in South Africa in terms of micro-climate and crop growth, three different greenhouses, located in Pietermaritzburg, KwaZulu-Natal was used for microclimate data collection and micro-climate and crop yield performance was evaluated. A greenhouse equipped with natural ventilation and insect netting, one with natural ventilation and fogging and a simple shade net tunnel were used for the experiments. In addition, four different varieties of lettuce crops were planted in each greenhouse and their growth was monitored. Two microclimate variables, air temperature and relative humidity, were measured in the greenhouses. The crop growth was measured in terms of number of new leaves developed, plant height, fresh weight, and dry mass. The effect of the microclimate on the lettuce colour was also analysed.

There was a significant difference in internal temperature and relative humidity (RH) between the naturally ventilated greenhouse with insect netting (NVG) and the naturally ventilated greenhouse fitted with a fogging system (NVFG). The difference in temperature between the NVG and the NVFG peaked at 9.4˚C, with NVG being the highest and the internal temperature of the NVG often peaked at 10˚C higher than external temperature. RH conditions in NVG were low and often dropped almost as low as the external RH during the day (down to 26%), where the RH for NVFG increased to between 80% and 90% when the fogging was switched on. The lettuce plant growth was mostly higher in the NVFG than in the other greenhouses for certain varieties. However, when it came to the red lettuce varieties grown in the shade net tunnel (SNT), the leaf colour was closer to the expected ideal colour. The fogging installation proved to be an effective cooling system in a greenhouse in subtropical conditions of KwaZulu-Natal. The other two greenhouses almost always experienced below optimal relative humidity and above optimal

temperatures. The specific greenhouses could be evaluated under different external climate conditions over a longer period and the market quality of the produce should also be evaluated. A cost benefit analysis should also be done on all three types of greenhouses.

3.2 Introduction

Crop yield, when grown in greenhouses, can reach up to four or five times the yield of crops grown in an open field. It is estimated that 35% of the South African population live with inadequate access to food (du Toit *et al.*, 2011). By utilizing resources such as sunlight, water, fertilizers and labour effectively, poverty and food insecurity can be significantly reduced (Venter, 2010). Controlled environmental agriculture enables the effective use of resources by controlling input factors more accurately, optimize plant growth thereby increasing economic yield.

The main advantage of utilizing greenhouses is that it enables the all-year round production of fresh produce crops and is not influenced by adverse climatic conditions, which would be the case if they were grown in open fields (Venter, 2010). The greenhouse has to be designed to accommodate local climatic conditions, as these directly affect the internal micro-climate of a greenhouse. A big challenge of greenhouse growing and greenhouse production is cooling the internal climate. Overheating is often experienced in greenhouses in South Africa, especially during summer months and in specifically warm regions. Orientation, shape and types of climate control systems should all be carefully considered when designing a greenhouse.

Several different cooling systems are designed to try and maintain the desired air temperature and relative humidity inside a greenhouse. These include natural ventilation, shading (Sethi and Sharma, 2007; Kumar *et al*., 2009), evaporative cooling (Sethi and Sharma, 2007; Arbel *et al*., 2003), solar radiation filtration (Hemming *et al*., 2006) and air humidification control (Venter, 2010). These methods are often used in conjunction to try and increase the cooling effect. Cooling systems that are used in South Africa include natural ventilation with different vent configurations and forced ventilation using pad and fan, or only fans. Shading is also used to reduce internal temperatures. Running costs for forced ventilation systems are very high and on the rise with increasing electricity costs, causing investors to move away from using these systems (Olsen 2013; van Niekerk, 2013; Venter, 2013). Natural ventilation requires less energy, in some cases no energy for fixed ventilation openings, and is therefore the cheapest method of cooling greenhouses (Kumar *et al.,* 2009). However, natural ventilation on its own is often not sufficient.

The effect of the different greenhouse cooling systems on microclimates and crop yield has been studied by several authors (Katsoulas *et al.*, 2001, Kittas *et al.*, 1997; Wang and Boulard, 2000). Utilizing fogging in a natural ventilated greenhouse resulted in reduced plant stress during extreme hot days (Katsoulas *et al.*, 2001). Natural ventilated greenhouses can be used when ambient conditions are not extreme, and are significantly impacted by solar radiation, free wind speed as well as the position and size of ventilation areas (Ganguly and Gosh, 2009). Greenhouses equipped with shade nets of different sizes and the effect this has on the climate has been studied. It has been found that air exchange rates can reduce by 50%, depending on the type of shadenet used (Harmanto *et al.*, 2006).

Research has also been done on greenhouse performance in regions that have similar agro-climatic conditions to certain areas in South Africa. Studies on micro-climates in greenhouses specific to the Mediterranean climate (Kittas *et al.*, 1997; Wang and Boulard, 2000) have been done for greenhouses fitted with natural and forced ventilation. Greenhouses operated in semi-arid areas have also been studied (Serir *et al.,* 2012). Greenhouse performance in the subtropics (Kumar *et al.*, 2010) as well as greenhouses with different polyvinyl covers in tropic conditions have been studied (Impron *et al.*, 2007). Additionally screenhouses in Wes-African tropical conditions have also been researched (Desmarais, 1996). However, little reliable information is available specifically on the performance of the different types of greenhouses and cooling systems in South Africa's climate regions. Even the success of existing greenhouses, in terms of cost-effectiveness and climate control, have not been documented properly and limited studies or experiments on crop production have been formally recorded.

It is also necessary to identify easily applicable greenhouse designs, specifically for the cooling of the micro-environment in a greenhouse in this region.
The study presented in this chapter was undertaken with the following objectives:

- to compare the internal temperature and relative humidity of the air inside the four different greenhouse designs and cooling systems, and
- to evaluate the effect of different microclimates in three greenhouses on the growth performance of selected sample lettuce

The benefits of utilizing a more capital intensive greenhouse such as the greenhouse equipped with fogging when compared to using a low-cost shade-net tunnel were also observed.

3.3 Materials and Methods

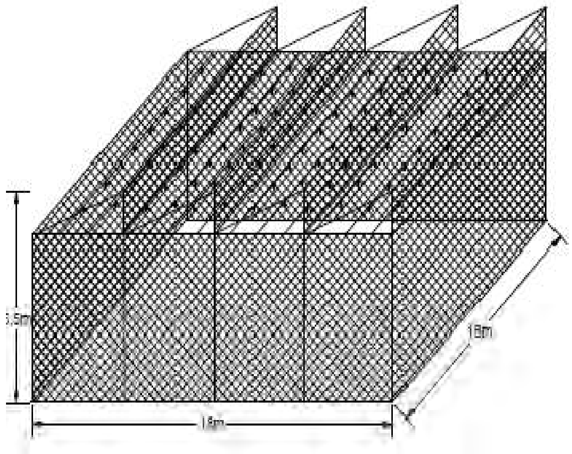
The following sections describe the research site, different greenhouses and materials as well as procedures that were used.

3.3.1 Experimental site

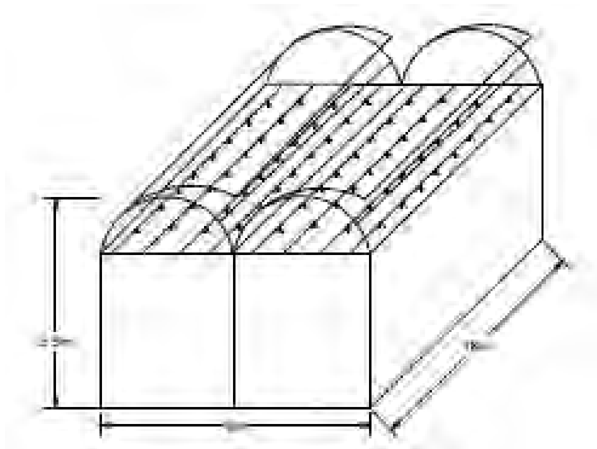
The research was conducted at the University of KwaZulu-Natal's College of Agriculture, Engineering and Science campus, Pietermaritzburg, South Africa (29°37'39.72''S, 30°24'09''E). The average maximum air temperatures vary between 20.6 and 27.8˚C and the average minimum temperatures vary between 6.0to 16.4˚C. Solar radiation varies between 15.1-27.8 $MJ.m^{-2}.day^{-1}$ and the daily average RH ranges between 61.1-75.3% (Schulze, 1997).

3.3.2 Greenhouses

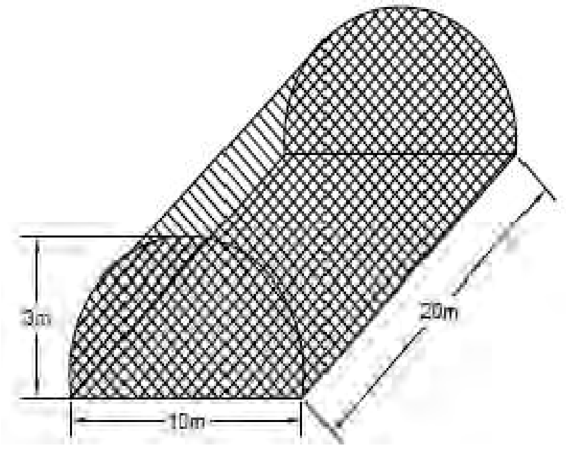
Three greenhouses were used in this study as presented in Figure 3.1. Schematic diagrams of the different greenhouses used for the research study can be found below. A naturally ventilated greenhouse (NVG) is covered with polyvinyl sheeting and is 18 m in length and width and 5.5 m high and equipped with fixed, continuous roof-ventilation covered with insect netting (55 mesh size). The naturally ventilated greenhouse fitted with roof vents and fogging (NVFG) is covered with polycarbonate and is 18 m in length, 9m in width and 5.5m high. The shade net tunnel (SNT) is 20 m long, 10 m wide and 3.5 m high. The shade net has 30% shade-effect.



a) Natural ventilation with insect netting (NVG)



b) Natural ventilation and fogging (NVFG)



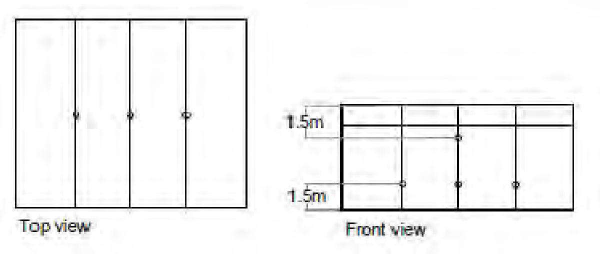
c) Shade net tunnel (SNT)

Figure 3.1 Schematic diagrams of the different greenhouses used in the research study

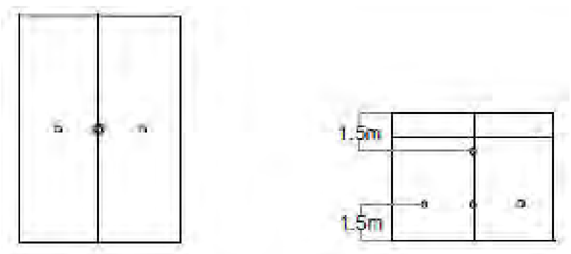
3.3.3 Experimental design

The measurements of temperature and relative humidity were done in all greenhouses. Digital data loggers (Hobo Pro v2 optic data loggers) were used to record the inside temperature and relative humidity. The RH sensors have a measuring range of 0-100% with a ± 2.5% accuracy and the temperature sensors have a measurement capacity of temperature ranging between -40˚C and 70˚C, with accuracy of ± 0.2%. The data was recorded at 10-minute intervals for four weeks and then averaged hourly.

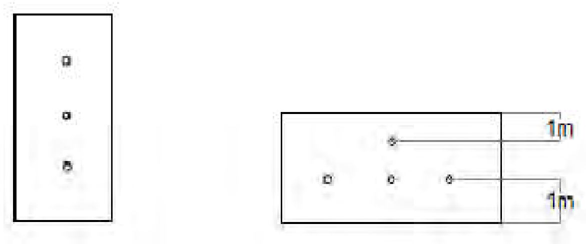
Four data loggers were used for each greenhouse as per the diagrams below (Figure 3.2). The arrangement of the loggers ensured that the distribution of temperature and relative humidity is more accurately observed. For NVG, three was placed 4.5 m apart and 1.5 m above the greenhouse floor and one was placed in the middle of the greenhouse at 1.5 m below the ridge height. Sensors in NVFG were placed 1.5 m apart in the middle of the greenhouse, 1.5 m above the greenhouse floor and the one in the middle, 1.5 m below the ridge height. For SNT, four data loggers were used. Three sensors were placed in the middle of the greenhouse every 6 m, at a height of 1 m above floor level, and one sensor was placed exactly in the middle of the greenhouse, 1 m below ridge height.



a) Natural ventilation with insect netting (NVG)



b) Natural ventilation and fogging (NVFG)



c) Shade net tunnel (SNT)

Figure 3.2 Experimental sensor setup

The external climate parameters, including global solar radiation and wind speed were obtained from a local meteorological weather station located on the site (http://agromet.ukzn.ac.za:5355).

3.3.4 Crop agronomic parameters and growth data collection

Lettuce crops were grown simultaneously in each of the greenhouses. Twenty-eight seedlings of the same age were planted in each greenhouse. Four different Salanova® cultivars were used in each, namely, Erasmus RZ; Gaugin RZ; Xerafin RZ and Cook RZ.
Drip irrigation was used to automatically supply water and nutrients to the plants, at a constant EC of 0.7 millisiemens per centimetre (mS/cm), three times a day. The effect of

the climate in each greenhouse on the lettuce crop was monitored by capturing the number of new leaves developed, dry mass and fresh weight yield (Ogbodo *et al.,* 2010, Urbonaviciute *et al.,* 2007). Eight random plants from each greenhouse were taken for sampling. To determine the number of new leaves developed, the number of leaves was simply counted at the start and end of the experiment. Fresh weight per plant was measured in grams using a digital scale and averaged per sample, after being cut from the roots. Fresh Dry mass was determined using the oven-drying method by drying the lettuce at 70˚C for a period of 48 hours and then weighing the plants with a digital scale. Colour measurements were also done on the plant samples in each greenhouse, using a Konica Minolta Chromameter® CR-400. Lightness (L*), chromaticity coordinates (a*, b*) and the hue angle of the leaves were measured at the end of the experimental period. Three measurements were taken of eight plants in each greenhouse and the average was calculated as the final value. Measurements were taken at the beginning and end of the experimental period.

3.3.5 Data analysis

Statistical analysis of temperature, relative humidity and plant growth was done using IBM® SPSS® statistical and a data management computer package and by analysis of variance (ANOVA). Comparisons between different treatments were done using Fishers' Least Significant Difference test (LSD test), with evaluations based on P = 0.05 significance level.

3.4 Results

3.4.1 Average day-time micro-climate conditions

Day-time mean temperatures measured between 6 am and 6 pm for five similar external climatic temperatures during the experimental period are presented in Figure 3.3 below. These results show that for the naturally ventilated polycarbonate greenhouse (NVG) with no cooling installation for the relevant days, temperatures were significantly ($P<0.05$) higher than external temperature, often reaching internal temperatures up to 10˚C higher than outside. It also reached a peak temperature of 32.87 ˚C. The internal temperatures of the fog-cooled, natural ventilated greenhouse (NVFG) were often lower than the other two greenhouses, and often reached temperatures lower than the measured external temperature. However, the mean internal temperatures in NVFG and SNT on average didn't show significant ($P>0.05$) differences when compared to the external temperature during the day. The fogging in the NVFG was set to start when the internal temperature reached 27˚C. It is clear to see from the graphs that the internal temperatures in the greenhouse decreased when the fogging had started. The peak temperature difference between NVG and NVFG temperatures were 9.4˚C at a specific time.

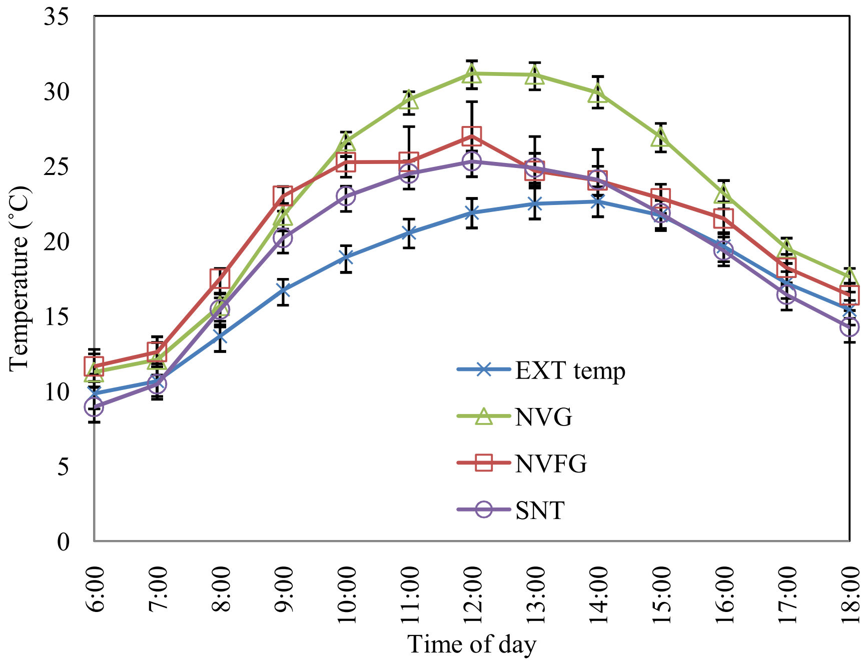


Figure 3.3 Mean hourly day-time temperatures for the natural ventilated (NVG), fog-cooled and natural ventilated (NVFG) and shade net tunnel (SNT) as well as external (EXT) measurements for five similar temperature days

Figure 3.4 below shows the difference in relative humidity in the three different greenhouses measured against external relative humidity. There is a small difference in relative humidity in the shade net tunnel (SNT) and outside for each day ($P>0.05$). The RH measurements in the NVG are generally lower than the outside and the other two greenhouses for the relevant days, especially on the day where the global solar radiation was the highest (Figure 3.5) but significantly ($P<0.05$) different to specifically the RH in the NVFG. The RH of the NVG drops as low as 26% during warm days and when the external RH is 24%. The RH in the NVFG increases when the solar radiation and temperature reaches certain values. Due to the fogging switching on at approximately 27˚C, it is clear to see that the RH increases drastically over that period and ranges between 70-90% when the external RH is in the range of 30-40%. Figure 3.5below shows the global solar radiation measured over these specific days. Relative humidity drops significantly (P<0.01) when the global solar radiation increases during the day.

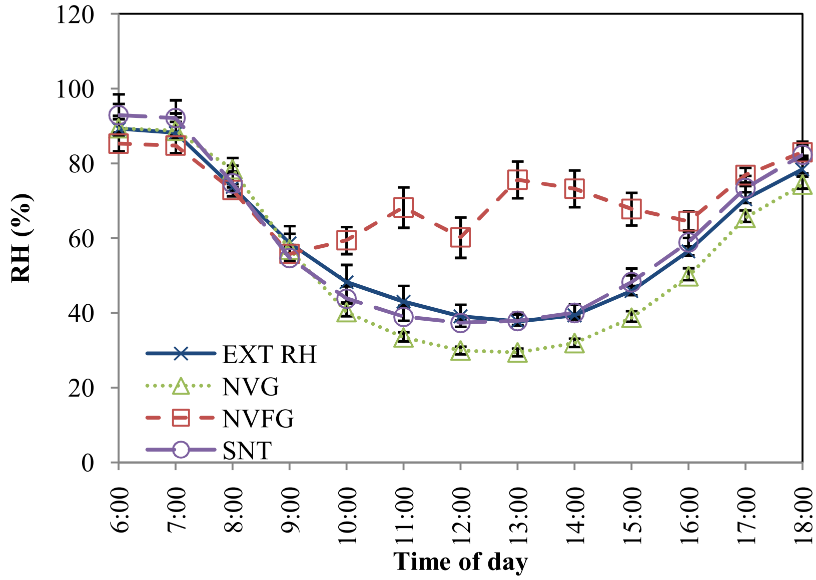


Figure 3.4 Mean hourly day-time relative humidity for the natural ventilated (NVG), fog-cooled and natural ventilated (NVFG) and shade net tunnel (SNT) as well as external (EXT) measurements for five similar external climate days

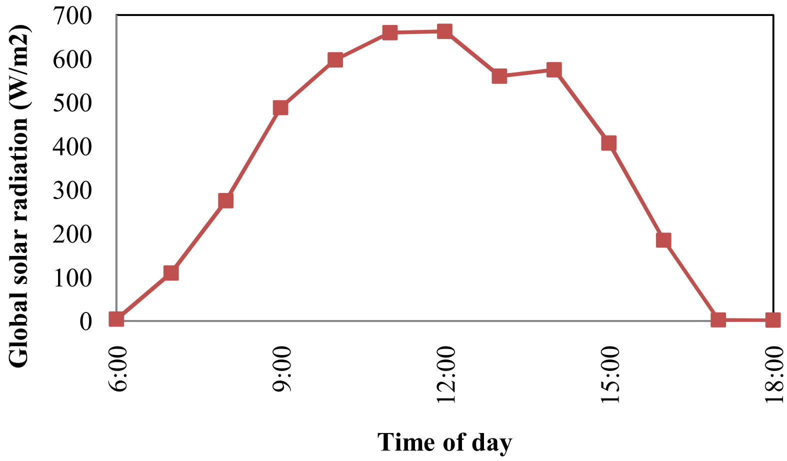


Figure 3.5 Mean hourly solar radiation measured over the five days with similar external climate conditions

3.4.2 Average night-time micro-climate conditions

Night time (6 pm – 6 am) air temperatures and relative humidity measured over the same five days are presented in Figure 3.6 and Figure 3.7. Temperatures in NVG and NVFG are very similar (P>0.05) and follow a similar curve during the evenings. The air temperature in the SNT are similar (P>0.05) to the external temperature. RH measured outside varies significantly (P<0.05) from the internal RH of the NVG and NVFG greenhouses and are similar (P>0.05) to the external measured RH.

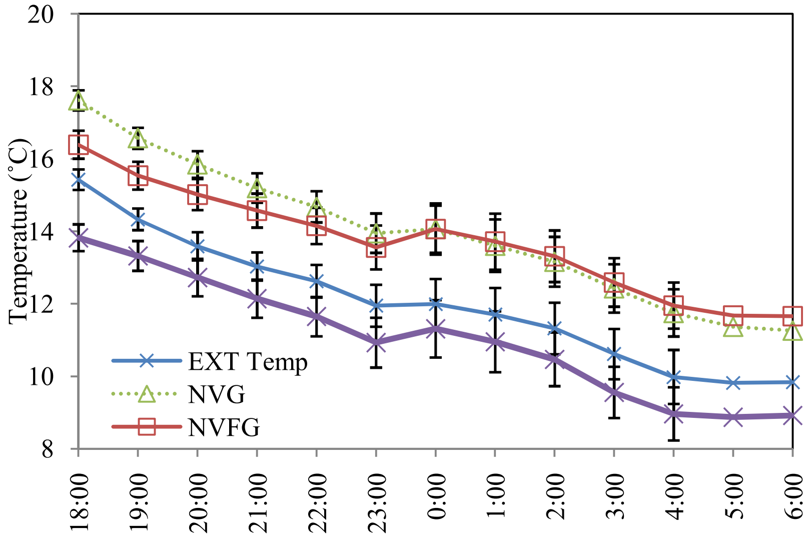


Figure 3.6 Mean hourly night-time temperatures for the natural ventilated (NVG), fog-cooled and natural ventilated (NVFG) and shade net tunnel (SNT) as well as external (EXT) measurements for five similar temperature days

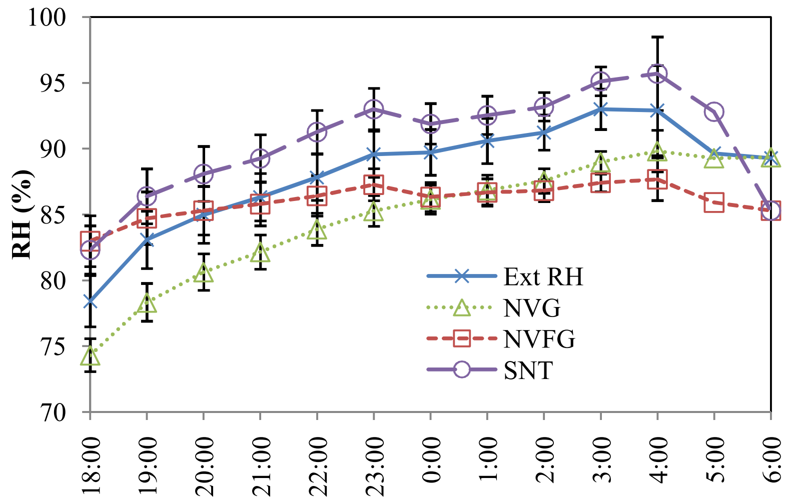
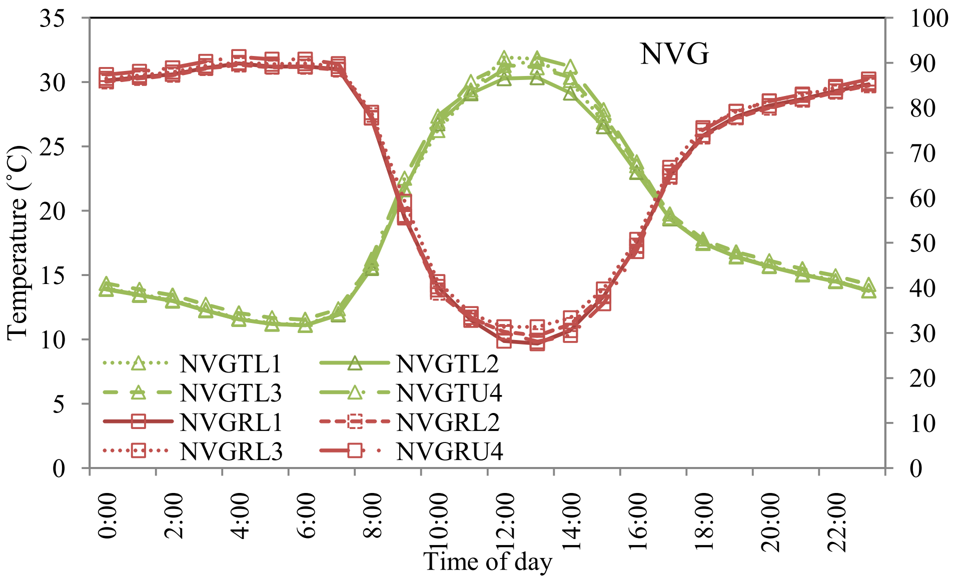


Figure 3.7 Mean hourly night-time relative humidity for the natural ventilated (NVG), fog-cooled and natural ventilated (NVFG) and shade net tunnel (SNT) as well as external (EXT) measurements for five similar temperature days

3.4.3 Evaluation of the internal microclimates

Figure 3.8 shows the hourly mean temperatures and relative humidity at different positions inside the greenhouses. There were no significant differences between the different sensors located in different positions different positions in all the greenhouses (P>0.05) in the measured temperature and humidity values.



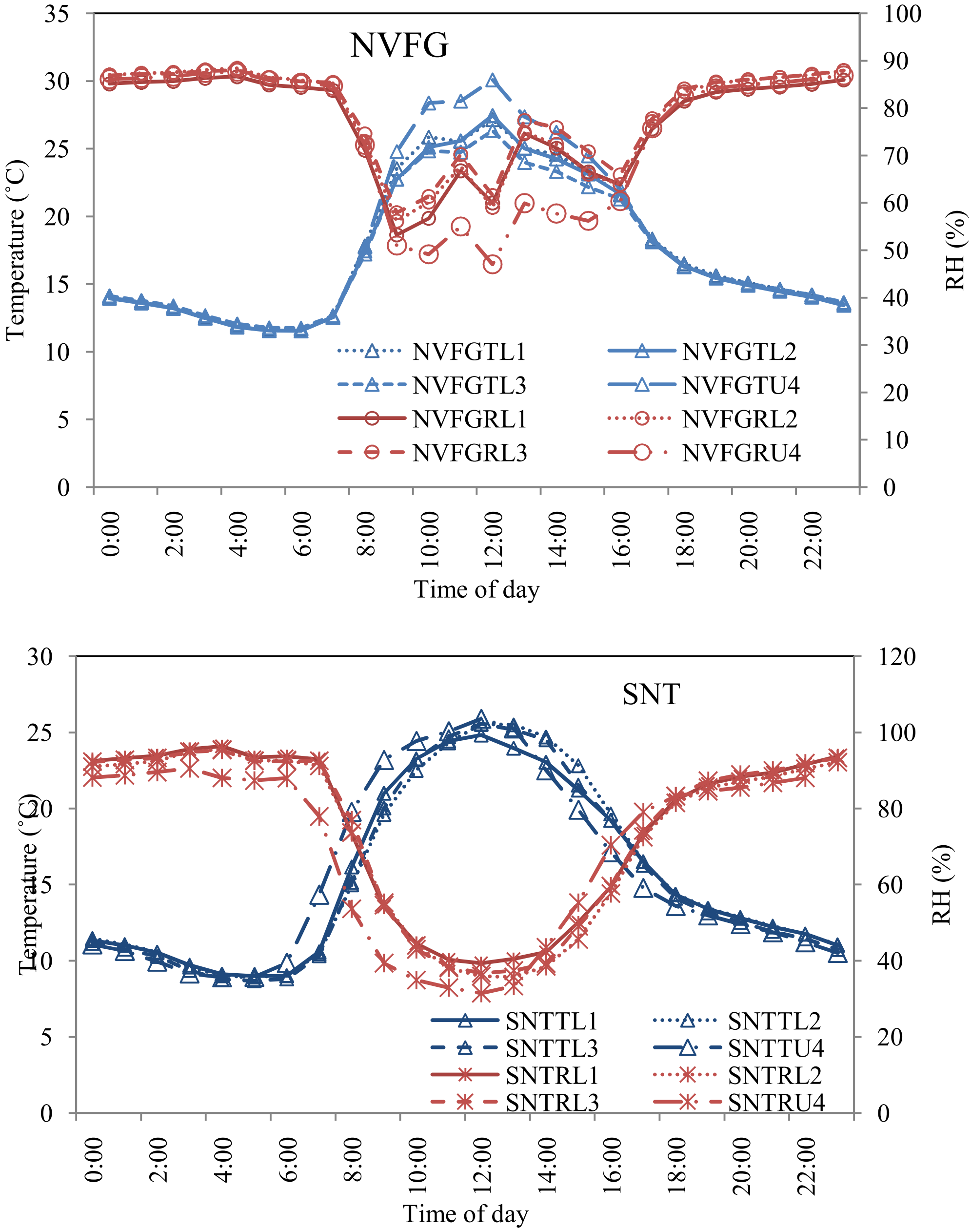


Figure 3.8 Twenty four hour mean temperature (T) and relative humidity (RH) for the natural ventilated (NVG), fog-cooled and natural ventilated (NVFG) and shade net greenhouse (SNT) as well as external (EXT) measurements for five similar temperature days. TL1, TL2 and TL3 are the lower placed temperature sensors. TU4 is the temperature sensor placed in the upper section of the greenhouse. RL1, RL2 and RL3 are the lower placed relative humidity sensors and RU4 is the RH sensor placed in the upper section of the greenhouses

In naturally ventilated greenhouses, especially those with roof ventilation only, external wind speed and air temperature differences are the parameters that have the main influence on ventilation rates in a greenhouse, and in turn influence internal temperature and relative humidity (Baptista *et al*., 2010). Ventilation openings covered with insect netting also influence the air exchange rates and the microclimate of a greenhouse (Harmanto, 2006), as well as the different types of netting used. Wind effect (caused by external wind) is a major cause in ventilation for all different types of vent configurations. The ventilation caused by air temperature differences (the "chimney" effect) is only significant at low external wind speed (Boulard *et al.,* 1997). The wind effect on air distribution also depends on the wind direction. If the wind is in the direction of the open vents (windward), studies have shown that the internal temperature decreases more significantly and air distribution is higher, compared to when the wind comes from the opposite direction (lee-ward) (OuldKhaoua *et al.,* 2006). It should however be noted that strong wind in the windward direction might cause mechanical damage to the greenhouse.

Ventilation in the shade net tunnel is less restricted and the air permeability of the cover directly effects the air distribution in the tunnel more than anything else (Castellano and Misttriolis, 2008).

The roof vent configuration of NVG and NVFG are similar, although the windows for NVG are fixed and covered with insect netting. Vents in NVFG are motorized and can open and close. All the vents open to the West. All three greenhouses are North-South orientated. When wind from the North-West, West, or South-West blows, it would, according to literature, thus have had the biggest effect on climate inside the roof ventilated greenhouses. Air distribution was not measured in the greenhouses during the experimental period. Figure 3.9 below represents a period in which the wind direction was almost directly west as an example.

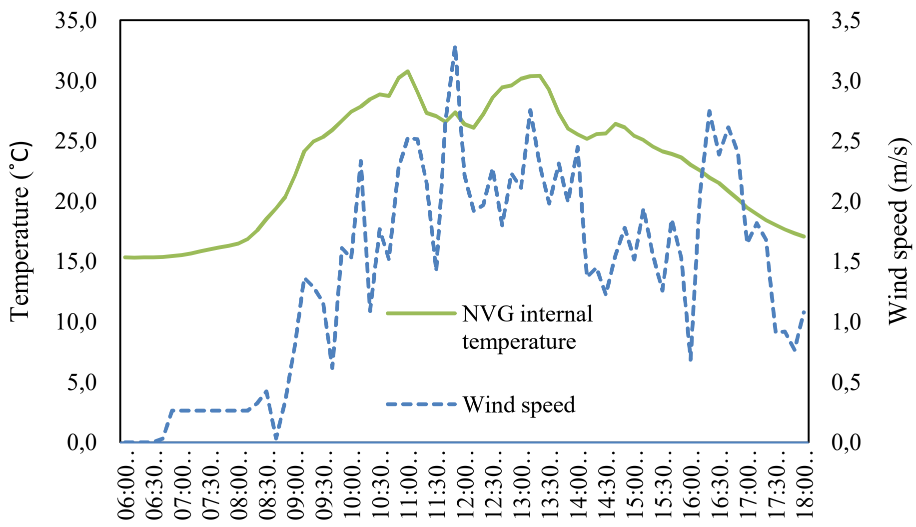


Figure 3.9 Graph representing the experimental data of the internal temperature in the NVG when wind was blowing in the windward direction

Since the air distribution inside the greenhouse was not measured during the experimental period, the change in internal temperature cannot be directly associated with wind speed based on the data retrieved. It should have an impact on the microclimate of the greenhouse (Baptista *et al.* 2010).

3.5 Plant growth analysis

3.5.1 Growth

Seedlings of 21 days old were used and planted at the start of the experiments. Measurements such as plant height, number of new leaves and fresh plant weight were taken at the start of the experiment on a sample of eight plants of four different varieties in each greenhouse. The same samples measurements were taken again 30 days after planting. The growth in terms of the following parameters, as indicated in Table 3.1below, was captured.

Table 3.1 Plant growth captured over the experimental period. SD = standard deviation, V1 = Erasmus RZ, V2 = Gaugin RZ, V3 = Xerafin RZ and V4 = Cook RZ

Growth in terms of	Variety	Plant height (cm) ±SD	Number of new leaves ±SD	Fresh plant weight (kg) ±SD	Dry matter (kg) ±SD
NVG	V1	3.25 ±2.13	80.75 ±13.05	0.163 ±0.02	0.008 ±0.001
	V2	4.38 ±1.49	64.00 ±14.49	0.124 ±0.02	0.009 ±0.001
	V3	3.95 ±1.25	44.25 ±8.77	0.080 ±0.03	0.007 ±0.002
	V4	1.73 ±1.57	65.00 ±4.97	0.144 ±0.03	0.009 ±0.002
NVFG	V1	2.60 ±0.56	86.50 ±9.19	0.180 ±0.008	0.011 ±0.001
	V2	6.45 ±0.49	72.50 ±0.70	0.122 ±0.001	0.006 ±0.002
	V3	6.50 ±0.14	47.50 ±17.67	0.099 ±0.03	0.005 ±0.001
	V4	1.80 ±0.56	90.50 ±7.77	0.148 ±0.017	0.010 ±0.002
SNT	V1	2.20 ±1.70	47.50 ±4.95	0.079 ±0.041	0.005 ±0.002
	V2	3.25 ±1.06	43.00 ±1.14	0.059 ±0.007	0.003 ±0.001
	V3	1.05 ±0.35	25.50 ±7.78	0.025 ±0.004	0.002 ±0.001
	V4	0.75 ±0.50	52.50 ±2.12	0.102 ±0.008	0.007 ±0.001

The data shows that the Erasmus variety planted in NVG had grown 20% taller than those grown in NVFG and 32% taller than plants grown in SNT. The Gaugin variety planted in NVFG resulted in a 32% higher growth in terms of plant height than those grown in NVG and 50% higher growth than the plants in the SNT. The Xerafin RZ variety planted in NVFG had grown 40% taller than those planted in the NVG and almost 75% taller than the plants in the SNT. The Cook RZ variety planted in NVFG was 5% taller than those planted in NVG and 60% taller than plants grown in SNT. The Erasmus and Cook varieties did not show significant difference in height in the different greenhouses ($P>0.05$).

The table presents the plant growth in terms of number of new leaves developed in NVG, NVFG and SNT measured at the beginning and after 30 days from planting. The different microclimates had a significant effect on leave accumulation on the Erasmus and Cook especially comparing the growth in the NVG and NVFG to SNT ($P<0.05$). For the Gaugin and Xerafin variety, no significant effects were seen ($P>0.05$).The Erasmus variety showed 7% more leaf accumulation in NVFG than in NVG and 55% more than in the SNT. The Gaugin variety showed a 12% higher leaf accumulation in NVFG than in NVG and 40% more than in SNT. Xerafin plants grown in NVFG accumulated 7% more than in NVG and 47% more than in SNT.

The effect of the different microclimates on the fresh plant weight was more significant ($P\leq0.05$) for the Erasmus, Gaugin and Xerafin varieties grown in NVG and NVFG comparing to the SNT. The Erasmus variety again showed a 10% higher fresh weight in NVFG than NVG, and 55% higher than in SNT. The Gaugin variety, however, showed an 18% higher fresh weight in NVG than in NVFG and a 52 % higher weight than in SNT. Furthermore Xerafin plants grown in NVFG showed a 16% higher fresh weight achieved than in NVG and a 71% higher fresh weight in SNT. The Cook variety showed higher fresh weight in NVG than in NVFG and 25% higher than in SNT, but generally no significant difference in weight between the three greenhouses.

The effect of the different microclimates on the dry biomass plant weight was more significant ($P\leq0.05$) for the Erasmus, Gaugin and Xerafin varieties in NVG and NVFG comparing to the plants grown in SNT. The Erasmus variety's dry weight was 25% more in the NVFG than in NVG and 53% more than the plants grown in SNT. The Gaugin variety showed a 25% higher weight in NVG than in NVFG and a 62% higher weight than in SNT. The Xerafin plants grown in NVG showed a 15% higher dry mass than those grown in NVFG and 31% higher than those of SNT. The Cook variety presented a 20% higher weight in NVFG than in NVG and 30% higher than in SNT.
All the varieties in the NVFG were observed to have softer leaves, which is a result of a climate suitable for a more vegetative growth. The leaves in the NVG and SNT were

observed to be harder, which is a result of a climate more suitable for generative growth (Fourie, 2015).

3.5.2 Colour

Colour changes in the different varieties and within the different greenhouses were apparent during the experimental period. Colour analysis was done only at the end of the experiments. Figure 3.10 below shows the seedlings prior to being planted out in the greenhouses. Erasmus RZ is a vigorous, medium green butterhead multi-leaf type lettuce variety. The Gaugin RZ variety is a dark red butterhead multi-leaf type lettuce. Xerafin RZ variety is a dark red multi-leaf oak-type lettuce. Cook RZ is a green oak-type multi-leaf lettuce variety.

Figure 3.10 Illustration of the seedlings prior to transplanting in the greenhouses. V1 = Erasmus RZ, V2 = Gaugin RZ, V3 = Xerafin RZ, V4 = Cook RZ

The results from the measurements done with the chromaticity meter are shown and summarized in Table 3.2 below. The colour is defined in the L*, a*, b* colour space, Chroma (C*) and hue angle (h˚).

Table 3.2 Summary of colour analysis done on the lettuce plants in each greenhouse. The prefixes NVG, NVFG and SNT represent the three different greenhouses. SD = standard deviation, V1 = Erasmus RZ, V2 = Gaugin RZ, V3 = Xerafin RZ and V4 = Cook RZ

	L*	a*	b*	C*	h^0

	L*	a*	b*	C*	h^0
	Lightness ±SD	chromaticity coordinates ± SD	chromaticity coordinates ±SD	Chroma ±SD	Hue angle ±SD
V1.NVG	56.38±4.38	-19.66±3.15	34.46±7.71	39.70±8.18	120.01±2.37
V1.NVFG	53.14±2.29	-21.30±0.86	35.99±1.92	41.83±2.09	120.72±0.37
V1.SNT	50.93±3.17	-19.59±2.40	32.47±5.10	37.93±5.61	121.23±0.70
V2.NVG	39.61±5.94	-10.51±5.48	19.52±6.09	22.30±7.86	116.16±6.93
V2.NVFG	48.70±0.79	-18.81±1.22	30.41±1.13	35.76±1.61	121.76±0.82
V2.SNT	29.88±2.42	1.49±1.20	6.51±2.91	8.10±3.21	56.58±10.46
V3.NVG	50.43±3.77	-18.63±3.85	30.31±3.41	35.59±4.07	121.60±13.46
V3.NVFG	43.11±0.47	-13.98±0.34	23.63±1.13	27.51±1.17	119.99±0.98
V3.SNT	26.64±1.40	3.98±0.43	1.90±1.07	4.58±0.91	20.73±8.91
V4.NVG	50.43±1.78	-18.63±0.57	30.31±1.09	35.59±1.21	121.60±0.35
V4.NVFG	50.45±2.35	-19.44±0.19	31.43±0.64	36.96±0.45	121.76±0.76
V4.SNT	45.12±0.40	-17.09±0.54	24.90±0.47	30.21±0.70	124.51±0.40

The colour results from the Erasmus variety were very similar for the plants in all three greenhouses and fell in the slightly darker green range. The Cook RZ variety also did not show significant variance in colour between the plants in different greenhouses. With regard to the other two varieties, significant differences in colour were observed. Illustrations of colour differences observed in the same varieties planted in different greenhouses are presented in the figures below.

Figure 3.11 Plant V2 (Gaugin RZ) in NVG showing light red colour 30 days after planting

Figure 3.12 Plant V2 (Gaugin RZ) in NVFG showing only green colour 30 days after planting

Figure 3.13 Plant V2 (Gaugin RZ) in SNT showing dark red colour 30 days after planting

Figure 3.14 Plant V3 (Xerafin RZ) in NVG showing light red colour 30 days after planting

Figure 3.15 Plant V3 (Xerafin RZ) in NVFG showing almost only green colour 30 days after planting

Figure 3.16 Plant V3 (Xerafin RZ) in SNT showing dark red colour 30 days after planting

The leaves of the Erasmus RZ and Cook RZ variety maintained the original colour of the seedlings in all three greenhouses. As indicated in Figure 3.11 - Figure 3.16, the Gaugin RZ and Xerafin RZ plants in the NVG and NVFG in particular lost their dark red colour. From Figure 3.11 - Figure 3.13, the Gaugin RZ variety plants in NVG still retained a slight red colour at the tips of the leaves ($a^* = -10.51 \pm 5.48$, $b^* = 19.52 \pm 6.09$). The same variety planted in NVFG lost all red colour, and the values fell within the dark green colour space ($a^* = -18.81 \pm 1.22$, $b^* = 30.41 \pm 1.13$). The ideal results in terms of colour (dark red colour space) were achieved in the plants planted in the shadenet tunnel (SNT) ($a^* = 1.49 \pm 1.20$,$b^* = 6.51 \pm 2.91$). Other than the small amount of red colour still visible in the Xerafin RZ variety plants in NVG, Figure 3.14, the Xerafin RZ variety plants exhibited similar results to those experienced with the Gaugin RZ variety.

3.6 Discussion

3.6.1 Average day-time micro-climate conditions

Greenhouse internal temperature and relative humidity is mainly affected by the external temperature, global solar radiation, air exchange, crop transpiration and the radiative properties of the cover material used (Bot, 1993, Papadakis *et al.,* 2000). The two major factors is the air exchange and radiation interception (Bot, 1993). Air exchange is driven by the difference between the inside and outside temperature (chimney effect) and external wind speed (Katsoulas *et al.,* 2006) through ventilation openings. Studies have shown that the effect of the wind speed on the air exchange and internal temperature of naturally ventilated greenhouses with one-sided roof ventilation is more significant when it comes to smaller greenhouses up to 2 spans (Baeza *et al.*, 2006). Boulard *et al.* (1997) and Baeza *et al.* (2006) have conducted research on different greenhouse types with different vent configurations and their research shows that there is a linear relationship between the ventilation rate and external wind speed. Studies also show that the chimney effect can mostly be ignored for wind speed over 1.5 - 2 $m.s^{-1}$ (Boulard *et al.,* 1997; Wang and Boulard, 2000, Katsoulas *et al.,* 2006) and that the external wind speed still has an effect on air exchange for wind speed exceeding $2m.s^{-1}$. With regard to a greenhouse with insect netting and natural ventilation, the wind speed and wind direction also has a direct linear effect on the ventilation rate in the greenhouse; therefore the chimney effect can be ignored for wind speed over $1m.s^{-1}$ (Shilo *et al.*, 2004). Since no air flow measurements were done in the greenhouses during the experimental period, determining the effect of the wind on the microclimates of three different greenhouses from experimental results is no simple matter. However, the analysis done on the greenhouse fitted with natural ventilation and insect screens on a specific day shows that the internal temperature decreased when the wind speed increased. From the experimental results, the factor that had the most significant impact on the internal temperature of the greenhouses was global solar radiation. This specifically had an effect on the polycarbonate covered greenhouses (NVG and NVFG) where the internal temperatures increased drastically with the increase of global radiation in the mornings and was always higher than the outside measured temperatures (Figure 3.3). When it comes to the naturally ventilated greenhouse fitted fogging, this changed when the internal temperature reached temperatures around 27˚C and the fogging systems started in the greenhouse. This resulted in quite a drastic drop in temperature that would often be below the outside temperature. These results correspond with studies done on naturally ventilated greenhouses with fogging (Kumar *et al.,* 2010; Ishii *et al.* 2006; Li *et al.*, 2006; Katsoulas *et al.,* 2012) and also with the findings that the fogging type evaporative cooling can be effective in subtropical climatic conditions (Kumar *et al.*, 2009). The high temperatures experienced in the natural ventilated greenhouse with roof vents covered with insect netting corresponds with the findings by Katsoulas *et al.,*2006. Screens limit ventilation, which in turn limits factors like the internal temperature and relative humidity (Sethi and Sharma, 2007; Teitel *et al.*, 2009).

The cover material properties have an effect on the amount of solar radiation transmitted into the greenhouse. The total solar transmissivity coefficient for polycarbonate covering material is 77%, 78% PAR (photosynthetically active radiation) and 78% direct sunlight (Papadakis *et al.,* 2000). This depends on the cell geometric properties and the age of the material, as the transmissivity coefficient of the material can decrease by 1% per year due to ageing (Papadakis *et al.,* 2000).The solar transmissivity in the experimental greenhouses covered with polycarbonate was probably much lower than the figures supplied by earlier literature, due to the condition of the material. Natural ventilation in the shadenet tunnel is directly influenced by the air permeability of the cover, since it normally does not have ventilation openings (Castellano, 2008). It is thus also clear from the experimental data that there is very little heat build-up in the shadenet tunnel and that the climate inside the tunnel was always very similar to the outside conditions (Figure 3.3) during the day.

From the data collected, it showed that the internal temperatures reached a maximum of 33 ˚C and 32 ˚C for the NVG, and 34 ˚C and 32˚C for NVFG on the 15th and 16th of May with a maximum external temperature of 24˚C. The data shows that there was a delay in switching on the fogging in NVFG for both these days, which explains the maximum temperatures in this greenhouse. After the fogging switched on, temperatures dropped down to around 24 – 25˚C. On May 18thand May 19ththe global solar radiation was at its highest and internal temperatures peaked at 31˚C, 25˚ and 24˚C on May 18th for NVG, NVFG and SNT respectively and on May 19thit peaked at 32˚C, 23 ˚C and 27˚C for NVG, NVFG and SNT respectively. The mean hourly external temperature peaked at 24˚C and 25˚C for these two days. Optimum temperature set points for lettuce production is around 15-20˚C (Ogbodo *et al.,* 2010), but should ideally never exceed 24˚C (Seginer *et al.*, 1991, Manrique, 1993; Peet, 1999). The internal temperatures experienced in NVG are thus on average always too high for optimum lettuce production and the temperature experienced in the other two greenhouses were more favourable for lettuce production.

The external relative humidity measurements reached -the lowest value each day around 13h00 and 14h00 which ranged between 30% and 43% as the minimum. It started rising each afternoon and reached high levels (>70%) from 18h00 onwards. The SNT internal RH measured very similar values throughout each day. The RH measurements in NVG were almost constantly 10% lower than the external humidity, reaching minimum RH between 26 and 32%. For all five days, the RH measured in NVFG corresponded with the time when the temperature reduced. The mean hourly RH for this greenhouse (Figure 3.4) was between 31% and 63%. The RH increased drastically due to the fogging being switched on and increased to 70-80% each day. High relative humidity is generally more of a problem in greenhouses, specifically in region with a subtropical climate (Kumar *et al.*, 2010). Relative humidity is also dependent on ventilation rate, condensation as well as the crop transpiration rate (Aguilar *et al.*, 2011; de Jong and Stangellini, 1995; Jolliet 1994). The low humidity levels in the greenhouses not equipped with fogging can thus be explained by the low external humidity experienced, as well as generally small plants grown in the greenhouse, with smaller LAI and thus lower transpiration rates. Minimum RH for lettuce plant production is 40% and maximum is 95% (Aguilar *et al.*, 2011). The RH measured in NVG and SNT are thus below the ideal levels.

3.6.2 Average night-time micro-climate conditions

The mean hourly night-time temperatures and measure relative humidity (Figure 3.6 and Figure 3.7) show that there were small differences experienced in temperatures for the polycarbonate covered greenhouses. More significant differences were experienced between the two polycarbonate covered greenhouses' internal temperatures and the external and internal shadenet temperatures. The temperature in the shade net greenhouse was always similar to the external measured temperature. There is a reduced heat build-up in the greenhouse due to losses through the cover, based on the overall coefficient of heat transfer of the greenhouse. This is affected by many factors, including the type and condition of the cover, air leakage, long-wave radiation exchange and the area of the covering material (Papadakis *et al.,* 2000). The overall heat transfer coefficient for polycarbonate covers are lower than for normal polyethylene plastic covers (Papadakis *et al.*, 2000) and obviously shade-net, which explains the difference in temperatures.

The average night-time temperatures for NVG for the five days are 13.5 ˚C, 17.0˚C, 11.5˚C, 12.7˚C and 13.5˚C respectively. For NVFG, these are 14.7˚C, 16.6˚C, 11.1˚C, 12.0˚C and 12.0˚C respectively. For the shade net tunnel, the temperatures experienced averaged at 11.1˚C, 15.0˚C, 8.1˚C, 10.0˚C and 9.8˚C for these five days respectively, whereas the external temperatures were 12.3 ˚C, 15.1 ˚C, 9.4 ˚C, 10.3 ˚C and 11.6 ˚C. The minimum temperatures experienced for the five days for the three different greenhouses (NVG, NVFG and SNT) were 8.0 ˚C, 8.2 ˚C and 6.3 ˚C, respectively. The average night time temperatures experienced in NVG and NVFG are within the optimum temperature range of 12.0-15.0˚C (Djevic and Dimitrijevic, 2009). The minimum temperatures experienced however, are below the optimum levels for all the greenhouses.

The relative humidity measured in all the greenhouses was very similar to the external RH during the night time for each of the five days. The RH measured in the two polycarbonate covered greenhouses was always lower than that of the external and shadenet measured RH. This is expected for NVG with fixed roof ventilation where humid air can escape through the vents during night time. The lower humidity experienced in NVFG implies that the air leakage is high, and can be due to the fact that the vents were not always 100% closed during the night. The humidity levels in the greenhouses did not often exceed the acceptable maximum level of 95% (Aguilar *et al.*, 2011).

3.6.3 Plants growth performance analysis

All varieties thus showed higher growth in NVFG than the other greenhouses, except for the Erasmus variety, that showed a higher increase in height in NVG. All four varieties also showed higher leaf accumulation in NVFG than in the other greenhouses. The increase of fresh plant weight was higher in NVFG for the Erasmus and Xerafin varieties than in the other greenhouses. The fresh weight of the Gaugin and Cook varieties increased more in NVG than in the others. The dry mass measured at the end of the experiment however, varies slightly from the fresh weight results, where the Erasmus and Cook varieties increased more in NVFG than in the others, and the Gaugin and Xerafin varieties increased more in NVG than in the other greenhouses. The growth in terms of all the factors was always significantly less for the plants in SNT than the other two. This can be due to the climate and light conditions in the greenhouse being more conducive for generative growth. These conditions include high intensity sunlight, limited water, low humidity, cold nights and warm days (Fourie, 2015).The more optimal humidity and temperature conditions experienced in NVFG could have had the positive impact on most of the measured growth factors during the experimental period. The low humidity and high temperatures in NVG without fogging could have had the negative effect on some of the varieties in terms of growth, since the internal humidity levels often fell below 40% and the temperatures were above 24˚C most of the time during the day, thus not within the optimum conditions for lettuce production. Although the internal climate of NVFG were more often optimal than that of greenhouse NVG (Figure 3.3 and Figure 3.4), the difference in plant growth between the varieties in the two greenhouses does not show such a significant difference, and in some cases the plants did better in NVG than in NVFG. Extremely high temperatures in a greenhouse, even if only experienced for a few minutes or hours can have direct implications on the plant growth. The delay in the fogging machines switching on caused the internal temperatures to reach high levels for too long. It is possible that this event occurred on several days during the 30 day experimental period, and not only during those two days.

The plants in the SNT experienced between 25% and 75% less growth than in the other greenhouses. Since conditions were similar to that experienced outside, the plants were exposed to low humidity and high temperatures during the day. At night, temperatures were often below the minimum acceptable level for lettuce production, which restricted optimal plant growth in terms of size and weight.

The amount and quality of light allowed through the cover of the greenhouse is also important to the plant development (Gonzalez-Real and Baille, 2006). Light measurements were not done inside the respective greenhouses. The colour differences in leaves of some of the varieties however indicate that the transmission of light through the respective greenhouse covers had an effect on the plants. The Gaugin variety displayed mostly green leaves in NVG and NVFG after the experimental period and red leaves in SNT (Figure 3.11 - Figure 3.13). The Xerafin variety (Figure 3.14 - Figure 3.16) showed similar results. This corresponds with results achieved by Shioshita *et al.* (2007) where red lettuce plant varieties grown outside, with higher UV-radiation produced smaller heads and more red coloration in the leaves than those grown in film-covered greenhouse tunnels. According to Shioshita *et al.* (2007) and Fourie (2015), UV intensity has a bigger influence on colour developing in red-leave lettuce plants than temperature or other climate conditions. The ideal results in terms of colour for this study were achieved in the plants planted in the shadenet tunnel (SNT). Although light measurements were not done, the SNT experienced more direct sunlight at plant level than the other greenhouses, which explains the difference in colour results.

3.7 Conclusion

The internal microclimates of the greenhouses were largely affected by the global solar radiation, and internal temperatures increased drastically during the morning with the increase of solar radiation. The relative humidity decreased similarly. The fogging in NVFG decreased the temperature inside the greenhouse by up to 8˚C and increased the relative humidity up to 80% from the 35% it was before the fogging system was switched on. The microclimates in the greenhouses were similar at night, with the temperatures in the polycarbonate greenhouses being only slightly higher than outside.

During the day the internal temperature for the shadenet greenhouse were similar to that of the external temperatures. The temperatures in the naturally ventilated greenhouse fitted with insect screens always experienced very high temperatures, almost always exceeding 30˚C during the day.

The microclimate was always more favourable for lettuce growth in the fog-cooled greenhouse compared to the other two. Although temperatures in the shadenet tunnel also proved to be sufficient, relative humidity were often too low for optimal conditions. Night-time temperatures in the shadenet were also too low and influences plant production. Plant yield was generally higher in the fog-cooled greenhouse for lettuce varieties Erasmus RZ and Cook RZ and slightly higher in the naturally ventilated greenhouse for varieties Gaugin RZ and Xerafin RZ. The colour of the red lettuce was maintained only in the shadenet greenhouse due to better light transmission. However, all lettuce varieties produced the lowest yield in the shade net greenhouse. The conditions achieved in the fog-cooled greenhouse would be preferable for many other types of plants, and a cost-benefit analysis should be done to determine whether the investment and operational costs associated with fogging can be justified by increased crop yield and quality.

3.8 References

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4 MODELLING CLIMATE CONDITIONS FOR THREE DIFFERENT GREENHOUSE DESIGNS

4.1 Abstract

Mathematical modelling can be used as a cheaper method to predict micro climatic conditions for different greenhouse designs in various South African climatic conditions. In this study, an existing model was used and tested for the ability to predict the internal microclimatic conditions for three different greenhouse designs using experimental results. The three designs included a naturally roof ventilated greenhouse, with the fixed vents fitted with insect netting; a naturally roof ventilated greenhouse fitted with a high pressure fogging system; and a simple shadenet tunnel. The most desired climatic conditions for greenhouse crop growth can be characterized by air temperature and air humidity. A simple model developed from greenhouse heat and water balance equations with two unknowns, temperature and humidity differences, incorporating both natural ventilation and fog cooling was selected. Certain variables from the equations were determined from literature. The experimental data was used to optimize coefficients for the different models. The developed coefficients were then used to calculate the predicted values of changes in temperature and relative humidity. This was subsequently analysed and compared to the actual measurements taken during the experiments to determine the accuracy of the model. Coefficients of determination and a regression analysis were done as part of the accuracy analysis. It was found that the accuracy of the model used for the shadenet tunnel was satisfactory in predicting the difference in external and internal temperature (R^2 = 0.85). The other models for the NVG and NVFG were less satisfactory (R^2 = 0.65 and R^2 = 0.63). The accuracy of the model to predict the other important factor, relative humidity in the form of vapour pressure, was unsatisfactory for all three greenhouses ($R^2 < 0.55$). To improve the accuracy of predictability for the unsatisfactory results from the models, variables that affect air exchange needs to be more accurately determined by collecting more detailed experimental data for these specific greenhouse designs. Further investigations can also be done to use more complex models such as CFD to accurately predict the temperature and humidity conditions.

4.2 Introduction

Mathematical modelling can be used to simulate and predict micro-climatic conditions inside greenhouses (Mashonjowa *et al*. 2013; Litago *et al.* 2005). Over the years, several different greenhouse climate models have been developed to evaluate or predict the performance of greenhouse designs (Abdel-Ghany and Kozai, 2006a, Abdel-Ghany and Kozai, 2006b).Certain developed models, based on energy and mass balance equations, can be classified as static, dynamic or homogeneous models (Abbes *et al*., 2010) and generally assume steady-state conditions and uniform distribution inside a greenhouse. Computational fluid dynamics (CFD) can be used for more complex real time micro-environment analysis, where crop requirements and air state variables are combined and measure the system performance over time or for heterogeneous models (Abbes *et al*., 2010) and can perform two- or three-dimensional numerical analysis of equations (Kittas and Bartzanas, 2007). Some models focus on specific phenomena, for instance, natural ventilation, forced ventilation, evaporative cooling, insect netting and heating.

Since most of the models have been developed for and applied to greenhouses in Europe and Israel, (Mashonjowa *et al*. 2013), the need exists to investigate the performance of traditional low-investment, as well as modern high-investment, greenhouses under South African climate conditions. Although, accurate results can be obtained by conducting experimental research in greenhouses across South Africa, it will be cheaper, quicker and more flexible to use models to predict or estimate micro-climatic conditions inside any greenhouse. Due to the many different agro-climatic zones in South Africa, the results obtained through experiments may also not be accurate and applicable throughout all the zones (Mashonjowa *et al*. 2013).

Experimental results from experiments done on three greenhouses with different cooling systems have been reported on in Chapter 3. The performance of typical cooling systems such as natural ventilation and evaporative cooling in a subtropical region were studied. The main aim of this study is to evaluate the performance of these three greenhouse designs. The specific objectives of the study are to use an existing model and the experimental data obtained, and evaluate the accuracy of the model to predict the performance of the identified greenhouses in terms of microclimate temperature and control systems for various external climates.

4.3 Modelling

The experimental design and data collection methods used are described in detail in Chapter 3. The following section describes the procedures that were followed in the process of modelling the climate conditions. The model developed by Boulard and Baille (1993) was used for modelling and predicting temperature (ΔT) and water vapour pressure (humidity) (Δe). The models were developed by linearization of the greenhouse heat and water balance equations.

The following factors were considered when the specific model was selected:

- Simplicity and ease of use (Baptista *et al.,* 2010, Abreu *et al.,* 2005),
- Its applicability to different cooling systems such as evaporative cooling from fogging and natural ventilation (Bouzo *et al*. 2006), and
- Low computational requirements (Lee *et al.,* 2013) by not using CFD modelling.

The selected equations for the water vapour and energy balance combination are provided in Table 2.2, Eq. 2-22, 2-23, 2-25, 2-26, 2-27 and 2-28 (Boulard and Baille, 1993).

4.3.1 Determination of model coefficients and constants

The coefficients a and b in Eq.2-22 were optimized by fitting experimental data to the selected models using IBM® SPSS® Statistics statistical and data management package (Katsoulas *et al.,* 2009). Eq. 2-22 was used in the non-linear regression application as the model expression. The non-linear regression application in the package was used to optimize the coefficients, and the Standard Error (SE) for each was determined from each calculation. ΔT was used as the dependant variable and the parameters that had to be determined and optimized by running the model were coefficients a and b. All other parameters required for the optimization of the selected models were obtained from the existing literature, since the values are within a narrow range (Boulard and Baille, 1993).

The methods used to determine the parameters that will be used in the analysis is summarized and presented in Table 4.1 below.

Table 4.1 Summary of methods to determine parameters

Parameter description	Unit	Method of determination
Inside/outside temperature (T_0, T_i)	Kelvin	Experimentally measured
Global solar radiation (G_0)	W.m^{-2}	
Wind speed (V)	m.s^{-1}	
Relative humidity (RH)	%	
Ventilation rate (N)	h^{-1}	Calculated values based on formulas (Boulard and Baille, 1993)
Coefficient of ventilation heat exchange for sensible heat (K_s)	W.m^{-2}.K^{-1}	
Coefficient for latent heat (K_1)	W.m^{-2}.Pa^{-1}	
Heat transfer coefficient of the cover (K_c)	W.m^{-2}.K^{-1}	
Outside vapour pressure deficit (D_0)	Pa	
Effective cooling rate (F)	W.m^{-2}	
Vapour pressure difference (VPD) between the greenhouse and outside (Δe)	Pa	
Coefficient A, B	Dimensionless	Determined from literature presented in Table 4.2 below
Solar efficiency (η)	Dimensionless	
Canopy absorption coefficient (α)	Dimensionless	
Greenhouse global transmission (τ)	Dimensionless	
Slope of water vapour saturation curve at T=T_0 (δ)	Pa.°C^{-1}	
Air density (ρ)	kg.m^{-3}	
Air thermal capacity (C_p)	J.kg^{-1}.C$^{\circ-1}$	
Latent heat of vaporization (λ)	J.kg^{-1}	
Wind coefficient (C)	Dimensionless	
Discharge coefficient (ζ)	Dimensionless	
Conversion factor between air and vapour content (γ)	kg$_w$.kg$_a^{-1}$.Pa^{-1}	
Water application rate (W)	kg.m^{-2}.h^{-1}	Experimental values
Surface of ventilation openings (S_o)	m^2.m^{-2}	
Greenhouse volume (V_g)	m^3	
Greenhouse ground area (S_g)	m^2	

4.4 Data Analysis

Table 4.2 provides the values for the parameters that were determined from literature and used to optimise the remaining coefficients and constants in the models. The value of the greenhouse global transmission (τ) for the shadenet greenhouse was taken from a study done by Kitta *et al.* (2014) on predicting evapotranspiration for greenhouse grown crops where a dark green shadenet material was used. The values for the other two greenhouses were taken from studies done on polycarbonate covered greenhouses in a study done by Wang and Deltour (1999).

Table 4.2 Values of parameters recorded and determined from literature

Parameter	**Greenhouse**	**Value**	**Reference**
A	a, b, c	6	Boulard and Baille (1993)
B	a, b, c	0.5	Boulard and Baille (1993)
η	a, b, c	0.65	Boulard and Baille (1993)
α	a, b, c	0.95	Bouzo *et al.* (2006)
τ	a, b	0.70	Wang and Deltour (1999)
	C	0.56	Kitta *et al.*(2014)
δ (Pa.°C^{-1})	a, b, c	$\frac{-53\ 8\ 5}{T^2} 2.229\text{x}10^{11} e^{\left(\frac{-53\ 8}{T}\right)5}$	Impron *et al.*(2007)
e_s	a, b, c	$2.229\text{x}10^{11} e^{\left(\frac{-53\ 8}{T}\right)5}$	Impron *et al.*(2007)
ρ (kg.m^{-3})	a, b, c	1.204	Abreu *et al.* (2005)
C_p (J.kg^{-1}.C$^{\circ-1}$)	a, b, c	1010	Abreu *et al.* (2005)
λ (J.kg^{-1})	a, b, c	2454000	Abreu *et al.* (2005)
$\zeta C^{0.5}$	A	0.028	Katsoulas *et al.* (2006)
	B	0.18	Boulard *et al.* (1997)
	C	0.043	Teitel and Barak (1999)
γ (kg$_w$.kg$_a^{-1}$.Pa^{-1})	a, b, c	$6.25\text{x}10^{-6}$	Boulard and Baille (1993)
W (kg.m^{-2}.h^{-1})	B	0.35	Experimental recorded values
S_o (m^2.m^{-2})	A	0.33	
	B	0.22	
	C	1.20	
V_g (m^3)	A	1782	
	B	891	
	C	600	
S_g (m^2)	A	324	
	B	162	
	C	200	

Soil evaporation is ignored due to the fact that soilless crop production is used. Condensation is ignored during the modelling, due to the data that applies to day time summer/autumn periods, where condensation is not common. Heat storage (thermal mass of the greenhouse) can be neglected since it is much smaller than the other heat factors. It is also assumed that the high pressure fogging system that is used does not result in dripping and that all sprayed water is vaporized. Certain parameters regarding crop and greenhouse cover were taken from literature where similar greenhouse studies have been conducted.

The wind related coefficient ($\zeta C^{0.5}$) for the developed model for NVG was obtained from the experiments and modelling done by Katsoulas *et al.* (2006) on a naturally ventilated greenhouse with a 55 mesh size that functions as insect cover on the vents, which is similar to the 50 mesh installed on the experimental greenhouse. For greenhouse (b), this value was obtained from a model developed and reported by Boulard *et al.* (1997) for natural ventilation in a greenhouse with continuous roof ventilation, without insect nets. The value for the same parameter for a shadenet tunnel was acquired from the study done by Teitel and Barak (1999) on the impact of insect screens on ventilation, using a 22% insect screen, which is similar to the 20% shadenet used in this experimental study.

Day-time climate measurements, where solar radiation was found to be above zero for five similar external climatic conditions during the experimental period, were used for the modelling. Since the specific equations for natural ventilation ignores the stack effect for V > 1 $m.s^{-1}$ (Boulard and Baille, 1993; Abreu *et al.,* 2005), data was further filtered to exclude the data for where V < 1$m.s^{-1}$ only take into account the relevant data points in order to test the validity. After the experimental data was filtered based on the latter conditions, 215 data points were used in the application of the model for each greenhouse. The predicted values for the difference between the internal and external temperatures and vapour pressure (ΔT and Δe) were determined using Eq. (2-22) and Eq. (2-23) respectively, along with the optimized coefficients and experimental data.
In order to test the suitability of the model, the predicted values were compared to the actual measured values.

4.5 Results

The results obtained by optimizing coefficients for the equations and the model suitability test results of the model, as per the selected model, for the different greenhouses are presented in this section. The estimated coefficients (a and b) and standard errors were determined by using the IBM® SPSS® Statistics statistical and data management package and are presented in Table 4.3. The coefficient of determination (R^2) was calculated and residual analysis was done to determine the suitability of the model to each different greenhouse. Coefficient of determination (R^2) was determined by plotting the data points using Microsoft Excel. Suitability was further tested by calculating the residual analysis, which was used to determine whether additional terms in the model would be useful. The residual analysis was done by plotting the residual ($\Delta T_{measured} - \Delta T_{predicted}$) against $\Delta T_{predicted}$ and other independent variables in the model. The findings are summarized in Table 4.3.

Table 4.3 Summary of factors describing the suitability of the three applied models: n=number of observations used; SE = Standard Error; R^2= coefficient of determination

	n	**a**	**SE (a)**	**b**	**SE (b)**	**R^2 for ΔT**	**R^2 for Δe**	**Residual analysis**
NVG	215	0.482	0.056	0.002	0.001	0.65	0.55	Non-randomly distributed
NVFG	215	0.495	0.025	0.001	0.001	0.63	0.45	Non-randomly distributed
SNT	215	-1.198	0.531	0.052	0.015	0.85	0.48	Randomly distributed

4.5.1 Evaluation of model suitability NVG

Figure 4.1 presents the measured and predicted values for the difference between inside and outside temperatures (ΔT) of the NVG over day-time with the optimized coefficients being a=0.482 and b=0.002, as presented in Table 4.3. The predicted data generally followed the same pattern as that of the curve of the measured data over the five day period. The measured ΔT values remained higher than the predicted values, especially during the day-time. Although the data followed the same pattern, the predicted values presented a more uneven curve when compared to that which represents the measured data, where frequent dips and spikes are apparent. The peaks presented by the predicted values are seen in the data when there is a sudden increase or decrease in external wind speed. This might mean that the actual climate in the greenhouse is not as sensitive to change to the external conditions as the model is.

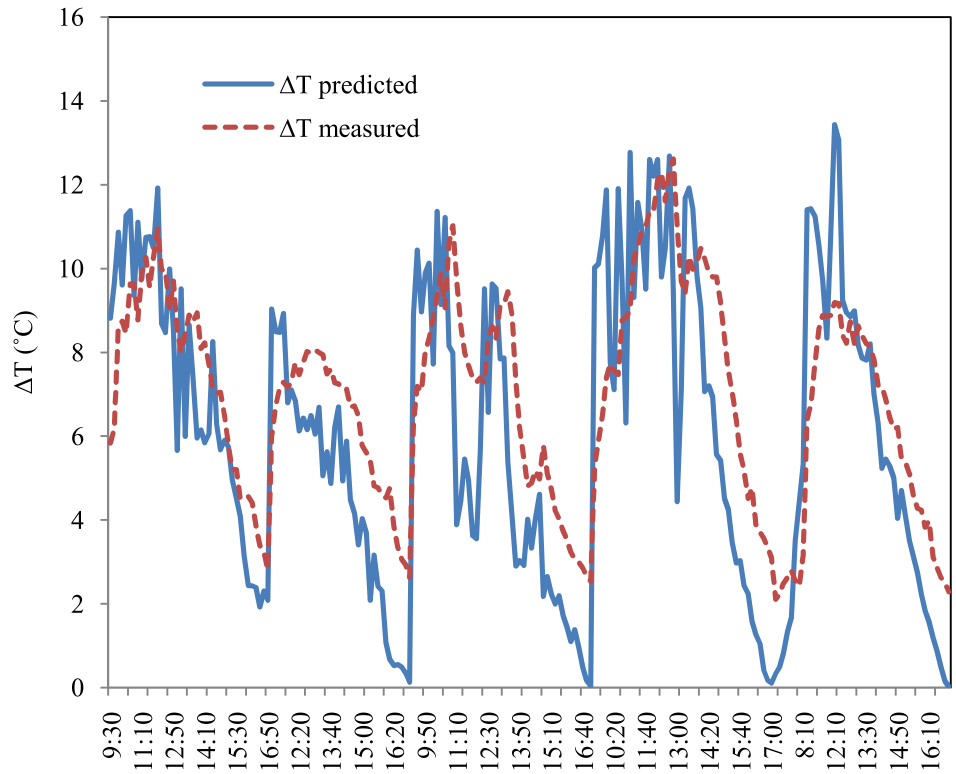

Figure 4.1 Time courses of the difference in temperature in the natural ventilated greenhouse (NVG)

Figure 4.2 presents the comparison of the measured and calculated data and the associated coefficient of determination (R^2=0.65). This coefficient of determination does not represent the best fit (Mashonjawa *et al.,* 2013; Litago *et al.,* 2005). The below graph makes it clear that there are a number of outliers where the difference between the measured and calculated values is up to 5 and 6 °C. The amount of data points where the predicted values are much higher or lower than the measured values specifically impacts the accuracy and skews the regression line. It is also clear that the difference in internal and external temperatures for the predicted and measured values is never zero.

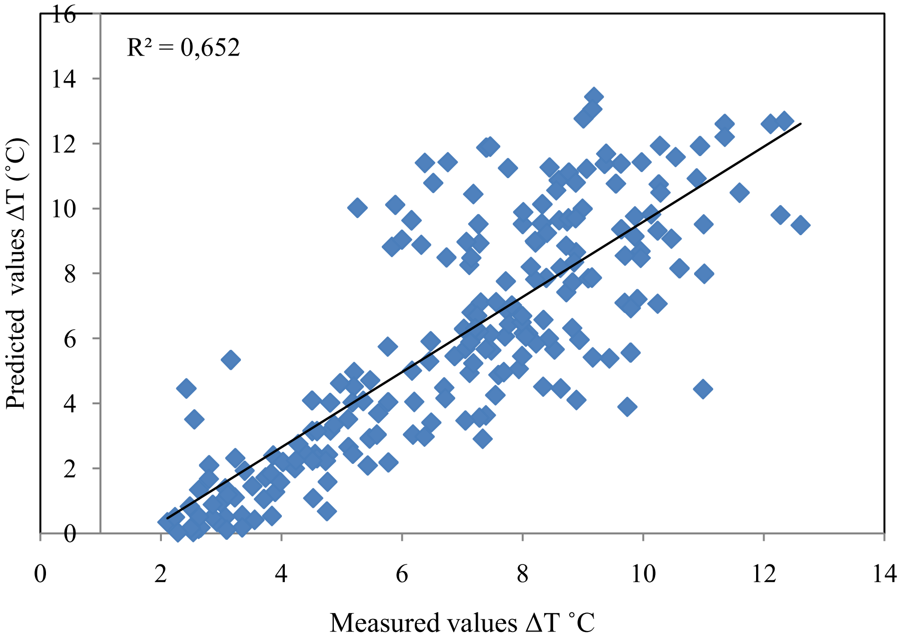

Figure 4.2 Predicted and measured values for ΔT in the NVG; R^2, coefficient of determination

The predicted values for ΔT were used and fitted into Eq. (2-23) to predict the difference in the inside and outside water vapour pressure (Δe). Figure 4.3 shows the comparison against the values measured for NVG. The predicted values are not in the same scale as the measured values, and the model can thus not be used to predict the water vapour pressure of this greenhouse. The measured values show that the differences between the internal and external vapour pressure are much smaller than what was predicted.

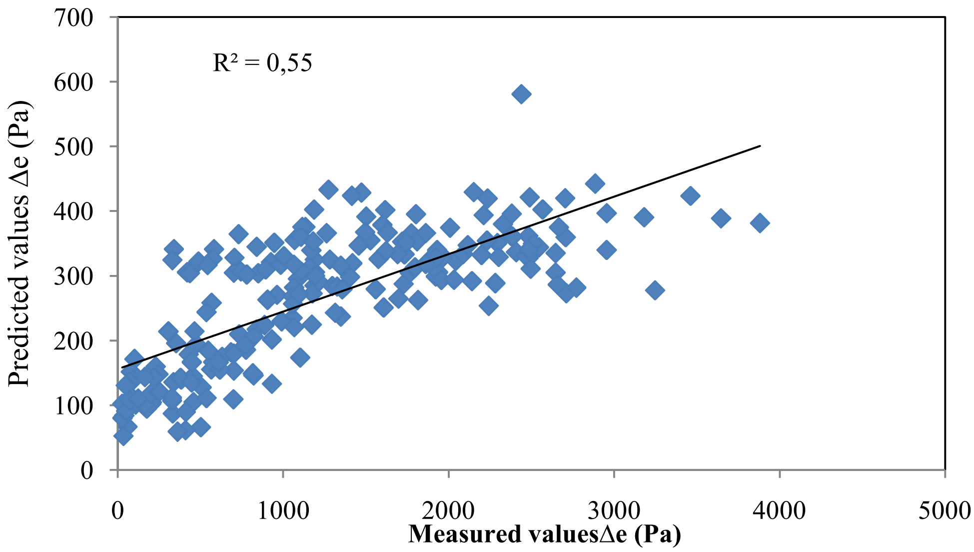

Figure 4.3 Predicted and measured values for Δe in the NVG;

4.5.2 Evaluation of model suitability NVFG

Figure 4.4 presents the measured and predicted values for the difference between inside and outside temperatures (ΔT) of the NVFG over time with coefficient a=0.459 and b=0.001. The temperatures inside the greenhouse were often lower than the external temperatures which explain the negative values of ΔT, for both the measured and predicted results. This is due to the fogging switching on at certain temperatures which drastically reduces the internal temperatures as well as the model calculations presenting the same. This corresponds with findings from Boulard and Baille (1993) and experimental results from studies done by Katsoulas *et al.* (2009) and Ishii *et al.* (2006). The negative values are also seen in Figure 4.5, where the predicted and measured values show that the outside temperature is higher than the inside temperature. The predicted data generally follows the shape of the curve of the measured data over the five-day period, although it was often lower than the measured values. Both the measured and predicted graphs vary over time. In cases where the global radiation decreases, wind speed increases and fogging is applied, the predicted values are much lower than the actual measured ΔT. This is also seen for the opposite situation, where the wind speed and global solar radiation increase and fogging is applied, resulting in higher predicted values when compared to the actual measured values.

Figure 4.5 presents the comparison of the data and the calculated coefficient of determination (R^2=0.63), which represents a relatively poor fit (Mashonjawa *et al.,* 2013; Litago *et al.,* 2005). The graph shows some outliers in the data and in some cases the difference between the predicted and measured values are up to 6°C. The graph again proves that the inside and outside temperatures are never the same.

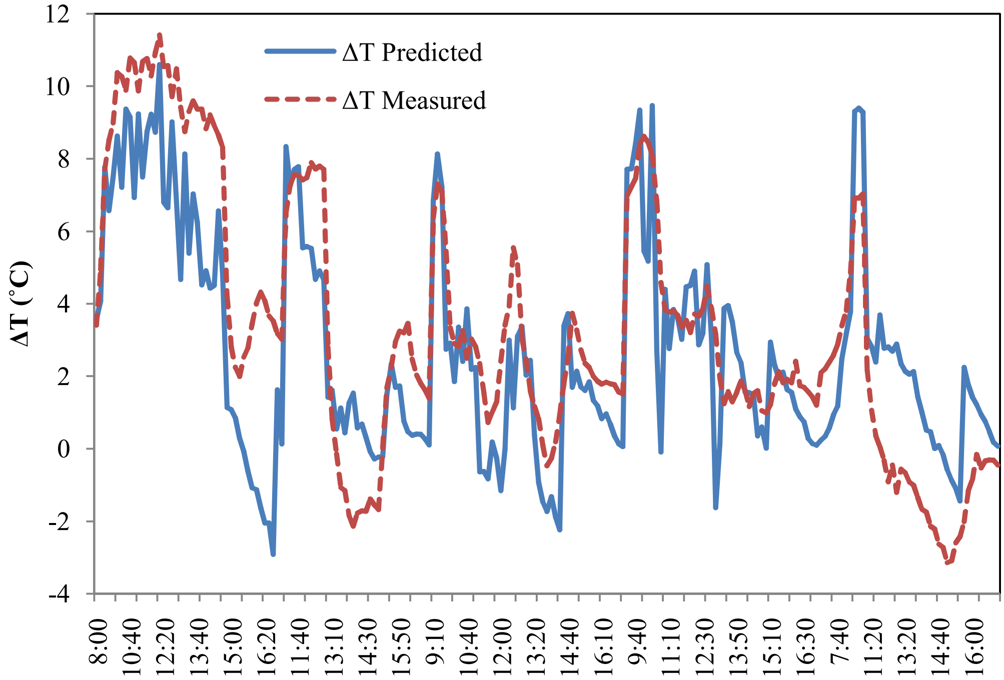

Figure 4.4 Time courses displaying the difference in temperature in NVFG

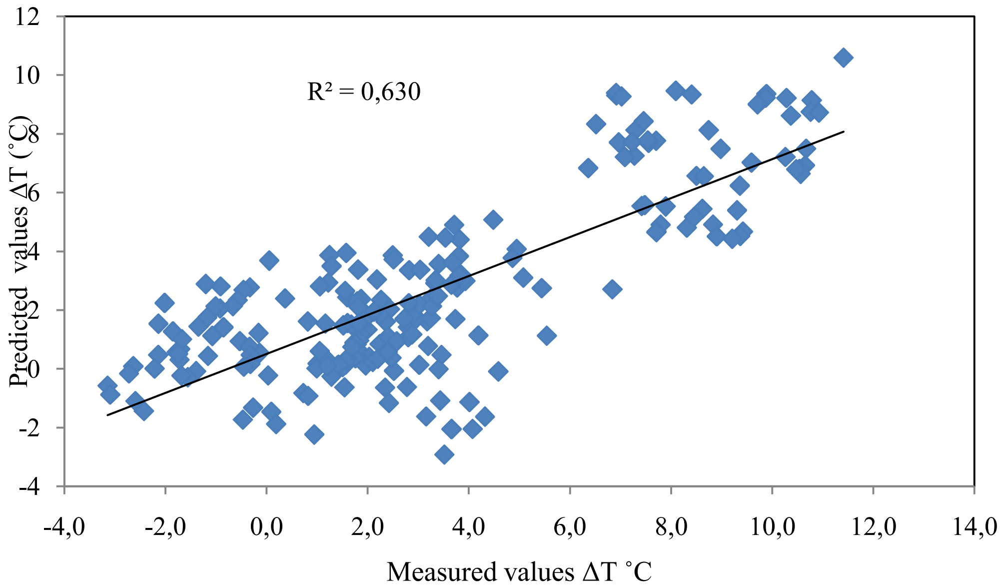

Figure 4.5 Predicted and measured values for ΔT in NVFG; R^2, coefficient of determination

Figure 4.6 below shows the comparison of the predicted values of Δe, by using Eq.(2-23), against the measured values and the coefficient of determination ($R^2 = 0.45$) for the NVFG model. This shows a poor fit to the model and can thus not be used to accurately predict the vapour pressure difference in the greenhouse. In some instances, there is a difference ranging from approximately 800 up to 1000 Pa between the measured and predicted values.

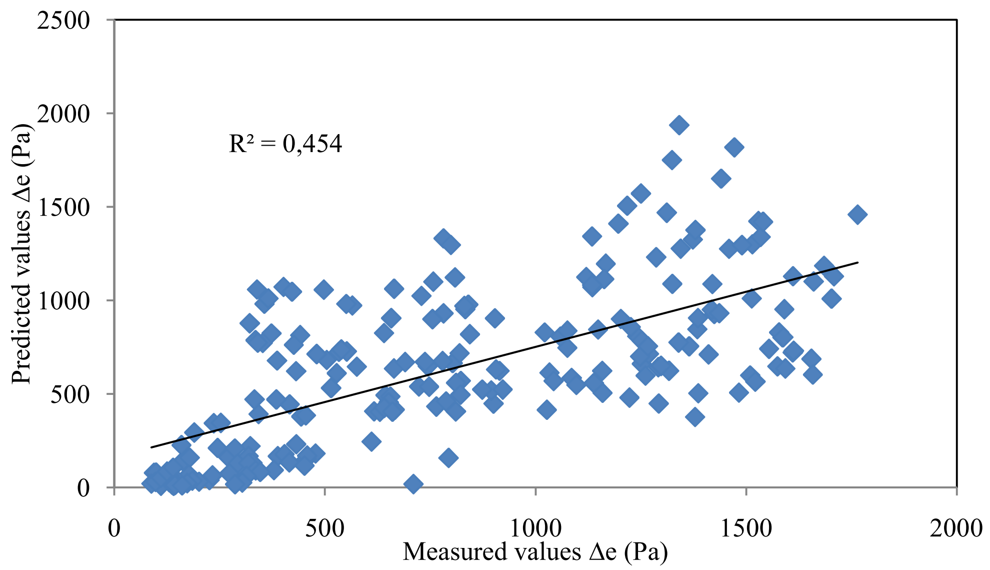

Figure 4.6 Predicted and measured values for Δe in NVFG; R^2, coefficient of determination

4.5.3 Evaluation of model suitability SNT

Figure 4.7 shows the measured and predicted values for the difference between inside and outside temperatures (ΔT) of the SNT over time with coefficient a = -1.198 and b = 0.052. Negative values of ΔT are again explained by the temperatures inside the tunnel sometimes being slightly lower than the external temperatures for both the measured and predicted results. The predicted data generally follows the shape of the curve of the measured data over the five-day period. Figure 4.8 presents the comparison of the data and the coefficient of determination (R^2 = 0.85). This coefficient represents a good fit to the model with minimal outliers in the data (Montgomery and Runger, 2007).

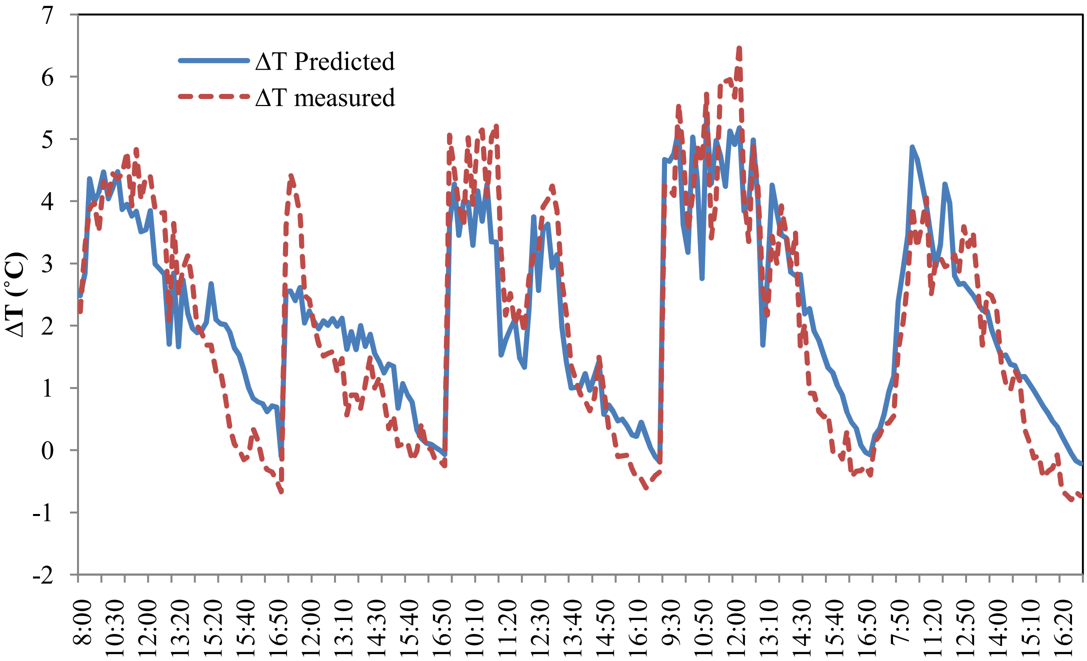

Figure 4.7 Time courses of the difference in temperature in SNT

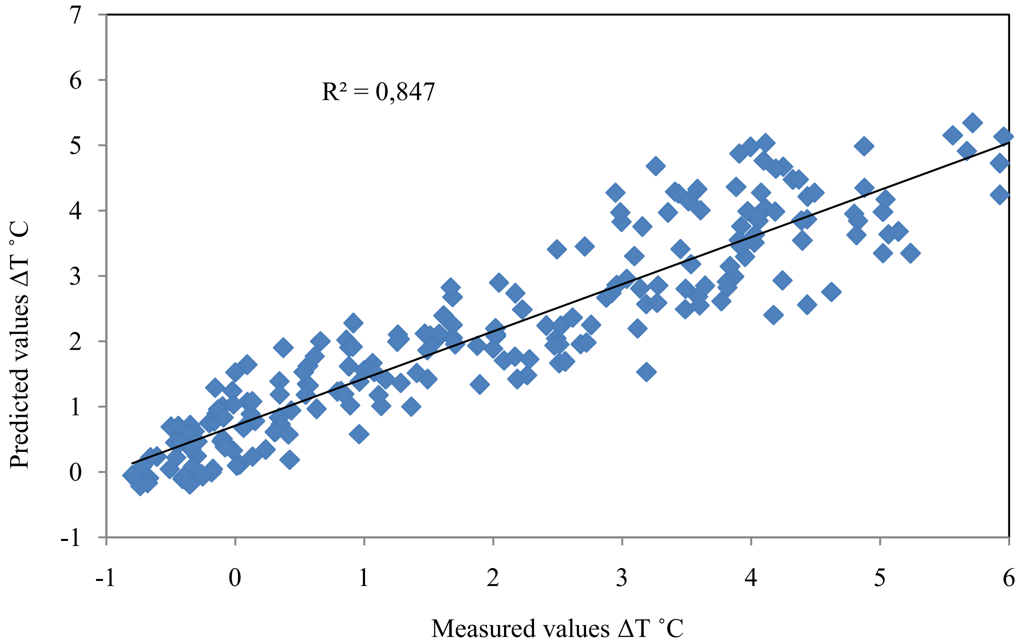

Figure 4.8 Predicted and measured values for ΔT in the SNT; R^2, coefficient of determination

Figure 4.9 below shows the comparison of the predicted values of Δe, by using Eq. (2-23) against the measured values and the coefficient of determination (R^2=0.50) for the SNT model. There are many outliers in the data with differences in the measured and predicted values of between 200 and 400 Pa. Although it is an improvement compared to the other two greenhouses, it still shows a poor fit to the model and can thus not be used to accurately predict the vapour pressure in the SNT.

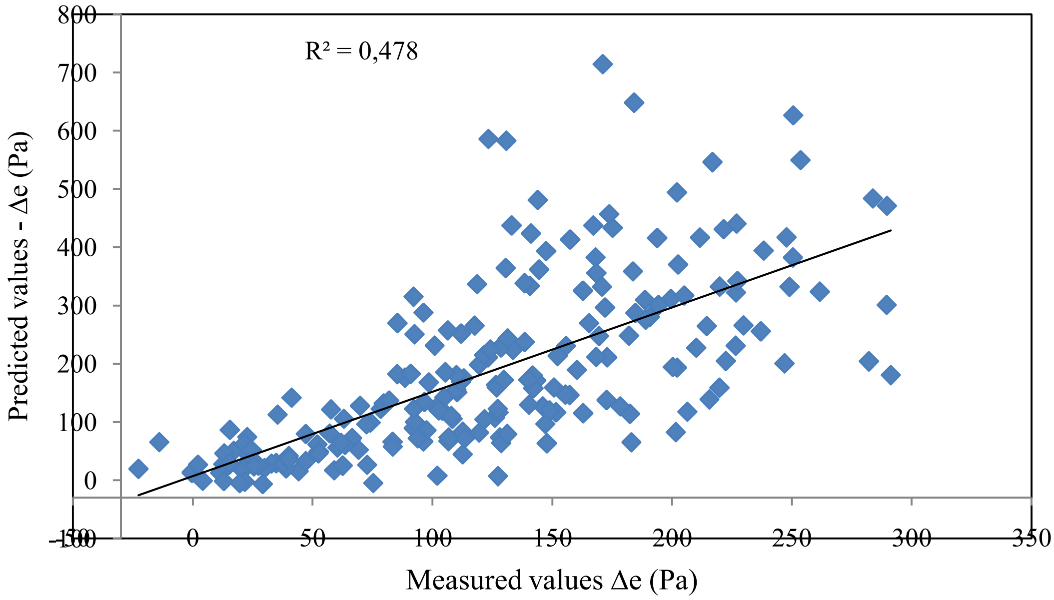

Figure 4.9 Predicted and measured values for Δe in the SNT; R^2, coefficient of determination

4.5.4 Residual analysis

A residual population analysis was performed for ΔT for each greenhouse and plotted against the dependent and other variables such as solar radiation. If any of these plots are randomly distributed, the model represents a good fit and it is not necessary to add additional terms to the model (Montgomery and Runger, 2007). The results for the NVG (Figure 4.10) and NVFG (Figure 4.11) show non-random distribution of the data, and are thus not a good fit for the model. The only residual analysis that represented a randomly distributed plot was the SNT model shown below in Figure 4.12. The residual population analysis also represents a good fit if 95% of the errors fall within the interval [-2, 2]. A frequency distribution was performed with regard to the residuals calculated for each model (Montgomery and Runger, 2007). Only approximately 52% of the errors from the residual analysis done on the NVG and 61% of the errors from the NVFG were within the specified interval. However, 95% of the errors from the SNT were within this interval, indicating a good fit for the model. The frequency distribution for the SNT is presented in Figure 4.13 below.

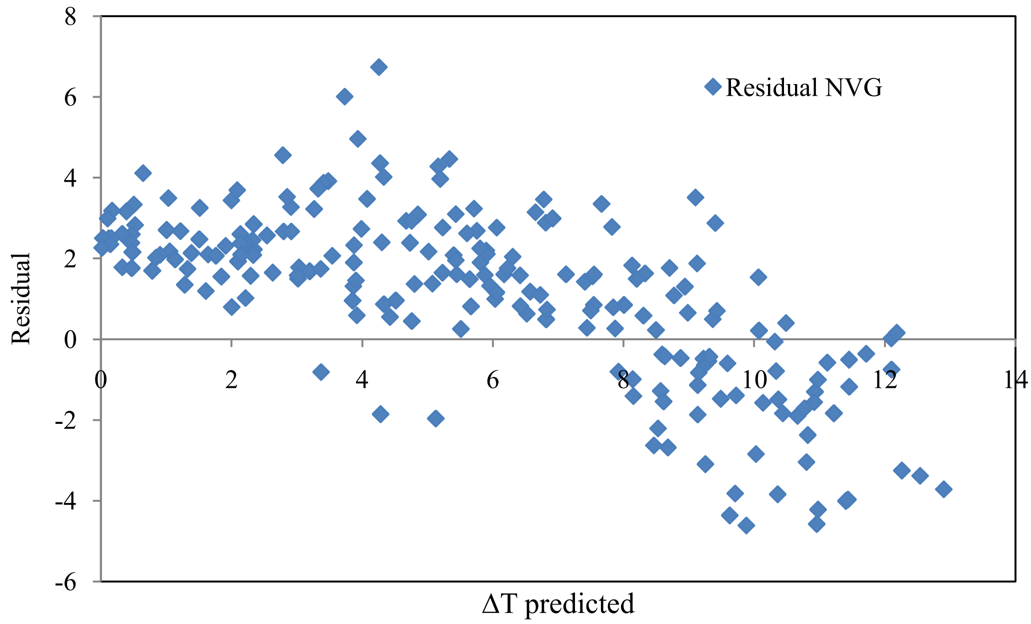

Figure 4.10 Residual analysis for the NVG model

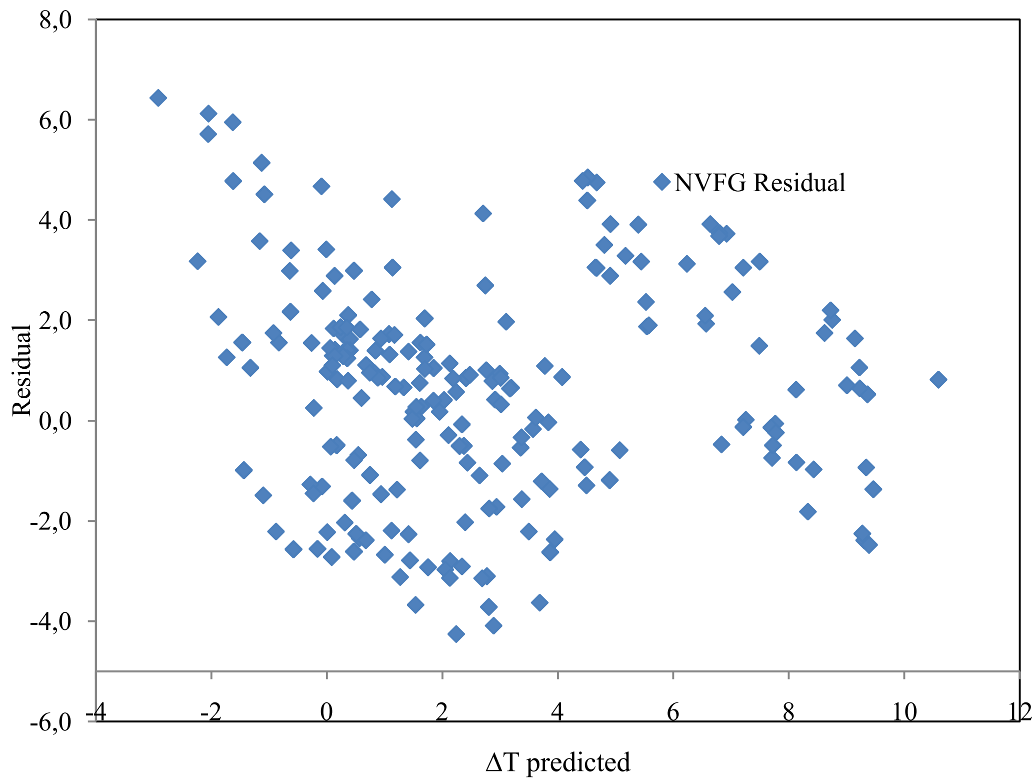

Figure 4.11 Residual analysis for the NVFG model

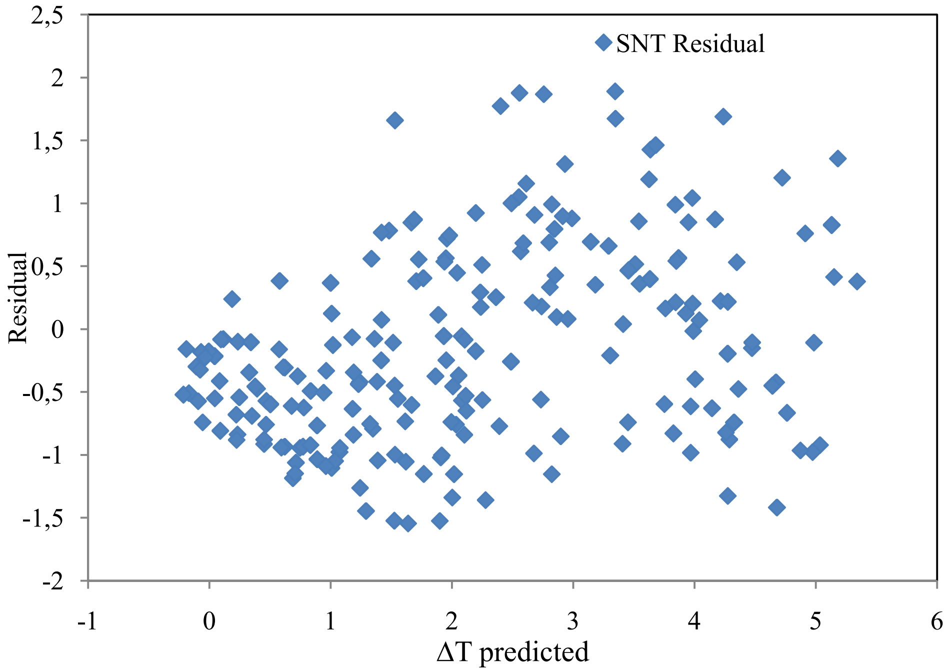

Figure 4.12 Residual analysis for the SNT model

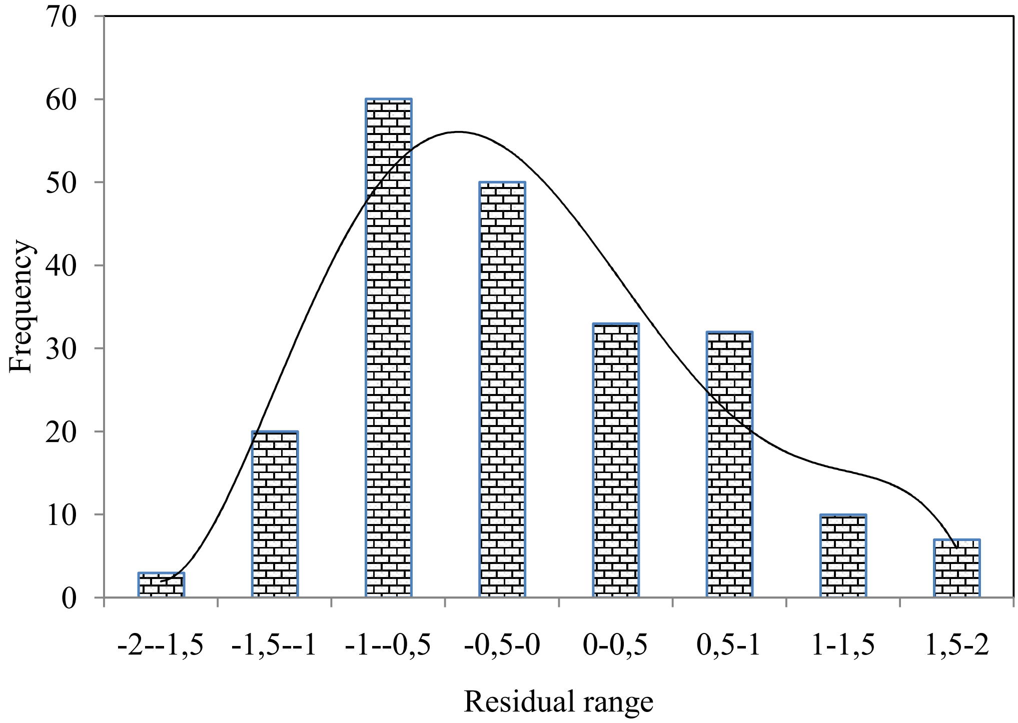

Figure 4.13 Frequency distribution graph for the residual values from the SNT model

4.6 Discussion

Many models have been developed to try and accurately describe and predict the complexity of the phenomena involved in heat and mass exchanges inside a greenhouse. Complex models exist that are in many cases difficult to validate with experimental data and often requires large computing capacity. The more variables there are, the more complicated it becomes to apply one model to various different greenhouse designs.

The simple model developed by Boulard and Baille (1993) that was used in this study has been proven to be sufficient to predict two important climate factors in naturally ventilated and fog-cooled greenhouses. These factors include internal temperature and relative humidity. The crop transpiration rate and temperature could also be determined by the model, but was not used during this study. The same model was applied to the three different greenhouses, although only one greenhouse was fitted with a fogging system.

4.6.1 Model suitability for predicting temperature

Abreu *et al.* (2005) used similar equations to select a suitable greenhouse ventilation model and estimated that a = 0.235 and b=0.0218 where the leaf area index is (LAI) <3 and a = 0.321; b = 0.0095 where the leaf area index is (LAI) >3. The coefficients a and b that were estimated for the NVG, NVFG and SNT were similar to that found by Abreu *et al*. (2005). The SE values related to these estimates were also smaller than 0.05, except for the coefficient a, determined for the SNT, which implies that it is not an accurate estimate of the value. However, these values were used to further estimate ΔT and Δe for the different greenhouses. The coefficient of determination was found to be 0.652 for the data from the NVG (Figure 4.2). This means that the applied model accounts for 65.2% of the variability in the data. For the NVFG, R^2 was 0.63, and thus 63% accurate. The model was best suited to the SNT, where R^2 was 0.85 and was thus 85% accurate.

In addition to this suitability test, the residual values were determined and plotted against the dependent and other variables such as global solar radiation. Again, only the SNT model was shown to be the most suitable, because of the plot being randomly distributed. The residual values for the SNT model ranged between -2 and 2 and thus also confirmed accuracy.

The variances in the data sets representing the predicted and calculated values of ΔT against the time courses can be seen for each greenhouse (Figure 4.1, Figure 4.4 and Figure 4.7). The graph for the predicted ΔT from the NVG analysis at times displayed sudden spikes and dips in ΔT, where the measured ΔT graph presents more gradual changes. The data shows that these sudden changes in the predicted values are experienced when the global solar radiation (G_0) drastically drops, possibly caused by cloud cover, between two time intervals. Sudden changes in the predicted values are also apparent with the increase in external wind speed and where the global solar radiation gradually changes. This corresponds with findings by Villarreal-Guerrero *et al.* (2013). From this information it can be deduced that the changes in temperatures predicted by the model for the NVG is more sensitive to changes in global solar radiation and wind speed than the actual internal measured greenhouse conditions. It also corresponds with findings by Buozo *et al.* (2006) where modelling and experiments were done on a naturally ventilated greenhouse fitted with fogging. This large number of outliers, also visible from Figure 4.2, explains the weak coefficient of determination and a poor model fit (Montgomery and Runger, 2007). The wind coefficient factor used in the natural ventilation calculation was determined from literature, used for greenhouses fitted with insect netting over the roof vents. The wind coefficient factor influences the natural ventilation capacity and impacts the change in temperature (Bouzo *et al.,* 2006). The model was run using a lower wind coefficient value and resulted in the coefficient of determination increasing slightly to 0.7. The residual analysis, however, still remained non-randomly distributed.

Although the prediction of the effect of fogging on the reduction of temperature is mostly in line with the actual measurements, it is visible from the NVFG data (Figure 4.4) that at certain intervals, the predicted values for ΔT vary from the measured values. Similar to the NVG graphs (Figure 4.1), the finding that the predicted values for ΔT are much lower than the actual values measured when global radiation decreases and wind speed increases and fogging is applied corresponds with findings reported by Bouzo *et al*. (2006) and Villarreal-Guerrero *et al.* (2013). There are time periods where the measured values are lower than the predicted values, specifically seen when the global radiation increases, wind speed decreases and fogging is applied. It can therefore be interpreted that, in the case of the NVFG model, the model is more sensitive to change in the external conditions than conditions experienced in the actual greenhouse. If the wind coefficient is reduced for this model, the coefficient of determination does not change significantly and the residual analysis plot remains non-randomly distributed. The suitability of this model applied to the NVFG remains average.

From Figure 4.7, it is seen that the measured and the predicted data plotted for the SNT model shows close correlation with the graphs throughout the period. This means that the internal climate conditions in the tunnel can be accurately predicted by using the developed model.

4.6.2 Model suitability for predicting vapour pressure difference

The application of the model in the prediction of vapour pressure differences was unsuitable as R^2 values for the NVG, NVFG and SNT greenhouses were 0,55 0,45 and 0,48, respectively.

With regard to the NVG model, the predicted value for Δe is continuously much higher than the actual measured difference between the internal and external vapour pressure difference. The predicted values for Δe for the SNT are closer to the actual measured data, but the analysis still shows a low coefficient of determination. The difference between the data of the three greenhouses that influences the large predicted values of Δe in the NVG compared to that of the NVFG and SNT were briefly investigated. The factor that was found to most significantly influence the dependent variable Δe is one of the aeration factor K_1. This corresponds with findings in the Boulard and Baille (1993) and Villarreal-Guarreo *et al*. (2012) studies. K_1 is a factor of natural ventilation air exchange, constants and the greenhouse size. The larger the natural ventilation factor, the larger the K_1 value, and the lower the predicted Δe values. In the case of the NVG model, it can therefore be deduced that the low natural ventilation values calculated contributes to the large difference in values that do not correspond with the actual measured data.

With regard to the NVFG model, the actual and predicted values for Δe mostly follow similar trends when plotted over the five-day period and the specific values do not vary as much as experienced in the NVG model. It is only during fogging in the NVFG when internal relative humidity increases, that the predicted Δe is much lower than the actual measured values and that the fogging has a much bigger effect on the vapour pressure inside the greenhouse. This shows that the model cannot sufficiently predict the effect of fogging on the vapour pressure in the greenhouse.

For the SNT model, the calculated values for Δe are mostly higher than the actual measured values. The largest differences are seen when there is a reduction in the calculated natural ventilation values. This shows that the effect of the change in air exchange has less of an impact on the actual measurements than what the model represents.

Thus, for all three models, the accuracy in predicting the vapour pressure difference is poor. This can be improved by using modified wind, aerodynamic and crop coefficients factors influence the inside humidity (Bouzo *et al.,* 2006). Since predicting RH as part of the internal microclimate conditions in a greenhouse is critical to determining the best suited design, future work has to be done to improve the accuracy and suitability of the model.

4.7 Conclusion

The coefficients that were optimized using the mathematical equations and experimental data were similar to coefficients determined during another study in past literature on the subject and the standard errors calculated for the coefficients were mostly below 0.05. The predicted values for the difference between the internal and external temperature and vapour pressure were determined by using these coefficients.

The accuracy of the models developed to predict ΔT for the three different greenhouses were only satisfactory for the SNT. With regard to the other models the accuracy was less satisfactory and proven to be more sensitive to change in the external conditions such as global solar radiation and wind speed than to what was actually experienced in the greenhouses. To improve the accuracy of predictability, variables that affect air exchange need to be more accurately determined by collecting experimental data for these specific greenhouse designs. The factors that influence the effect of global solar radiation can also be more accurately determined by measuring the solar transmission of the covers and determining the actual solar efficiency.

The accuracy of the models developed to predict the difference between the internal and external vapour pressure were unsatisfactory with regard to all three greenhouses. Similar to predicting the difference in temperature, it is evident from the data that the air exchange has a more significant effect on the predicted vapour pressure than on the actual conditions. The complexity in specifically measuring the effect of the fogging applied to the internal greenhouse should be considered and perhaps complex models should be used to predict this more accurately.

From the results from testing the model in this study, only the micro climatic conditions for a shadenet tunnel can be accurately predicted within different external agro climatic conditions. This suggests that it will be helpful with regard to the development of low-cost infrastructure for agricultural production in different provinces within South Africa.

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5 FINANCIAL COMPARISON OF THREE GREENHOUSE DESIGNS

5.1 Abstract

As much as the capacity of a specific greenhouse design should be able to obtain optimal internal climate conditions, a critical factor to firstly consider is whether the capital expenditure for the greenhouse infrastructure can be justified. In South Africa, the benefits of investing in more advanced controlled environmental agriculture have not been sufficiently researched and documented. In this study, the capital costs as well as equipment operation costs for the three different greenhouses were captured and compared. The three designs included a naturally roof ventilated greenhouse (NVG), with the fixed vents fitted with insect netting; a naturally roof ventilated greenhouse fitted with high pressure fogging system (NVFG); and a simple shadenet tunnel (SNT). The yearly operating and maintenance cost for the equipment for NVG, NVFG and the SNT are calculated to be R60 114, R 76 157 and R 5 072, respectively. The capital costs associated with each greenhouse are R 380 000, R 1 571 520 and R 30 000, respectively. The equipment operating and maintenance costs of the SNT are approximately ten times lower than the costs associated with the NVG and NVFG and the capital cost approximately fifty times lower than that of the NVFG. The equipment operating and maintenance costs for the NVFG and the NVG are similar, while the capital investment required for the NVFG is approximately four times higher than the NVG. The equipment operating and capital costs associated with a bigger 1ha structure with specific design specifications were predicted and compared with the experimental greenhouses. It was found that, with the exception of the SNT, it is cost-effective to construct larger greenhouses for crop production.

5.2 Introduction

Greenhouse production can lead to higher yields per hectare, compared to open field cultivation, because of the optimal growing conditions and balanced plant nutrient supply (Jensen, 2002). In some cases, it has shown up to five times higher crop production than growing in an open field. Greenhouse crop production can be classified as one of the most intensive forms of agriculture (Djevic and Dimitrijevic, 2009). It is expensive and energy-intensive and, therefore, needs to be significantly more productive to be competitive, compared to open field agriculture (Jensen, 2002), before the decision is made to invest. In terms of greenhouse construction and design in South Africa, greenhouse suppliers, regularly take the role of designing the complete greenhouse structure and environmental control systems for a specific investor. International suppliers in particular rarely take the local climate and economic conditions into account at all (Venter, 2013). Suppliers use their own design techniques based on models or experience and have their own limited range of products. Therefore the resulting greenhouse may not be the most desirable outcome for the investor.

When it comes to the economic analysis of greenhouse production, different studies have been done to compare costs associated with greenhouses production. The main greenhouse crop production costs can be identified as construction, energy (indirect and direct), labour and supply costs (Short, 2004; Djevic and Dimitrijevic, 2009). Direct energy inputs relate to the fuel energy inputs used for heating a greenhouse, such as wood, coal, oil and gas (Djevic and Dimitrijev, 2004). Indirect energy inputs relate to energy used in the production processes, for example equipment, fertilizers, chemicals, labour and transportation (Djevic and Dimitrijev, 2004). Running equipment that would require energy would include irrigation, climate control computers, cooling, heating, ventilation and humidification systems (Short, 2004). Production costs, income and capital costs required for sweet pepper production in different greenhouse systems have been analysed and compared for Almeria, Spain, and the Netherlands (Pardossi *et al.*, 2004). Similar studies have been done for greenhouse operations in Turkey (Canakci and Akinci, 2006) and Iran (Heidari and Omid, 2011), comparing the cost-benefit ratios for cucumber, pepper and tomato production on different greenhouse systems. Water use efficiency has been compared with regard to different greenhouse production types in different countries (Pardossi *et al.,* 2004). Energy consumption as relates to different greenhouse designs in

Serbia has been evaluated by Djevic and Dimitrijevic (2009), taking into consideration direct and indirect energy input costs. Energy usage in a naturally ventilated, fogged cooled greenhouse in the USA has been evaluated by Villameal-Guerrero *et al.* (2012), without comparing it to other system designs. Water and energy consumption of a greenhouse was evaluated, under different fog rates and ventilation opening by Villameal-Guerrero *et al.* (2013).

A model-based approach to inform financial investment and greenhouse design is shown in Figure 2.1. A large amount of data collection is required to do a full cost-benefit analysis on different greenhouse structures and designs. Market prices, crop yield, resource consumption input costs and other economic variables have to be considered in order to evaluate the economic feasibility of a greenhouse system.

Limited literature is available detailing the evaluation of production and operating costs when it comes to different greenhouse designs in South Africa. In order to do a detailed cost-benefit analysis of each greenhouse type in different areas of South Africa, detailed information on the costs related to construction, energy (indirect and direct), labour and supply costs are required. To study the benefits, long-term crop response to the different climate conditions during each season and financial gain should be studied.

In the previous chapter, the performance of three different greenhouse designs was evaluated in terms of climate management and growth of lettuce crops. The objective of this study is to compare costs associated with different greenhouse designs and their equipment requirements. Since heating was not used in these greenhouses, it is excluded from the study and only construction costs and equipment operation and maintenance costs for these three greenhouses were compared. Labour and other indirect costs were not captured and are excluded from the analysis. Since a typical greenhouse size for farming in South Africa is bigger than 1ha (de Visser and Dijkxhoorn*,* 2012), costs associated with a 1ha greenhouse, with added climate control systems and equipment were added, and were also projected and compared to the smaller experimental greenhouses.

5.3 Methodology

Certain parameters of the equipment of each different greenhouse that influences the equipment running costs were captured from their specification plates and data that was provided by the operators (van der Merwe, 2015). These included the pump specifications (in kW) for the fogging and irrigation, the running time of each pump per cycle according to the operating settings and the estimated maintenance cost per year according to the owners of the greenhouses. The design specifications were assumed to be sufficient to use for the purposes of this study since the actual current and voltage was not measured during the experimental period. The pump specifications are captured in Table 5.1 below.

Table 5.1 Greenhouse pump specifications

Greenhouse pump system	**Quantity**	**Pump size (kW)**
NVG Irrigation	1	0.90
NVG Fertigation	2	0.75
NVFG Fogging	1	2.2
NVFG Irrigation	1	0.90
NVFG Fertigation	2	0.75
SNT Irrigation	1	0.75

All three irrigation systems turn on three times a day and run on three-minute cycles each. The irrigation remains unchanged during the different seasons in the year.

The fogging in the NVFG turns on at 28˚C, runs for two minutes, stops for four minutes and continues until the internal greenhouse temperature reaches 24˚C. From the experimental data captured as pertains to the NVFG greenhouse, the fogging turned on for an average of four hours a day. The experimental data was only captured during the winter months (May and June). The months May to August can be classified as 'winter months' and the rest of the twelve months as 'summer months' (Benhin, 2006). It is, therefore, assumed that for these four months of the year, the fogging runs its cycle for four hours a day, similar to what was experienced during the experimental period. For the remaining eight months, it is assumed that the fogging runs its cycle for an average of six hours a day. From the experimental data taken during May and June, the fogging only turned on for approximately 75% of the total number of days. It is then also assumed that the fogging turns on during the summer months for 90% of the total number of days. It is seen from the experimental data that the fogging rarely turned on before 10am in the morning and is used as an assumption for the analysis.

The yearly maintenance costs associated with the equipment and structure of each greenhouse was retrieved from the operators and owners of the facilities (van der Merwe, 2015; Laing, 2015). The capital infrastructure costs relating to the greenhouses and their systems were also provided.

To calculate the electricity costs for the operation, the electricity tariff was taken from the Pietermaritzburg municipal register of tariffs and charges for 2015/2016. The different peak, standard and off-peak tariffs were applied for low demand (summer) and high demand (winter) months. According to the classification, high demand periods refer to June, July, August, while low demand periods refer to all other months. The tariffs and time associated with the different tariffs for 2015/2016 are provided in Table 5.2 below. The time periods that can be classified as peak, standard and off-peak times in a week day are presented in the table below. The different rates that are charged for the peak, standard and off-peak times are also presented. The rates differ from winter (high demand season) and summer (low demand season) periods.

Table 5.2 Electricity tariffs

	Peak times	**Standard times**	**Off-peak times**
Week day			00:00-06:00
		06:00-07:00	
	07:00-10:00	10:00-18:00	
	18:00-20:00	20:00-22:00	22:00-24:00
Rates (high demand season) (c/kWh)	285.91	103.11	66.79
Rates (low demand season) (c/kWh)	109.20	82.53	61.00

The impact of the difference in rates between weekdays, weekends and public holidays are neglected.

The assumptions and information used to analyse the data are presented in Table 5.3. The operating information was derived from the experimental data and from consultation with the operators of the facilities (van der Merwe, 2015).

Table 5.3 Operating specifications used for data analysis for three experimental greenhouses

NVG	**Values**
Size (m^2)	324
Irrigation	
Number of irrigation cycles per day	3
Running time per cycle (sec)	180
Number of days per month	30
Maintenance cost per year	R 60 000
NVFG	
Size (m^2)	162
Fogging	
Number of fogging cycles per winter day	40
Number of fogging cycles per summer day	60
Running time per cycle (sec)	120
Number of days per summer month for fogging	27
Number of days per winter month for fogging	22.5
Irrigation	
Number of irrigation cycles per day	3
Running time per cycle (sec)	180
Number of days per month	30
Maintenance cost per year	R 75 000
SNT	
Size (m^2)	200
Irrigation	
Number of irrigation cycles per day	3
Running time per cycle (sec)	180
Number of days per month	30
Maintenance cost per year	R 5 000

To analyse the costs associated with other climate control installations on a 1ha greenhouse, information was collected from greenhouse suppliers around the country (Olsen, 2013; van Niekerk, 2013; Venter, 2013). The summary of costs associated with the different greenhouse system installations are provided in Table 5.4 below. The equipment operational costs such as electricity and maintenance costs depend on the type of systems installed.

Table 5.4 Greenhouse installation costs in South Africa

Multi-span 1 ha greenhouse	
Component	Cost/m^2 (ZAR)
Structure with continuous double sided ridge ventilation	150-200
Screens for shading	60-80
Drip irrigation with fertigation system	40-50
Fogging	30-50
Hot water heating	150-180
Hot air heating	40-50
Computer climate control system (controlling only critical aspects)	15-30
Ground cover (plants grown on ground)	5-10
Gutter growing system	40-50
Pad and fan	40-50
Shade net greenhouse (low cost) – multi-span 1ha structure	
Structure and cover	50-60
Irrigation	40-50
Ground cover	5-10

A scenario was created for a 1ha greenhouse design. Since only cooling technologies are reviewed and analysed throughout the chapters, heating operational costs are excluded from this study. The following design scenario was used:

- Structure with continuous double sided ridge ventilation
- Screens for shading
- Drip irrigation with fertigation system
- Fogging

- Computer climate control system (controlling screening, fogging, ventilation, irrigation)
- Ground cover (plants grown on ground)
- Gutter growing system

Operating and maintenance costs for this scenario were calculated by estimating the power requirements for the equipment associated with each system for a 1ha installation. The same frequency and cycle times for the irrigation and fogging systems used in the experimental greenhouses were used in the 1ha greenhouse. There were an estimated number of four screen cycles per day, two cycles during the normal peak time and two cycles during the standard time, according to the electricity tariffs presented in Table 5.2. The number of ventilation cycles per day was estimated to take place twice per day, one cycle in the peak time and one cycle in standard time, according to the electricity tariffs presented in Table 5.2. The equipment operational costs associated with the climate computer are neglected. A summary of the assumptions made regarding the 1ha greenhouse is provided in Table 5.5 below.

Table 5.5 Operating assumptions for a 1ha greenhouse

1ha greenhouse assumptions	
Power requirements	**Value**
Number of irrigation pumps	2
Number of fertigation pumps required	2
kW rating on irrigation pump	4
kW rating on fertigation pump	0.9
Number of fogging pumps per 1ha	4
kW rating on fogging pump	11
Number of screen motors	2
kW rating on screen motor	1.5
Number of vent motors	22
kW rating on vent motor	1.1
Running times	
Ventilation	
Number of cycles per day	2
Running time per cycle (sec)	300
Screens	
Number of cycles per day	4

Running time per cycle (sec)	180
Irrigation	
Number of cycles per day	3
Running time per cycle (sec)	180
Fogging	
Number of fogging cycles per winter day	40
Number of fogging cycles per summer day	60
Running time per cycle (sec)	120
Number of days per summer month for fogging	27
Number of days per winter month for fogging	22.5
Number of days per month	30

5.4 Analysis and Results

By using the experimental data and information provided by the operators, the equipment operating and maintenance costs as well as capital costs were calculated. The capital costs associated with added climate control installations and different size greenhouses are provided.

The results from the analysis of the equipment operating and capital costs as pertains to the different greenhouses are summarized in Table 5.6 below. Since the only operational and electrical equipment in the NVG tunnel is the irrigation system, the equipment running costs amount to roughly R114 per year. The maintenance costs of the whole greenhouse is estimated to be R60 000 per year. Since the same irrigation and fertigation system is used for the NVFG, the cost for the irrigation equipment in this greenhouse is the same that of the NVG. The electricity costs associated with running the fogging pumps is calculated to be R1042.99 per year and the maintenance costs are given as R75 000 per year. The costs for operating the SNT irrigation equipment is calculated to be R71.51 per year and the maintenance cost only R5 000 per year.

Table 5.6 Results from operating, maintenance and capital cost analysis for the three different greenhouses

NVG	
Running cost for irrigation per year	R114.42
Maintenance cost per year	R60 000.00
Total equipment running cost per year	*R60 114.42*
Capital cost	*R380 000.00*

NVFG	
Running cost for fogging per year	R1042.99
Running cost for irrigation per year	R114.42
Maintenance cost per year	R75 000.00
Total equipment running cost per year	*R76 157.42*
Capital cost	*R1 571 520.00*
SNT	
Running cost for irrigation per year	R71.51
Maintenance cost per year	R5 000.00
Total equipment running cost per year	*R5 071.51*
Capital cost	*R30 000.00*

The results from simulating and predicting the costs as associated with a 1ha multi-span greenhouse fitted with screens, irrigation and fertigation, fogging, a climate control computer, growing gutters and ground cover is presented in Table 5.7 below. According to the data collected from these three experimental greenhouse installations, maintenance can vary from 5-15% of the initial capital investment per year. The yearly maintenance cost associated with the 1ha greenhouse is therefore assumed to be 5%. The total equipment running cost on a 1ha greenhouse with the described specifications is therefore estimated to be R 252 055.58 per year, with an investment amount of R 4 550 000.

Table 5.7 Results from simulating the equipment costs for a 1ha greenhouse

1ha greenhouse summary of equipment running and capital cost	
Running cost calculated for irrigation per year	R579.88
Running cost calculated for fogging per year	R21,965.33
Running cost calculated for screens per year	R260.34
Running cost calculated for ventilation per year	R1,750.04
Maintenance cost per year	R227,500.00
Total equipment running cost per year	*R252,055.58*
Capital cost	*R4,550,000.00*

5.5 Discussion

The decision to invest in greenhouse technology that improves the control of greenhouse climatic conditions is a strategic decision and should positively affect the outputs of the system. For an accurate evaluation with regard to profitability of a specific greenhouse system and technology improvements, many different factors should be considered. All possible impacts on climate, crop biology and crop techniques should be assessed to accurately determine the long-term benefits of the applied technology. As described in Section 5.2, several studies have been done on the profitability of crop production in certain greenhouse systems across specific countries in the world (Pardossi *et al*. 2004; Heidari and Omid, 2011; Canakci, and Akinci, 2006). Crop and climate models have been developed to try and assist with the strategic decisions regarding greenhouse designs and can realistically predict the response of climatic conditions on crop production (Vanthoor *et al.*, 2011). For South African conditions and greenhouses, however, limited research has been published. In this specific chapter, the running costs associated with the equipment in three different greenhouse design types were monitored and compared. The equipment running and capital costs were predicted for a 1ha greenhouse, with certain design specifications.

The results show that the equipment operating and maintenance costs are very similar with regard to the NVG and NVFG systems. It is, however, approximately ten times higher than the operating and maintenance costs associated with the SNT. The capital costs are also presented in Table 5.6. The installation costs of the NVFG are approximately four times higher than the NVG and approximately fifty times higher than the SNT costs. The benefits these different types of greenhouses have on the growing lettuce crops over a two-month period were evaluated in a previous chapter.

The results from the analysis for the 1ha greenhouse shows that the investment costs and equipment operating costs are proportionally lower when compared to the NVFG, with similar design specifications. The NVFG is approximately 60 times lower than a 1ha greenhouse, and even though it has lower specifications, the capital cost is only approximately 3 times higher. If compared to the NVG, the 1ha greenhouse, the capital costs are approximately 12 times higher, even though it is only approximately 30 times smaller in size. The equipment running costs are also proportionally lower. If however, the capital and operational costs are compared to the shadenet tunnel, it is much higher.

5.6 Conclusion

The costs associated with the operating equipment of the three experimental greenhouses were logged and analysed. Since experiments were only done for a short period, certain assumptions were made with regards to the equipment cycles to get annual costs and have been presented. Capital installation costs for the three experimental greenhouses were also captured. The results show that the equipment operating and maintenance costs for the NVG and NVFG systems are approximately ten times higher than the costs associated with the SNT. The installation costs of the NVFG are approximately four times higher than the NVG and approximately fifty times higher than the SNT costs. Based on this alone, the benefits of growing in a more advanced greenhouse should be significantly higher than in a low cost greenhouse. In a previous chapter, the yield of lettuce crops grown in the different types of greenhouses was evaluated over a two-month period. Although market prices and other input costs were not taken into account, the benefits in crop yield from the three different greenhouses do not correlate with these differences in the operating costs. It is recommended that further studies are done where the actual equipment operating data is captured over a 12 month period, for more accurate results. Labour and other indirect costs and market prices should be captured over the same 12 month period in order to evaluate and compare the economic benefits when it comes to producing crops in the three different structures.

Since typical greenhouse sizes for all types of undercover farming in South Africa is larger than 1ha, equipment operating capital costs for a 1ha greenhouse was estimated. It is clear from the information presented that, except for the shadenet greenhouse, it is more cost-effective with regards to equipment costs, to invest and construct larger greenhouses.

This chapter gives an indication of the costs associated with operating different types and size of greenhouses. In order to do a detailed cost-benefit analysis for investment in greenhouse production, more factors impacting the total input costs and economic benefits should be captured and evaluated. Labour, energy (direct and indirect) and supply costs should be captured for crop production throughout a minimum period of 12 months. To effectively evaluate the benefits of the greenhouse on crop production, crop yield, market quality and market prices should be determined as pertains to the crop over a twelve-month period. Economic and crop yield models can be created in combination with a climate model and validated by using experimental data.

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6 CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

Controlled environment agriculture is seen as a powerful tool to increase crop production. Increasing the productivity of agriculture by utilizing protected agriculture can contribute towards the reduction of poverty and food insecurity problems in developing countries (Pack and Mahta, 2012). Greenhouse production in South Africa during summer months requires ventilation and cooling to ensure that optimum temperatures and relative humidity are maintained (Maboko *et al.*, 2012). Different greenhouse cooling technologies are available in South Africa. Some types require higher investment and operating costs (Maboko *et al*., 2012). To ensure success and a positive return on investment, many factors should be considered during the decision-making process before investing in greenhouse technology. Limited studies are available to evaluate the performance of different greenhouse designs specifically for different South African agro-climatic conditions.

This study was undertaken to compare the microclimatic conditions of three different types of greenhouses as well as the effect on the yield of lettuce crops over the course of a growth cycle. The research was undertaken at the University of KwaZulu-Natal's School of Agriculture Environment and Earth Sciences, Life Science campus, Pietermaritzburg, South Africa in 2014. The three greenhouses that were used included a naturally ventilated greenhouse fitted with insect nets on the roof vents (NVG), a naturally ventilated greenhouse fitted with fogging (NVFG) and a shadenet tunnel (SNT).The microclimates for the greenhouses were compared using data from five similar external climatic days. Four different lettuce varieties were used to evaluate the effect of the microclimates on the plant growth in terms of plant height, weight and colour over one growth cycle of 30 days.

The findings show that in terms of internal microclimatic conditions, the temperatures measured for the naturally ventilated polycarbonate greenhouse (NVG) with no cooling installation for the relevant days, were significantly higher than the external temperature. In fact internal temperatures of up to 10°C higher than outside temperatures were measured upon occasion, often peaking at 32˚C. This is above optimum temperatures for lettuce production and proved that natural ventilation is not sufficient for air circulation and temperature reduction in this type of greenhouse.

The internal temperatures of the fog-cooled and natural ventilated greenhouse (NVFG) were often lower than the other two greenhouses, peaked at around a 10°C difference, and regularly reached temperatures lower than the external temperature. This was observed specifically when the fogging switched on in the greenhouse and presented desirable temperatures for crop production. The mean internal day-time temperatures in the SNT were similar to the external temperatures. The day-time temperatures (11 - 24°C) in the NVFG and SNT were on average acceptable for lettuce production. Night temperatures in the SNT often reached undesirable minimum temperatures. Night temperatures experienced in the NVG and NVFG were similar throughout the experimental period and slightly higher (2-3°C) than the external temperatures and those experienced in the SNT, however, on average, it was still within a minimum acceptable temperature range.

With regard to the SNT, the day-time RH measured followed the external RH levels, which are also below optimal for lettuce production. The internal RH measured in the NVFG was impacted with the fogging operations and increased from 35% to between 70-80% and, on average, humidity conditions were acceptable for the production of lettuce and most other vegetables. The day-time RH measurements in NVG were almost constantly 10% lower than the external humidity, reaching minimum RH between 26 and 32%, which is below optimum levels for lettuce production.

The microclimatic conditions presented for the NVFG over the period suggested that the climatic conditions should be more suited to lettuce production in this greenhouse than in the other two greenhouses. The data, however, shows a small difference in growth between the plants grown in the NVFG and the NVG. Data from specific days presented indicated that there was a delay in the fogging switching on, causing undesirably high temperatures, similar to that experienced in the NVG. This could have affected the growth of the lettuce plants negatively. The growth of plants in terms of certain measured such as plant height and dry weight in the SNT was up to 75% less compared to that of the plants in the NVG and NVFG. This can be attributed to the fact that the climate conditions inside the SNT more or less followed the external conditions, the plants were exposed to low humidity and high temperatures during the day and undesirable low temperatures at night, all factors that negatively influence crop production. Although, light intensity was not measured in the different greenhouses, the red colour of the Gaugin and Xerafin varieties were maintained in the SNT which indicates better light transmission experienced in this greenhouse (Fourie, 2015).

The experimental data from the microclimatic conditions were used in a study and fitted into a suitable mathematical model in order to predict the internal microclimatic conditions of the three different greenhouse designs, when exposed to different external climatic conditions. It was found that the accuracy of the model to predict the difference in external and internal temperature for the shadenet tunnel was satisfactory ($R^2 = 0.85$). This indicates that it is possible to accurately predict the temperature difference (ΔT) for the SNT type tunnel for different external climatic conditions and these predictions can thus be applied in the design process for similar structures in different agro-climatic regions around South Africa. The results from the suitability test for the models applied to the NVG and NVFG were less accurate ($R^2 = 0.65$ and $R^2 = 0.63$), but can still be used to get some idea of the effect of external climatic conditions specific to a climatic region on the internal temperature of a greenhouse. The data shows that the model is more sensitive to external conditions such as global solar radiation and wind speed for the NVG and NVFG greenhouses than what is experienced in reality, causing the accuracy of the model to be less satisfactory. The results of testing the accuracy of the model to predict the other important factor, relative humidity in the form of vapour pressure, were unsatisfactory in relation to all three models ($R^2 < 0.55$).

There is a lack of scientific research and data with regards to the costs and benefits associated with investing in more controlled agricultural production equipment, specifically in developing countries. As much as the capacity of a specific greenhouse design should be able to obtain optimal internal climate conditions, a critical factor to firstly consider is whether the capital expenditure for the greenhouse infrastructure can be justified. In this study, the equipment operating and capital costs for three different greenhouse designs were captured and compared. The yearly equipment operating and maintenance costs for the NVG, NVFG and SNT were estimated to be R60 114, R 76 157 and R 5 072 respectively. The capital costs associated with each greenhouse were R 380 000, R 1 571 520 and R 30 000 respectively. The operating and maintenance costs related to the greenhouse equipment are thus similar for the NVG and NVFG, while the capital cost for the NVFG is approximately four times higher than that of the NVG. It is much cheaper to run and construct a shade net tunnel, compared to the other two greenhouses. Costs were predicted for a 1ha structure with exact design specifications and compared with the smaller greenhouse used for the experiments. It was found that, except for the SNT design, it is more cost-effective, in terms of operating and maintenance costs, to construct larger greenhouses for crop production.

6.2 Recommendations

Based on the outcomes of the study, it is recommended that the following research also be undertaken:

- Accuracy of the model to be improved by adding more experimental data points by conducting experiments over a longer period and adjusting the values of certain coefficients,
- Test other climate models for more accurate predictability,
- Expand research on the performance of other crops such as tomatoes, peppers and cucumbers in the three different greenhouse systems over a full crop cycle for different seasons,
- Expand the research to add studies on the micro-climatic conditions in greenhouses fitted with other cooling installations such as screening and alternative evaporative cooling methods, and
- Conduct detailed cost-benefit analysis for crop production in the typical NVG, NVFG and SNT greenhouses in South Africa by evaluating additional input costs as well as financial benefits of crop yield and quality with regard to lettuce production.

6.3 References

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Maboko, MM, du Plooy, CP, Bertling, I. 2012. Performance of tomato cultivars in temperature and non-temperature controlled plastic tunnels. *Acta Hort.* 927:405-411.

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7 APPENDICES

7.1 Appendix 1.1 ANOVA Tables for plant growth parameters

Variable: Plant height

			Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
V1	NVG	NVFG	0.650	1.641	0.708	-3.568	4.868
		SNT	1.050	1.641	0.550	-3.168	5.268
	NVFG	NVG	-0.650	1.641	0.708	-4.868	3.568
		SNT	0.400	1.895	0.841	-4.471	5.271
	SNT	NVG	-1.050	1.641	0.550	-5.268	3.168
		NVFG	-0.400	1.895	0.841	-5.271	4.471
V2	NVG	NVFG	-2.075	1.099	0.118	-4.901	0.751
		SNT	1.125	1.099	0.353	-1.701	3.951
	NVFG	NVG	2.075	1.099	0.118	-0.751	4.901
		SNT	3.200	1.269	0.053	-0.063	6.463
	SNT	NVG	-1.125	1.099	0.353	-3.951	1.701
		NVFG	-3.200	1.269	0.053	-6.463	0.063
V3	NVG	NVFG	-2.550	0.855	0.031	-4.748	-0.352
		SNT	2.900	0.855	0.019	0.702	5.098
	NVFG	NVG	2.550	0.855	0.031	0.352	4.748
		SNT	5.450	0.987	0.003	2.912	7.988
	SNT	NVG	-2.900	0.855	0.019	-5.098	-0.702
		NVFG	-5.450	0.987	0.003	-7.988	-2.912
V4	NVG	NVFG	-0.075	1.094	0.948	-2.886	2.736
		SNT	0.975	1.094	0.413	-1.836	3.786
	NVFG	NVG	0.075	1.094	0.948	-2.736	2.886
		SNT	1.050	1.263	0.444	-2.196	4.296
	SNT	NVG	-0.975	1.094	0.413	-3.786	1.836
		NVFG	-1.050	1.263	0.444	-4.296	2.196
*. The mean difference is significant at the 0.05 level.							

Variable: Number of new leaves developed

			Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
V1	NVG	NVFG	-5.750	9.642	.577	-30.53	19.03
		SNT	33.250*	9.642	.018	8.47	58.03
	NVFG	NVG	5.750	9.642	.577	-19.03	30.53

			Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
		SNT	39.000*	11.133	.017	10.38	67.62
	SNT	NVG	-33.250*	9.642	.018	-58.03	-8.47
		NVFG	-39.000*	11.133	.017	-67.62	-10.38
V2	NVG	NVFG	-8.500	9.740	.423	-33.54	16.54
		SNT	21.000	9.740	.084	-4.04	46.04
	NVFG	NVG	8.500	9.740	.423	-16.54	33.54
		SNT	29.500*	11.247	.047	.59	58.41
	SNT	NVG	-21.000	9.740	.084	-46.04	4.04
		NVFG	-29.500*	11.247	.047	-58.41	-.59
V3	NVG	NVFG	-3.250	9.516	.747	-27.71	21.21
		SNT	18.750	9.516	.106	-5.71	43.21
	NVFG	NVG	3.250	9.516	.747	-21.21	27.71
		SNT	22.000	10.989	.102	-6.25	50.25
	SNT	NVG	-18.750	9.516	.106	-43.21	5.71
		NVFG	-22.000	10.989	.102	-50.25	6.25
V4	NVG	NVFG	-25.500*	4.566	.003	-37.24	-13.76
		SNT	12.500*	4.566	.041	.76	24.24
	NVFG	NVG	25.500*	4.566	.003	13.76	37.24
		SNT	38.000*	5.273	.001	24.45	51.55
	SNT	NVG	-12.500*	4.566	.041	-24.24	-.76
		NVFG	-38.000*	5.273	.001	-51.55	-24.45

*. The mean difference is significant at the 0.05 level.

Variable: Fresh plant weight

			Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
V1	NVG	NVFG	-.018	.023	.481	-.077	.042
		SNT	.084	.023	.015	.024	.143
	NVFG	NVG	.018	.023	.481	-.042	.077
		SNT	.101	.027	.013	.033	.169
	SNT	NVG	-.084	.023	.015	-.143	-.024
		NVFG	-.101	.027	.013	-.169	-.033
V2	NVG	NVFG	.002	.013	.915	-.033	.036
		SNT	.065	.013	.005	.030	.099
	NVFG	NVG	-.002	.013	.915	-.036	.033
		SNT	.063	.015	.009	.023	.103
	SNT	NVG	-.065	.013	.005	-.099	-.030
		NVFG	-.063	.015	.009	-.103	-.023

			Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
V3	NVG	NVFG	-.020	.023	.431	-.078	.039
		SNT	.055	.023	.062	-.004	.113
	NVFG	NVG	.020	.023	.431	-.039	.078
		SNT	.074	.026	.037	.006	.142
	SNT	NVG	-.055	.023	.062	-.113	.004
		NVFG	-.074	.026	.037	-.142	-.006
V4	NVG	NVFG	-.005	.024	.859	-.066	.057
		SNT	.042	.024	.146	-.020	.103
	NVFG	NVG	.005	.024	.859	-.057	.066
		SNT	.046	.028	.159	-.026	.118
	SNT	NVG	-.042	.024	.146	-.103	.020
		NVFG	-.046	.028	.159	-.118	.026
*. The mean difference is significant at the 0.05 level.							

Variable: Dry biomass plant weight

			Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
V1	NVG	NVFG	-.003	.001	.081	-.006	.000
		SNT	.003	.001	.043	.000	.006
	NVFG	NVG	.003	.001	.081	.000	.006
		SNT	.006	.001	.008	.002	.009
	SNT	NVG	-.003	.001	.043	-.006	.000
		NVFG	-.006	.001	.008	-.009	-.002
V2	NVG	NVFG	.002	.001	.057	.000	.005
		SNT	.005	.001	.003	.003	.008
	NVFG	NVG	-.002	.001	.057	-.005	.000
		SNT	.003	.001	.049	.000	.006
	SNT	NVG	-.005	.001	.003	-.008	-.003
		NVFG	-.003	.001	.049	-.006	.000
V3	NVG	NVFG	.001	.001	.355	-.002	.004
		SNT	.005	.001	.010	.002	.008
	NVFG	NVG	-.001	.001	.355	-.004	.002
		SNT	.004	.001	.049	.000	.007
	SNT	NVG	-.005	.001	.010	-.008	-.002
		NVFG	-.004	.001	.049	-.007	.000
V4	NVG	NVFG	-.001	.001	.485	-.005	.003
		SNT	.002	.001	.204	-.002	.006
	NVFG	NVG	.001	.001	.485	-.003	.005

			Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
		SNT	.003	.002	.113	-.001	.007
	SNT	NVG	-.002	.001	.204	-.006	.002
		NVFG	-.003	.002	.113	-.007	.001
*. The mean difference is significant at the 0.05 level.							

7.2 Appendix 1.2 ANOVA Tables for temperature and RH parameters

Multiple Comparisons

Variable: Day time Temperature

(I) GH			Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
LSD	0	1	-4.985	2.195	0.028	-9.398	-0.573
		2	-2.974	2.195	0.182	-7.386	1.439
		3	-1.335	2.195	0.546	-5.747	3.078
	1	0	4.985	2.195	0.028	0.573	9.398
		2	2.011	2.195	0.364	-2.401	6.424
		3	3.651	2.195	0.103	-0.762	8.063
	2	0	2.974	2.195	0.182	-1.439	7.386
		1	-2.011	2.195	0.364	-6.424	2.401
		3	1.639	2.195	0.459	-2.773	6.052
	3	0	1.335	2.195	0.546	-3.078	5.747
		1	-3.651	2.195	0.103	-8.063	0.762
		2	-1.639	2.195	0.459	-6.052	2.773

*. The mean difference is significant at the 0.05 level.
0 = External measurements
1 = NVG
2 = NVFG
3 = SNT

Multiple Comparisons

Variable: Day-time RH

(I) GH			Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
LSD	0	1	4.726	7.351	0.523	-10.054	19.505
		2	-12.267	7.351	0.102	-27.046	2.512
		3	-0.542	7.351	0.941	-15.322	14.237
	1	0	-4.726	7.351	0.523	-19.505	10.054

		2	-16.993	7.351	0.025	-31.772	-2.213
		3	-5.268	7.351	0.477	-20.048	9.511
	2	0	12.267	7.351	0.102	-2.512	27.046
		1	16.993	7.351	0.025	2.213	31.772
		3	11.725	7.351	0.117	-3.055	26.504
	3	0	0.542	7.351	0.941	-14.237	15.322
		1	5.268	7.351	0.477	-9.511	20.048
		2	-11.725	7.351	0.117	-26.504	3.055

*. The mean difference is significant at the 0.05 level.
0 = External measurements
1 = NVG
2 = NVFG
3 = SNT

Multiple Comparisons

Variable: Night temperature

(I) GH			Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
LSD	0	1	-1.968	0.616	0.003	-3.213	-0.722
		2	-1.743	0.616	0.007	-2.989	-0.498
		3	0.915	0.616	0.146	-0.331	2.160
	1	0	1.968	0.616	0.003	0.722	3.213
		2	0.224	0.616	0.718	-1.021	1.470
		3	2.882	0.616	0.000	1.637	4.128
	2	0	1.743	0.616	0.007	0.498	2.989
		1	-0.224	0.616	0.718	-1.470	1.021
		3	2.658	0.616	0.000	1.413	3.904
	3	0	-0.915	0.616	0.146	-2.160	0.331
		1	-2.882	0.616	0.000	-4.128	-1.637
		2	-2.658	0.616	0.000	-3.904	-1.413

*. The mean difference is significant at the 0.05 level.
0 = External measurements
1 = NVG
2 = NVFG
3 = SNT

Multiple Comparisons

Variable: Night RH

(I) GH			Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
LSD	0	1	3.627	1.224	0.005	1.154	6.100

		2	2.590	1.224	0.041	0.117	5.063
		3	-2.764	1.224	0.029	-5.237	-0.291
	1	0	-3.627	1.224	0.005	-6.100	-1.154
		2	-1.037	1.224	0.402	-3.509	1.436
		3	-6.391	1.224	0.000	-8.863	-3.918
	2	0	-2.590	1.224	0.041	-5.063	-0.117
		1	1.037	1.224	0.402	-1.436	3.509
		3	-5.354	1.224	0.000	-7.827	-2.881
	3	0	2.764	1.224	0.029	0.291	5.237
		1	6.391	1.224	0.000	3.918	8.863
		2	5.354	1.224	0.000	2.881	7.827

*. The mean difference is significant at the 0.05 level.

0 = External measurements
1 = NVG
2 = NVFG
3 = SNT

7.3 Appendix 1.3Tables for coefficients optimized for modelling

NVG

Parameter Estimates				
Parameter	Estimate	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
a	.482	.056	.373	.592
b	.002	.001	.000	.004

NVFG

Parameter Estimates				
Parameter	Estimate	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
a	.459	.025	.411	.508
b	.001	.001	.000	.002

SNT

Parameter Estimates				
Parameter	Estimate	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound

a	-1.198	.531	-2.245	-.152
b	.052	.015	.021	.082