The influence of different production systems, planting densities and levels ofshading on the yield, quality and growth potential of 'Chandler' strawberry plants (*Fragaria ananassa*) grown in coir

Johannes Jacobus de Villiers

Thesis presented in fulfilment of the requirements for the degree of Master of Agricultural Sciences at Stellenbosch University.

Study leader: Prof. G.A. Agenbag

December 2008

Declaration

By submitting this thesis electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the owner of the copyright thereof (unless to the extent explicitly otherwise stated) and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

Date: 05 December 2008

ABSTRACT

The use of hydroponic strawberry production systems is increasing worldwide. Although higher planting densities are possible in vertical production systems, these higher planting densities may have a negative effect on individual plant yield and fruit quality due to lower light levels when compared to conventional (horizontal) production systems. Optimum planting densities will for this reason be affected by light intensities inside the greenhouse and configuration of the vertical production systems.

Two experiments were conducted in a plastic cladded greenhouse, fitted with a wet-wall and fan cooling system, at the Department of Agronomy, University of Stellenbosch, South Africa during the period of April 2007 to November 2007 (late autumn to early summer). Mean daily maximum temperatures exceeded 26 ^{o}C during most of the 14 week harvest period (22 August to 30 November 2007), while photosynthetic active radiation (PAR), measured at 12h00 on cloudless days, inside the greenhouse increased from about 200 μMol m^{-2} s^{-1} to about 460 μMol m^{-2} s^{-1} during this period. The first experiment compared the effect of two vertical production systems (vertical system and 'A-shape' system), subjected to different planting density (16.7, 23.3 and 33.3 plants m^{-2}) and shading (0%, 20%, 50%) treatments, as measured on selected yield, quality and growth factors. The second experiment studied the effect of different planting density (3.3, 5.6 and 10 plants m^{-2}) and shading (0%, 20%, 50%) treatments on the same yield, quality and growth factors in a conventional production system. A comparison with regard to these factors was also made between the highest planting densities of the conventional-, vertical- and 'A-shape' system.

The highest yield plant^{-1} was produced in the conventional system, while plants in the 'A-shape' system tended to produce higher yields compared to plants in the vertical system. Although yield plant^{-1} tended to decrease with increasing planting densities, yield m^{-2} was increased. Due to higher planting densities in the vertical and 'A-shape' systems, higher yields m^{-2} were produced compared to the conventional system. Planting density did not affect the fruit quality (fruit size and soluble solids content of

fruits) in the vertical and 'A-shape' systems and in general better fruit quality was achieved in the 'A-shape' system compared to the vertical system. In the conventional system, an increase in planting density increased the fruit size, but the average soluble solids content of fruits (%SS) decreased slightly. The best fruit quality with the lowest percentage malformation was however produced in the conventional system.

In the vertical and 'A-shape' systems, shading had a negative effect on the yield plant^{-1}, as well as the yield m^{-2}. Plants in the conventional system, subjected to 20% shading, tended to produce higher yields compared to unshaded plants. Shading tended to reduce fruit quality in all three production systems.

From this study it became clear that the 'A-shape' production system is the most promising of the three production systems evaluated, but more studies need to be done to increase the productivity at high planting densities ($\geq$ 33.3 plants m^{-2}). The 'A-shape' system might be more productive by decreasing the number of gutters per production system, as well as the in-row plant spacing. This might increase light penetration through the production system without decreasing plant density and thus increase production.

UITTREKSEL

Hidroponiese aarbei produksie sisteme toon ‘n toename wêreldwyd en alhoewel hoër plant digthede moonlik is in vertikale produksie sisteme, kan die hoër plant digthede ‘n negatiewe effek op afsonderlike plant opbrengs en vrug kwaliteit hê as gevolg van laer lig vlakke in vergelyking met konvensionele (horisontale) produksie sisteme. Optimale plant digthede sal dus vir die rede beinvloed word deur lig intensiteit in die tonnel en deur die konfigurasie van die vertikale produksie sisteem.

Twee eksperimente is gedoen in ‘n plastiek tonnel, wat verkoel is met behulp van ‘n natmuur en waaier sisteem, by die Departement van Agronomie, Universiteit van Stellenbosch, Suid-Afrika tydens die tydperk April 2007 tot November 2007 (laat herfs tot vroeg somer). Gemiddelde daaglikse maksimum temperature het 26 ^{o}C vir meeste van die 14 week oes periode oorskry (22 Augustus to 30 November 2007), terwyl fotosinteties aktiewe bestraling, soos gemeet teen 12h00 op wolklose dae, binne in die tonnel verhoog het vanaf ongeveer 200 μMol m^{-2} s^{-1} tot ongeveer 460 μMol m^{-2} s^{-1} tydens hierdie tydperk. Die eerste eksperiment het die effek van twee vertikale produksie sisteme (vertikale sisteem en ‘A-vorm’ sisteem), onderworpe aan verskillende plant digtheid (3.3, 5.6 en 10 plante m^{-2}) en skadu behandelings (0%, 20%, 50%) vergelyk, soos gemeet op sekere opbrengs, kwaliteit en groei faktore. Die tweede eksperiment het die effek van verskillende plant digtheid (3.3, 5.6 en 10 plante m^{-2}) en skadu (0%, 20%, 50%) behandelings in ‘n konvensionele produksie sisteem op dieselfde opbrengs, kwaliteit en groei faktore vergelyk. ‘n Vergelyking ten opsigte van laasgenoemde faktore is ook gemaak tussen die hoogste plant digthede van die konvensionele-, vertikale- en ‘A-vorm’ sisteem.

Die hoogste opbrengs plant^{-1} is geproduseer in die konvensionele sisteem, plante in die ‘A-vorm’ sisteem het geneig om hoër opbrengste te produseer in vergelyking met plante in die vertikale sisteem. Alhoewel opbrengs plant^{-1} geneig het om af te neem met ‘n toename in plant digtheid, het die opbrengs m^{-2} toegeneem. As gevolg van hoër plant digthede in die vertikale en ‘A-vorm’ sisteme, is hoër opbrengste m^{-2} geproduseer in vergelyking met die konvensionele sisteem. Plant digtheid het nie vrug kwaliteit (vrug-grootte en oplosbare soliede stof inhoud van vrugte) in die vertikale en

'A-vorm' sisteme beinvloed nie, maar oor die algemeen was vrug kwaliteit beter in die 'A-vorm' sisteem in vergelyking met die vertikale sisteem. In die konvensionele sisteem, 'n toename in plant digtheid het vrug grootte laat toeneem, maar die gemiddelde oplosbare soliede stof inhoud van vrugte (%SS) het effens afgeneem. Die beste kwaliteit vrugte met die laagste persentasie misvorming is in die konvensionele sisteem geproduseer.

Skadu behandelings, in die vertikale en 'A-vorm' sisteme, het 'n negatiewe effek op die opbrengs plant^{-1}, asook opbrengs m^{-2}, gehad. Plante in die konvensionele sisteem, onderworpe aan 20% skadu behandeling, het geneig om hoër opbrengste te produseer in vergelyking met plante sonder skadu behandeling. Skadu behandelings het geneig om vrug kwaliteit in al drie produksie sisteme te verlaag.

Volgens hierdie studie is dit duidelik dat die 'A-vorm' produksie sisteem die mees belowendste van die drie produksie sisteme is, maar meer studies moet gedoen word om die produktiwiteit by hoër plant digthede ($\geq$ 33.3 plante m^{-2}) te verhoog. Die 'A-vorm' sisteem kan meer produktief wees deur die hoeveelheid geute per produksie sisteem, asook die binne-ry plant spasiëring te verlaag. Dit mag dalk die lig deurlating deur die produksie sisteem verhoog sonder om plant digtheid te verlaag en dus kan produksie verhoog word.

Acknowledgements

I wish to express my sincere gratitude to the following persons:

My parents, for the opportunity to study and all their love and support.

My study leader, Prof. G.A. Agenbag, for his help and guidance during this study and writing of this thesis.

Martin le Grange for his help in setting up the trials.

Chris de Villiers, André de Villiers, Michelle Kleinhans and Jowita Prusiewicz for their help and moral support.

Our Lord Jesus Christ, who gives me strength, all praise to Him.

CONTENTS

Chapter 4

The effect of planting density and shading on the growth and fruiting responses of hydroponically grown 'Chandler' strawberry plants in a conventional double row system

Chapter 5

A comparison between yield, quality and growth factors of unshaded 'Chandler' strawberry plants grown hydroponically in three different production systems

Chapter 6

Chapter 7

CHAPTER 1
INTRODUCTION

Strawberries are an ancient crop. The first written reference to strawberries comes from ancient Rome, but the fruit were likely to be collected from the wild for medicinal purposes and as a source of food long before recorded history (Bowling, 2000).

Strawberries belong to the family *Rosaceae* in the genus *Fragaria* (Hancock, 1999). The modern cultivated strawberry, *Fragaria ananassa*, is a hybrid between *F. virginiana* (meadow strawberry) and *F. chiloensis* (Chilean strawberry) (Hancock, 1999; Bowling, 2000).

Commercial production of strawberry crops through the 19 and 20th century escalated rapidly as strawberries became more popular. Tons of fresh fruit are consumed every year, but there are also opportunities for the use of second grade berries in frozen, juiced, dried and processed products. There is also an increasing interest in the health properties of strawberries, this factor helps to promote year round strawberry sales (Morgan, 2006).

Many European countries have been producing large volumes of greenhouse out of season strawberries. The cold winters that prevent outdoor production for much of the year, combined with high year round demand make heated hydroponic strawberry production economically viable. In the USA hydroponic strawberry production has not been adopted to the same extent, due to extensive field production in California and Florida (Morgan, 2006).

While hydroponically produced strawberries are still only a minor commercial crop compared to tomatoes and cucumbers, the number of growers world wide are increasing. In the USA small producers started to set up hydroponic production systems (Durner, 1999), mostly utilizing substrates in conventional systems, but there is also some Nutrient Film Technique (NFT) and vertical production systems (Morgan, 2006).

Greenhouse structures are very expensive to set up, that is why it is so important to use the volume of the greenhouse to increase yield per square meter. The only way to utilize the greenhouse volume with strawberry production is to set up a vertical production system (Ozeker *et al*., 1999; Linsley-Noakes *et al*., 2006). According to Ozeker *et al*. (1999) planting density can be increased three times by using a vertical system.

In South-Africa, a vertical hydroponic production system is used in George and the aim of this system is to maximise the capacity within polyethylene-clad tunnels, as well as to provide a picker- and spray-friendly growing system (Linsley-Noakes *et al*., 2006).

Productivity per square meter can be increased by using a vertical system, but light distribution in the system can be a problem that can seriously affect the yield and sugar levels of strawberries. Therefore, it is important to find the most suitable vertical production system, as well as optimal planting density within the system to maximise the utilization and distribution of light.

References

BOWLING, B.L., 2000. The berry grower's companion. Timber Press Inc., Portland, Oregon, USA.

DURNER, E.F., 1999. Winter greenhouse strawberry production using conditioned plug plants. *Hortscience* 34(4), 615-616.

HANCOCK, J.F., 1999. Strawberries. Crop production science in horticulture. CABI Publishing, Oxon, UK.

LINSLEY-NOAKES, G., WILKEN, L. & DE VILLIERS, S., 2006. High density, vertical hydroponics growing system for strawberries. *Acta Horticulturae* 708, 365-370.

MORGAN, L., 2006. Hydroponic strawberry production. A technical guide to the hydroponic production of strawberries. Suntec (NZ) Ltd, Tokomaru, New Zealand.

OZEKER, E., ELTEZ, R.Z., GUL, A., ONAL, K. & TANRISEVER, A., 1999. Investigations on the effects of different growing media on the yield and quality of strawberries grown in vertical bags. *Acta Horticulturae* 486, 409-413.

CHAPTER 2
LITERATURE REVIEW

2.1 Morphology

The strawberry is a small herbaceous perennial plant, which can be grown as an annual or perennial crop under commercial cultivation. Strawberry plants consist of a crown (shortened stem) from which all leaves, roots, flowers and runners grow (Maas, 1984; Bowling, 2000). The crown is very important for the survival of the plant due to its ability to store reserves for plant growth after chilling or dormancy. Strawberry plants can consist of a single crown or can exist as double or multiple crowned plants, depending on the age and stage of development. Freshly planted runners normally consist of a single crown, while 2 to 3 year old plants develop multiple crowns consisting of both auxiliary and branch crowns. Branch crowns do not have their own root system, but allow the plant to expand in width (Morgan, 2006).

Strawberry leaves are trifoliate and normally live for 1 to 3 months. During growth the crown elongates and produces new leaves. The buds in the leave axils can give rise to runners for the production of daughter plants or it can form secondary crowns as the plant age (Maas, 1984; Morgan, 2006).

Strawberry flowers are produced on a modified stem which is terminated by the primary flower. Further stems can arise from the main stem to produce secondary flowers from which tertiary flowers arise (Morgan, 2006). According to Hancock (1999), following the primary flower there are typically two secondaries, four tertiaries and eight quaternaries. This results into a highly branched flower stem or truss structure. These flowers open in succession, so if environmental conditions are ideal and pollination occurs, a successive fruit harvest can be obtained from each flower truss (Morgan, 2006).

The strawberry fruit is an ‘aggregate’, composed of numerous ovaries, each with a single ovule. The resulting seeds are called ‘achenes’ and are the true fruit of the strawberry. The embryo consists of two large, semi elliptical cotyledons, which contain protein and fat, but no starch. The receptacle is composed of an epidermal layer, a cortex and pith. The latter two layers are separated by vascular bundles that supply nutrients to the developing embryos (Hancock, 1999). The development of the fruit depends on maintenance of a hormonal balance during achene maturation. Any interruption of that balance, incomplete fertilization, or death of the achenes from any one of a number of pathogenic or nonpathogenic causes (e.g., infertile pollen, frost injury, insect attack or pathogenic fungal attack of flower parts) results in malformed fruit (Maas, 1984).

2.2 Phenotypes

There are primarily two types of strawberries now grown commercially, the day-neutral and short-day plants. Long-day (everbearing) plants are also available but rarely used commercially (Hancock, 1999; Bowling, 2000). There are also intermediate varieties which do not fall strictly into either category (Morgan, 2006).

The short-day types are actually facultative short-day plants and initiate flower buds under short-day conditions (less than 14h), or when temperatures are less than 15^{o}C. Long-day plants initiate their flower buds when day lengths are greater than 12h and temperatures are moderate. Day-neutral plants produce crowns and flower buds approximately three months after planting, regardless of day length. They initiate flower buds throughout the growing season, although high temperatures can inhibit bud formation as in short-day plants (Hancock, 1999; Bowling, 2000).

Runners in both short-day and day-neutral cultivars tend to be formed during the longer summer days until the day length shortens in the autumn. Leaves in all types of strawberry plants are produced continually during the growing season, but excessively hot or cold conditions (below 5^{o}C or above 30^{o}C) can inhibit leaf development. Crown formation in all strawberry types tends to increase under cool, short days (Morgan, 2006).

2.3 Fruit ripening processes

The ripening of strawberry fruit is accompanied by changes in colour, texture and flavour that give the fruit its unique characteristics (Manning, 1997). Strawberries are not climacteric, as they produce little ethylene and as a result the application of ethylene has little effect on the softening and flavour development of immature fruit (Abeles & Takeda, 1990), but strawberry ripening is associated with numerous biochemical changes including increases in pectins, hemicellulose and several other enzymes associated with anthocyanin and fatty acid biosynthesis (Hancock, 1999). Over 50 polypeptides have been identified that show prominent changes at different stages of fruit development (Manning, 1994). According to Abeles & Takeda (1990), pectinmethylesterase and cellulase are the most important softening enzymes in strawberry fruit.

The red colour develops through production of anthocyanins, primarily pelargonidin-3-glucosidase (Pg 3-gl). Almost 90% of the anthocyanins are Pg 3-gl although at least eight pelargonidin- and two cyanidin-based anthocyanins have been detected in strawberry juice (Bakker *et al*., 1994).

Hundreds of volatile esters have been identified during strawberry ripening and aroma development, with methyl and ethyl esters of butanoic and hexanoic acids being the most prevalent. Other components like trans-2-hexenyl acetate, trans-2-hexenal, trans-2-hexenol and furaneol can also be found in high concentrations, but vary widely between cultivars and produce large variations in aroma quality. The furaneol, mesifurane and furaneol glycoside content increases during the natural ripening of fruit, with the highest concentrations in overripe fruit (Hancock, 1999). According to Hancock (1999), knowledge about specific components of flavour is only beginning to emerge.

2.4 Malformed fruit and other fruiting disorders

Malformed fruit are caused by many different factors including poor pollination and damage to the achenes by frost, insects or diseases. All of these prevent the synthesis of auxin and result in uneven development. Cool temperatures can also have a negative effect on fruit development by reducing pollinator activity and limiting pollen production (Risser, 1997). According to Morgan (2006), pollen can loose viability at cool temperatures. If pollination occurs, pollen germination and subsequent fertilization may not occur or only at retarded rates, resulting in uneven achene development and berry growth. High temperatures have a similar effect on pollen and in some strawberry varieties fruit often fail to set at all above 26^{o}C (Morgan, 2006). Nutritional disorders like boron, zinc and copper deficiencies and excessive nitrogen can also affect fruit development and shape (Maas, 1984).

Woody textured berries are not common in hydroponic production, however high solution EC, high salinity and restricted irrigation practices can cause berries to be small and firm. On the other hand, EC levels that are very low will result in a higher percentage of water and less dry weight fruit^{-1}. This fruit will be soft and does not store well (Morgan, 2006).

Under warm growing conditions strawberry fruit can heat up rapidly to the point where cell damage occurs. Over heated fruit are often very soft, dark and may have an increased susceptibility to fruit rot diseases. Temperatures above 25^{o}C can reduce the soluble solids in the strawberry fruit (Morgan, 2006).

Occasionally, albino fruits, that are normal in size and appearance, but with a lack of colour and flavour, are produced. They are also soft and rot quickly after harvest. The primary cause of albino fruits is lower than normal translocation of sugar to the fruit during maturation. This may occur during periods of peak fruit production preceded by warm weather and overcast skies. Rapid vegetative growth brought on by excess nitrogen levels can also cause low translocation of sugar to the developing fruit (Maas, 1984).

2.5 Factors influencing fruit growth, quality and flavour

2.5.1 Fruit growth and size

The final size and shape of the berry is dependant on the number of achenes formed, which is determined by pollination and fertilization at the time of blooming. Cell division ceases relatively soon after flower opening, usually within 6 to 7 days and cell enlargement is then responsible for fruit growth. The enlargement normally takes 28 to 30 days, but is temperature dependent and can vary with many weeks (Morgan, 2006).

Cells in the cortex and pith are responsible for most of the receptacle growth, with the cortex being the primary contributor to fruit size. Cell division accounts for only about 20% of the total fruit growth, occurring mostly before anthesis. The rest of the growth is due to cell enlargement, with cell size increasing towards the inner part of the fruit (Hancock, 1999).

Elevated temperatures have a negative effect on fruit size and quality because of its high respiration rate, high surface to volume ratio and thin cuticle (Hancock, 1999). According to Galletta *et al.* (1981), high soil temperatures can also have a negative effect on fruit size. Draper *et al.* (1981) found that strawberries harvested in cool spring temperatures were two times bigger than fruit harvested in the hot summer. Any conditions such as limited leaf area, low light/temperature ratio or plant diseases that limit photosynthesis can have a negative effect on fruit size and can even cause flower shedding before fruit set. Small fruit size is a common problem with plants grown in low winter light conditions as out of season crops. This problem can be overcome by the use of artificial light and CO_2 enrichment to boost photosynthesis (Morgan, 2006).

Early fruit growth is heavily dependent on reserves stored in the crown and roots. Photo-assimilates only supply 25% of the carbohydrates required for the first 7 days of berry growth. This indicates that crown size should be taken into account when selecting planting stock. Management techniques that allow maximum development of the root system, crown health and good foliage development are important to support later fruit set and overall fruit size. Early flower removal is a common practice that can be used to support foliage development in planting stock with smaller crown diameter (Morgan, 2006).

2.5.2 Fruit quality and flavour

Flavour is one of the most important aspects of fruit quality. Out of season (winter) strawberries often lack flavour, particularly sweetness, due to low light conditions. Good light levels are essential for sugar production in the plant. Acid levels in the fruit seem to be less affected by low light conditions compared to sugar levels, thus out of season fruit can be acidic without the required sweetness to balance the flavour (Morgan, 2006).

Strawberry fruit can range from 7 to 11.5% dry matter, depending on cultivar, growing conditions, plant age and nutrition (Morgan, 2006). Sweetness is a function of sugar quantity and type. Therefore, the relative sugar composition is an important factor that affects fruit quality (Hamano *et al*., 2002). Glucose, fructose and sucrose are the major sugars found in strawberry fruit at all stages of ripening. Glucose and fructose are found in almost equal concentrations (Maas *et al*., 1996). Levels of these rise continuously during fruit development from 5% in small green fruit to 6 - 9% in mature berries (Spayd & Morris, 1981). Sucrose levels are generally much lower and only start to accumulate around the middle of fruit development (Hancock, 1999). Sugar content and composition is dependant upon the ripening stage, cultivar and growth conditions (Hamano *et al*., 2002). The average sugar level of strawberry fruit is around a Brix of 8 to 10, which gives acceptable flavour (Hancock, 1999).

The pH of strawberry fruit remains at about 3.5 during fruit development, although titratable acidity, representing predominantly organic acids like citric and malic acid, gradually drops during fruit development (Spayd & Morris, 1981). It is not only the total sugar and acid levels which contribute to flavour, but also the sugar:acid ratio. A ratio of 9 to 13.5 gives a good flavour balance (Morgan, 2006).

2.5.3 Effect of shading on plant growth, fruiting responses and quality

Strawberries have a reasonably high light requirement to produce good yield and quality fruit. Strawberry plants become light saturated at light levels between 800 to 1200 µMol m^{-2} s^{-1} photosynthetic photon flux, at ambient CO_2 and a temperature of 25°C (Morgan, 2006).

Light interception in the greenhouse can be affected by the cladding and structural components used. The more rafters and other structural components within the roof and walls of the greenhouse, the greater the shading effect on the crop. Covering the floor with reflective material will be beneficial, as the light reaching the ground will be reflected up onto the lower plants in a vertical system (Morgan, 2006).

According to Awang & Atherton (1995), low irradiance decrease total leaf growth, total leaf area, dry weight and number of crowns per plant. Shading also have a strong inhibitory effect on floral development. It can reduce the number of inflorescences per plant, as well as the number of flowers and fruits per inflorescence. Fruit yield under shaded conditions can also be lower (Awang & Atherton, 1995). According to Miura *et al.* (1993), fruits of strawberry plants under a black net with a 60% light transmittance took longer to reach the full red stage than fruits without shade treatment. They were also smaller than fruits of unshaded plants.

In a vertical system, production decreases downward in the system (Durner, 1999). According to Durner (1999), a 40 g decrease in yield $plant^{-1}$ was observed with every 30 cm decrease in planting height. This was attributed to a bigger shading effect on lower levels of the vertical production system.

In some countries hydroponic strawberries are provided with artificial supplementary light to boost production and sugar levels during months of low light intensities (Morgan, 2006). According to Awang & Atherton (1995), the effect of shading on the concentration of reducing sugars was dependant on salinity. At an EC of 2.6 mS cm^{-1} there was no difference between shaded and unshaded plants, but the reducing sugar concentration was much higher in unshaded plants at EC's of 5.9 and 8.6 mS cm^{-1}

(Awang & Atherton, 1995). Miura *et al*. (1993) found that fruits of shaded plants had lower fructose, glucose and sucrose content.

2.6 Hydroponic strawberry production

World-wide, soil grown strawberry production relies heavily on the use of fumigation chemicals to control soil borne pests, diseases and weeds. Without fumigation of soil beds, it's estimated that strawberry production would be cut by half in some regions. With the ban of methyl bromide as a soil fumigant and the resulting yield losses it might cause, many growers turned to soilless strawberry production (Morgan, 2006).

2.6.1 Strawberry nutrition in hydroponic systems

Water quality

Strawberries require a good quality water source, with an EC below 0.4 mS cm^{-1}, as the basis of the nutrient solution. Such a water source will most likely contain a number of elements that must be taken into account when creating a suitable nutrient formula. Water supplies with high levels of trace elements may for example require some treatment to remove these elements. High sodium levels (> 40 ppm for drain to waste systems) can also make water supplies unacceptable for hydroponic strawberry production, thus water needs to be analyzed before setting up any growing system (Morgan, 2006).

EC and pH

Optimum EC levels of nutrient solutions used for hydroponic strawberry production vary depending on environmental conditions, growing system and light conditions. The recommended EC for media based growing systems range between 1.4 and 3 mS cm^{-1}. During the harvest period a minimum EC of 1.6 mS cm^{-1} must be maintained for good quality. Under low light intensity (winter conditions), EC levels should be higher (2 – 2.4 mS cm^{-1}) than under warmer conditions with high light intensity (Morgan, 2006). The pH (H_2O) for hydroponic strawberry production should be maintained between 5.8 and 6, to facilitate maximum uptake of elements (Morgan, 2006).

Nutrient solutions

The amount of fertilizer salts to dissolve into two 100 litre stock solution tanks is shown in Table 1. A 1:100 dilution will give an EC of 2 mS cm^{-1}. The vegetative formulation must be used from plant establishment until fruit set on the first truss when a fruiting formulation should be introduced. The fruiting formulation maintains higher levels of potassium for fruit growth and quality (Morgan, 2006).

Table 2.1 Nutrient formulations for hydroponic strawberry production (Morgan, 2006)

Tank A	**Vegetative formulation (g)**	**Fruiting formulation (g)**
Calcium Nitrate	11035.6	7401.6
Potassium Nitrate	1370.2	2606.2
Iron Chelate (13%)	500	500
Tank B		
Potassium Nitrate	1370.2	2606.2
MonoPotassium Phosphate	3077.1	3924.4
Magnesium Sulphate	5897.8	5886.6
Manganese Sulphate	80	80
Zinc Sulphate	11	11
Boric Acid	39	39
Copper Sulphate	3	3
Ammonium Molybdate	1.0	1.02

Nutrient deficiencies

Nitrogen: An orange-red colouration is produced in older leaves. Roots and crowns are smaller and lighter. Blossoms are undersized and fruits are small and sweet (Maas, 1984).

Sulphur: Overall yellowing of young leaves and uneven leaflet size are observed. Dry weight of the roots is slightly reduced, but there are no apparent differences in blossoms or fruits (Maas, 1984).

Phosphorus: The veins in older leaves turn blue, this can eventually spread to the entire leaf surface. Phosphorus deficiency can severely reduce yield and plant growth (Maas, 1984).

Potassium: Brownish, dry necroses develop on the leaf margins (Morgan, 2006). Root and crown size are reduced and fruits are soft and flavourless (Maas, 1984).

Magnesium: Foliage shows a reddish colour between the veins, this may develop into a dark purple colouration (Morgan, 2006). The size of flowers and fruits are not affected, but berries may be soft and lighter in colour than normal berries (Maas, 1984).

Calcium: Folded emerging leaves show tip burn, followed by crimping as leaves expand. Root and crown size are reduced, the fruits are small, sour, hard and seedy or with seedy patches (Maas, 1984). Calcium is important for maintaining cell integrity and plays an important role in post harvest firmness, storage life and rot resistance of harvested berries (Morgan, 2006).

Boron: Boron is an important trace element in strawberry production, as it plays a major role in pollination and thus fruit shape and size. The leaves of boron deficient plants can be folded, distorted and stunted. They can also develop tip burn. Fruits tend to be deformed with lack of even seed development or loosely attached seeds (Maas, 1984; Morgan, 2006).

Iron: According to Morgan (2006), iron is the most common deficiency on strawberry plants in hydroponic systems and this is often caused by plant and environmental influences. The younger leaves of iron-deficient plants show yellow interveinal chlorosis with bright green veins. Root volume and crown growth are restricted (Maas, 1984).

Manganese: Manganese deficiency first appears as interveinal chlorosis of the new foliage (Maas, 1984). Fruit size is reduced and fruits are lighter in colour (Morgan, 2006).

Copper: Copper is not often deficient in hydroponic production (Morgan, 2006). According to Maas (1984), no effects have been noted on root growth or fruit development of plants grown under conditions of copper deficiency.

Molybdenum: According to Morgan (2006), deficiencies have not been reported or described in hydroponic strawberry production due to the small quantities required for growth.

Zinc: Foliar symptoms include interveinal chlorosis and a reduction in size of young leaves (Maas, 1984).

Silica: Silica enrichment can help strawberry plants to overcome the damaging effects of high salinity (Morgan, 2006). According to Miyake & Takahashi (1986), silica enrichment can increase yield and fruit size. It also plays an important role in pollen fertility.

Oxygen: Aeration of the root zone is very important in hydroponic strawberry production. Strawberries can not tolerate saturated conditions. Aeration in the root zone affects the amount of nutrients and water taken up by the plant. Signs of oxygen starvation include wilting during the warmest part of the day despite sufficient moisture, slow growth, die back and mineral deficiency symptoms as oxygen starved roots are inefficient in taking up mineral ions from solution (Morgan, 2006).

2.6.2 Cultivars

There are hundreds of strawberry cultivars in commercial production around the world and new cultivars are being bred continually. Growers should test a number of local and commonly grown varieties within their production system to determine which cultivar will produce the highest yields and has the most preferable characteristics (Morgan, 2006). According to Hancock (1999), Camarosa and Chandler are important worldwide cultivars, which can give good yields in hydroponic systems (Hancock, 1999; Morgan, 2006). They are also very important cultivars in South Africa (Hancock, 1999). Other commonly grown cultivars suited for hydroponic production are Aptos, Earliglow, Elsanta, Pajaro, Seascape, Selva and Sweet Charlie (Morgan, 2006)

According to Linsley- Noakes *et al.* (2006), the Californian cultivars, Camarosa, Aromas, Gaviota and Diamante did well in a vertical hydroponic system tested in George, South Africa. The Isreali cultivar, Tamar, also gave acceptable yields, but was very susceptible to powdery mildew (Linsley- Noakes *et al.* 2006).

2.6.3 Yields

Hydroponic strawberry yields range between 300 and 1500 g plant^{-1} over a growing season (El-Behairy *et al.*, 2001a). Winter production under heated conditions produce lower yields of 200 to 500 g plant^{-1}. Since plant density between different growers can be so variable, expressing yield on a per plant basis is only useful if the density of the crop is known (Morgan, 2006).

Studies in Greece have shown that the soilless vertical bag system can produce higher yields m^{-2} than the traditional soil based system (Mattas *et al.*, 1997). According to Paraskevopoulou-Paroussi & Paroussis (1995), vertical production systems can be up to 3 times more productive than soil based systems. El-Behairy *et al.* (2001b) have found that the ‘A-shape’ NFT system can give yields of almost 6 times higher than the conventional soil based system. Studies in the USA have also shown that vertical hydroponic systems in winter greenhouse production can reach yields of 7.8 kg m^{-2} (Durner, 1999).

2.6.4 Harvesting

Hydroponically grown fruit are usually harvested daily because they must be removed at just the right stage of development. Fruits can be harvested at the pink stage, but growers that produce for the local markets can allow fruit to ripen for longer as this practice results in fruit with better flavour and higher sugar levels (Morgan, 2006). Fruit should be picked in the morning just after the plants have dried to ensure good shelf-life (Bowling, 2000). Strawberries must be harvested with the calyx intact and can be harvested directly into punnets. This prevents double handling and reduces the occurrence of physical damage. Fruits need to be cooled below 5^{o}C as rapidly as possible after harvesting to prolong shelf life and fruit quality (Morgan, 2006).

2.6.5 Pests and diseases of hydroponic strawberries

Hydroponically grown strawberry crops are prone to a number of potentially serious pest and disease problems (Morgan, 2006).

Strawberry pests

Hydroponic production prevents infection from many soil borne pests (e.g. strawberry root weevil, black vine weevil and other beetle larvae). Armyworms and cutworms are also less common in hydroponic strawberries. Common pests of hydroponic strawberries include aphids, whitefly, various caterpillars and larvae, mites and thrips (Morgan, 2006).

Aphids can be a major pest of hydroponic strawberry crops and can quickly develop into epidemic proportions (Morgan, 2006). Aphids are found in every production area. They usually occur on new shoots and buds in the crown of the plant and also along the veins on the undersides of leaves (Maas, 1984). Aphids can be vectors of virus diseases, but can also cause stunted growth due to heavy feeding (Hancock, 1999).

Flower thrips are the most common in open field and greenhouse strawberry crops. They feed on the developing seed and the tissue between seeds. The damaged fruits are small and have a bronzed colour (Hancock, 1999). Thrips can also spread a number of strawberry virus diseases (Morgan, 2006)

Spider mites are a worldwide problem. The most troublesome species are the two-spotted spider mite, red spider mite and strawberry spider mite. Characteristic first symptoms of spider mite damage are brownish, dry areas on the lower leaf surfaces where the mites have been feeding (Maas, 1984). They also cover the undersides of leaves with a fine webbing (Hancock, 1999).

The strawberry whitefly, greenhouse whitefly and silverleaf whitefly are the most common species of whitefly which may infest hydroponic strawberry crops. Plants can be seriously weakened by heavy infestations because large volumes of sap can be removed in a short time (Morgan, 2006).

Strawberry diseases

Diseases of strawberry fruit are largely dependant on the particular environment the plants are growing in. Many modern cultivars have some resistance to common diseases such as root pathogens, but fungal diseases such as powdery mildew and botrytis are still common in strawberry crops grown under protection (Morgan, 2006).

Bacterial diseases like angular leaf spot and bacterial wilt can occur on strawberry plants, although bacterial wilt is rarely found on mature plants (Maas, 1984).

Powdery mildew is one of the most common fungal diseases of the leaf. Severe foliar infection damages leaves and reduces photosynthesis because of a thick covering of mycelium, necrosis, or even defoliation (Maas, 1984). Other common fungal diseases of the foliage include leaf spot, leaf scorch and leaf blight (Hancock, 1999).

Botrytis is probably the most serious cause of fruit rot in strawberries (Hancock, 1999; Bowling, 2000). It is a common and damaging disease of strawberry crops. Infected flowers may show browning and drying down to the stem and fruit may develop a soft, brown watersoaked area which later becomes covered in powdery grey spores. Botrytis is associated with humid conditions, which are required for successful spore germination, at temperatures around 20°C (Morgan, 2006). Other fruit rot diseases include black spot (anthracnose), leather rot, rhizopus rot (leak), powdery mildew of fruit, rhizoctonia fruit rot (hard rot) and mucor fruit rot (Maas, 1984).

Some of the most common fungal diseases of the roots and crowns include red stele root rot, crown rot, verticillium wilt, black root rot and pythium root rot. The most common symptoms of all these diseases are stunted growth or wilt, which can have a very serious effect on productivity (Maas, 1984)

2.6.6 Plant density, orientation and systems

Plant density

Hydroponic strawberry crops are usually grown at much higher planting densities than those produced in the field (Morgan, 2006). According to Vock (1991), plant spacing in open field production is between 2.4 to 5.1 plants m^{-2}.

Traditionally hydroponic strawberry plants have been grown at low average planting densities of 5 to 6 plants m^{-2}, however yields can be increased by as much as 50% by using planting densities of up to 17 plants m^{-2}. Strawberry plants can be closely spaced due to its small, compact nature. Planting densities of between 3 to 12 plants m^{-2} have shown that lower planting densities increase yield $plant^{-1}$, but does not compensate for lower yields m^{-2}. Plant spacing and overall planting density depends on factors such as cultivar, amount of light available for growth and system used (Morgan, 2006). According to Morgan (2006), the ideal planting density for conventional hydroponic systems is around 10 plants m^{-2} and can be as high as 20 plants m^{-2} in some systems.

An increase in planting density usually causes a decrease in yield $plant^{-1}$. In some cases yield reduction can be so sharp that with more plants m^{-2} no higher yield can be obtained. Higher planting densities can also lead to lower fruit quality and picking rates, but with a well designed planting system, yield loss $plant^{-1}$ can be minimized (Dijkstra *et al*., 1993).

Vertical production systems tend to use much higher planting densities than conventional (horizontal) systems and thus have the potential to significantly increase the yield m^{-2} (Morgan, 2006). Vertical production systems can accommodate planting densities of up to 50 plants m^{-2} (Linsley-Noakes *et al*., 2006).

Orientation

If the greenhouse site is far from the equator, the orientation of the greenhouse and crop rows becomes important, because at high latitudes the angle of the sun is lower especially during spring and autumn months. The greenhouse and crop rows should be in a north-south orientation to maximize light penetration (Morgan, 2006). The east-west orientation has generally less well illuminated surface and will also have no direct sunlight on the south side of the rows (Jackson, 1978).

Vertical production systems

Vertical production systems were developed 30 years ago in Italy (Linsley-Noakes *et al*., 2006). The aim of these systems is to utilize greenhouse space efficiently by increasing the planting density to many times what would normally be grown in a single layer system (Linsley-Noakes *et al*., 2006; Morgan, 2006). According to Ozeker *et al*. (1999), planting density can be increased 3 times with vertical systems compared to conventional systems. Vertical systems are particularly suitable for strawberry production due to its shallow canopy and small leaf area compared to other crops like tomato. Strawberries have the potential to produce high yields in vertical systems, but light intensity must be sufficient to maintain productivity on lower levels. In higher light climates such as Florida in the USA and Australia, vertical systems have been used for commercial strawberry production with high success rates. Maintenance of good light levels are essential for good production, particularly those produced out of season and with vertical systems light becomes more critical (Morgan, 2006). Substrates used in a vertical bag system should have low bulk density to avoid weight loads on the greenhouse construction. The substrate must also be well aerated (El-Behairy *et al*., 2001b).

Advantages

There is an increasing interest in soilless vertical production systems, because of better energy utilization and more efficient use of the greenhouse volume, resulting in higher yields per unit area compared to conventional methods (Paraskevopoulou-Paroussi & Paroussis, 1995). Vertical systems provide a convenient working height for plant maintenance and harvesting. Where moveable stacks are used there is the potential to transport planted stock into and out of cold storage for successive greenhouse crops (Morgan, 2006).

Disadvantages

According to Durner (1999), the yield plant^{-1} decreases down the vertical system due to lower light intensities. Leaf number, fresh and dry plant weight, as well as the number of crowns plant^{-1} also decreased in the lower parts of the vertical system (Paraskevopoulou-Paroussi & Paroussis, 1995).

To set up a vertical system, a high initial investment must be made and it might not be profitable in some production areas (Mattas *et al*., 1997). In some vertical systems the water distribution is non-uniform (Linsley-Noakes *et al*., 2006). The hanging bag system had the disadvantage that the growing media would become compacted and flooded in the lower levels of the system, resulting in root rot and a high percentage of plants that die off. Modern vertical systems however showed a vast improvement (Morgan, 2006).

2.7 Objectives of this study

Vertical production systems have the potential to increase the yield m^{-2} and to utilize greenhouse space more efficiently, but there are many different types of vertical production systems that can be used for strawberry production. The main objective was to compare two of these systems with each other and with a conventional production system. Different levels of planting density and shading were also used to determine the effect of these factors on the fruiting and growth responses in all three systems.

To obtain the above mentioned objectives, the following aspects will be dealt with in the thesis.

i. A thorough literature review on general information regarding strawberry production (Chapter 2).

ii. An experiment conducted to determine the effect of two vertical production systems, subjected to different planting density and shading treatments, on the yield, quality and growth responses of strawberries (Chapter 3).

iii. An experiment conducted to determine the yield, quality and growth potential of strawberries grown in a conventional production system at different levels of planting density and shading (Chapter 4).

iv. A comparison between unshaded plots subjected to the highest planting density of each production system (vertical-, ‘A-shape’- and conventional system) with regard to yield, quality and growth responses to determine the efficiency or maximum potential of each production system (Chapter 5).

2.8 References

ABELES, F.B. & TAKEDA, F., 1990. Cellulase activity and ethylene in ripening strawberry and apple fruits. *Scientia Horticulturae* 42, 269-275.

AWANG, Y.B. & ATHERTON, J.G., 1995. Growth and fruiting responses of strawberry plants grown on rockwool to shading and salinity. *Scientia Horticulturae* 62, 25-31.

BAKKER, J., BRIDLE, P. & BELLWORTHY, S.J., 1994. Strawberry juice colour: a study of the quantitative and qualitative pigment composition of juices from 39 genotypes. *Journal of Science, Food and Agriculture* 64, 31-37.

BOWLING, B.L., 2000. The berry grower's companion. Timber Press Inc., Portland, Oregon, USA.

DIJKSTRA, J., DE BRUIJN, J., SCHOLTENS, A. & WIJSMULLER, J.M., 1993. Effect of planting distance and peat volume on strawberry production in bag and bucket culture. *Acta Horticulturae* 348, 180-187.

DRAPER, A.D., GALETTA, G.J. & SWARTZ, H.J., 1981. 'Tribute and Tribestar everbearing strawberries. *Hortscience* 16, 794-795.

DURNER, E.F., 1999. Winter greenhouse strawberry production using conditioned plug plants. *Hortscience* 34(4), 615-616.

EL-BEHAIRY U.A., ABOU-HADID, A.F., MEDANY, M.A. & AWAD, M.M., 2001A. The effect of different cultivars, orientation and soilless culture systems on production and quality of strawberry. *Acta Horticulturae* 548, 59.

EL-BEHAIRY U.A., EL-SHINAWY, M.Z., MEDANY, M.A. & ABOU-HADAD, A.F., 2001B. Utilization of 'A-shape' system of nutrient film technique (NFT) as a method of producing some vegetable crops intensively. *Acta Horticulturae* 559(2), 581-586.

GALETTA, G.J., DRAPER, A.D. & SWARTZ, H.J., 1981. New everbearing strawberries. *Hortscience* 16, 726.

HAMANO, M., YAMATO, Y., YAMAZAKI, H. & MIURA, H., 2002. Change in sugar contents and composition of strawberry fruit during development. *Acta Horticulturae* 567(1) 369-372.

HANCOCK, J.F., 1999. Strawberries. Crop production science in horticulture. CABI Publishing, Oxon, UK.

JACKSON, J.E., 1978. Utilization of light resources by HDP systems. *Acta Horticulturae* 65, 61-70.

LINSLEY-NOAKES, G., WILKEN, L. & DE VILLIERS, S., 2006. High density, vertical hydroponics growing system for strawberries. *Acta Horticulturae* 708, 365-370.

MAAS, J.L., 1984. *Compendium of strawberry diseases*. American Phytopathological Society, St Paul, Minnesota, USA.

MAAS, J.L., WANG, S.Y. & GALETTA, G.J., 1996. Health enhancing properties of strawberry fruit. In: Pritts, M.P., Chandler, C.K. and Crocker, T.E. (eds) *Proceedings of the IV North American Strawberry conference*, Orlando, Florida, pp. 11-18.

MANNING, K., 1994. Changes in gene expression during strawberry ripening and their regulation by auxin. *Planta* 194, 62-68.

MANNING, K., 1997. Ripening enhanced gene of strawberry: their expression, regulation and function. *Acta Horticulturae* 439(1), 165-167.

MATTAS, K., BENTES, M., PAROUSSI, G. & TZOURAMANI, I., 1997. Assessing the economic efficiency of a soilless culture system for off-season strawberry production. *Hortscience* 32(6) 1126-1129.

MIURA, H., YOSHIDA, M. & YAMASAKI, A., 1993. Effect of light intensity on growth and ripening of strawberry fruit. *Acta Horticulturae* 348, 393-394.

MIYAKE, Y. & TAKAHASHI, E., 1986. Effect of silicon on the growth and fruit production of strawberry plants in solution culture. Soil Science and Plant Nutrition 32(2), 321-326.

MORGAN, L., 2006. Hydroponic strawberry production. A technical guide to the hydroponic production of strawberries. Suntec (NZ) Ltd, Tokomaru, New Zealand.

OZEKER, E., ELTEZ, R.Z., GUL, A., ONAL, K. & TANRISEVER, A., 1999. Investigations on the effects of different growing media on the yield and quality of strawberries grown in vertical bags. *Acta Horticulturae* 486, 409-413.

PARASKEVOPOULOU-PAROUSSI, G. & PAROUSSIS, E., 1995. Precocity, plant productivity and fruit quality of strawberry plants grown in soil and soilless culture. *Acta Horticulturae* 408, 109-117.

RISSER, G., 1997. Effect of low temperatures on pollen production and germination in strawberry. *Acta Horticulturae* 439(2), 651-658.

SPAYD, S.E. & MORRIS, R.S., 1981. Physical and chemical characteristics of puree from once-over harvested strawberries. *Journal of the American Society for Horticultural Science* 106, 101-105.

VOCK, N., 1991. Growing strawberries in Queensland. Department of Primary Industries, Brisbane, Queensland, Australia.

CHAPTER 3

THE EFFECT OF DIFFERENT VERTICAL PRODUCTION SYSTEMS, PLANTING DENSITY AND SHADING ON THE GROWTH AND FRUITING RESPONSES OF 'CHANDLER' STRAWBERRY PLANTS GROWN HYDROPONICALLY

Introduction

The aim of a vertical soilless production system is to utilize greenhouse space more efficiently by increasing the planting capacity (Linsley-Noakes *et al*., 2006; Morgan, 2006).

Studies have shown that vertical systems are more productive (yield m^{-2}) than the conventional soil based system due to much higher plant densities (Paraskevopoulou-Paroussi & Paroussis, 1995; El-Behairy *et al*., 2001). It is important that not only the plant density is increased, but also the yield m^{-2}. Yield m^{-2} generally increase with an increase in planting density up to an optimum beyond which an increase in planting density does not result in an increase of yield m^{-2}, but leads to a decrease in fruit quality (Dijkstra *et al*., 1993).

Strawberry plants have a reasonably high light requirement to produce high yields and good quality fruit (Morgan, 2006). Low light levels can cause excessive vegetative growth and a delay in reproductive development. Low yields, small fruit size and low sugar levels are also common problems with plants grown in low light conditions (Awang & Atherton, 1995; Morgan, 2006).

The yield $plant^{-1}$ tends to decrease down the vertical system due to lower light intensity. This lower light intensity is caused by the shading effect of the vertical system on the lower levels (Durner, 1999). It is clear that light intensity and distribution are the limiting factors with the use of vertical production systems and high planting densities. It is thus important to find the right combination between planting density and vertical production system used for strawberry production to obtain the best yield and quality fruit for the market.

The aim of this experiment was to determine the yield, growth and quality potential of two vertical production systems subjected to different levels of planting density and shading.

Materials and Methods

Locality

The experiment was conducted in a greenhouse at the Department of Agronomy, University of Stellenbosch, South Africa during the period of April 2007 to November 2007 (late autumn to early summer). The plastic cladded greenhouse, fitted with a wet-wall and fan cooling system, was constructed in an east-west orientation due to strong mountain winds.

Cultivation Practices

Field runners of the strawberry cultivar 'Chandler' obtained from Môrester farm, Op-die-berg, South Africa on 25 April 2007 were planted on 26 April 2007 in 800 ml black plastic pots. Two drainage holes were made about 1 cm above the base of each pot (opposite sides of the pot). The pots were filled with a coir (coco peat) medium a week before planting and irrigated with 100 ml municipal water day^{-1} to remove excess salts and to ensure the medium was moist on the day of planting.

Planted pots were divided between three different production systems, namely a conventional double row -, a vertical- and an 'A-shape' system, but only results of the vertical- and 'A-shape' system will be discussed in this chapter due to the fact that higher planting densities were used in these systems. The conventional double row system will be discussed in Chapter 4. Both the vertical- and 'A-shape' production systems were orientated north-south to ensure maximum light penetration during the day.

The vertical system consisted of north-south arranged white plastic gutters (Appendix A, Plate 7.1), with a length of 6 m each, supported by wooden poles every 1.5 m. Rows of poles with attached gutters were spaced 1 m apart. The gutters were attached horizontally on both sides of the poles. Vertical distances between gutters varied between 20 cm and 45 cm to make provision for different planting densities, with the highest gutter at 180 cm above ground level.

The 'A-shape' metal construction support system with an angle of 65^{o} was also used to support similar gutters for this production system (Appendix A, Plate 7.2). The gutters were attached horizontally on the outsides of the 'A-shape' construction system. Vertical distances between gutters also varied between 20 cm and 45 cm to give the same planting densities as the vertical system. Each 'A-shape' construction had a bottom width of 1.5 m and was spaced 0.5 m apart.

The gutters were covered with black plastic to ensure that leaves and fruits were protected from drainage water. Holes were then made (30 cm apart) in the black plastic to support each pot. Each gutter contained 20 plants, 30 cm apart and different planting densities were obtained by increasing the number of gutters. Five gutters were used for a density of 16.7 plants m^{-2}; seven for 23.3 plants m^{-2} and 10 for 33.3 plants m^{-2}.

Pots were initially irrigated with a standard Steiner nutrient solution (Steiner, 1984) at an EC of 1 mS cm^{-1}, but the EC was raised to 2 mS cm^{-1}, one week after planting. The nutrient solution was stored in a 1500 litre plastic tank and Netafim drippers (pressure compensated, non-leakage), with a capacity of 2.0 L hr^{-1}, were used to supply each pot with nutrient solution through spaghetti tubing. Application frequency and amount per irrigation were adjusted with temperature changes during the experimental period (increases in plant size and therefore water usage) to ensure a 30% drainage at all time.

Treatments

Two production systems (vertical and 'A-shape') in combination with three different planting densities were evaluated. Gutters of the vertical and 'A-shape' production systems were spaced to give planting densities of 16.7, 23.3 and 33.3 plants m^{-2}.

Both systems were also subjected to 20% shading, 50% shading and a control (no shading) to study the effect of lower light levels on fruiting (yield and quality) and growth (vegetative) of strawberry plants. All plants were left unshaded until the first flower buds were visible upon which different levels of shading were applied randomly. White shade net was used in both 20% and 50% shading treatments.

Experimental design

The randomised design was a split split plot in 2 blocks (replicates). Each block contained two equal sized main plots, which were divided into three subplots. The subplots were further divided into three equal sub subplots. Analysis was done with production system as the main plot factor, planting density as the subplot factor and shading as the sub subplot factor. Five plants represented an experimental unit. Data was analyzed using STATISTICA version 8.0 (Statistica, 2007). Fisher's protected Least Significant Difference (FPLSD) was calculated at a 5% level to compare the treatment means.

Data collected

Thermometers were set to record minimum and maximum temperatures during a 24 hour period and were reset at 10h00 on a daily basis. Temperatures (Figure 3.1) were taken at ground level (bottom) and at the top of the planting structures [± 1.8 m above ground level (top)].

Photosynthetic active radiation (PAR) was measured (Figure 3.2 and 3.3) at a height of ± 1 m above ground level inside and outside the greenhouse, as well as inside each production system (vertical and 'A-shape' systems at all planting densities) at 10h00, 12h00 and 14h00 on selected cloudless days.

Figures 3.1 and 3.2 clearly illustrate that temperatures increased with an increase in PAR from a mean monthly maximum temperature (top) of 23.2°C during July 2007 (± 2 months after planting) to a mean monthly maximum temperature (top) of 31.3°C during November 2007. A similar trend was observed for temperatures measured at ground level, but Figure 3.1 shows that temperatures measured at the top were slightly higher (1 to 2°C) compared to temperatures measured at ground level. Temperatures at the top exceeded 26°C from ± 15 August 2007, whereas temperatures at ground level only started to exceed 26°C at the beginning of September 2007. Average temperatures exceeded 26°C during most of the harvest period (22 August 2007 to 30 November 2007). According to Hancock (1999), elevated temperatures can have a negative effect on fruit size and quality. Optimal temperatures for leaf and fruit growth are stated to be between 15°C and 26°C (Morgan, 2006), therefore temperature probably had a negative effect on plant and fruit growth from ± 15 August 2007 until the end of the trial (30 November 2007). Plants that were positioned higher up in the production system were probably affected more negatively by elevated temperatures compared to plants lower down in the system due to a 1 to 2°C temperature difference between the top and bottom measurements.

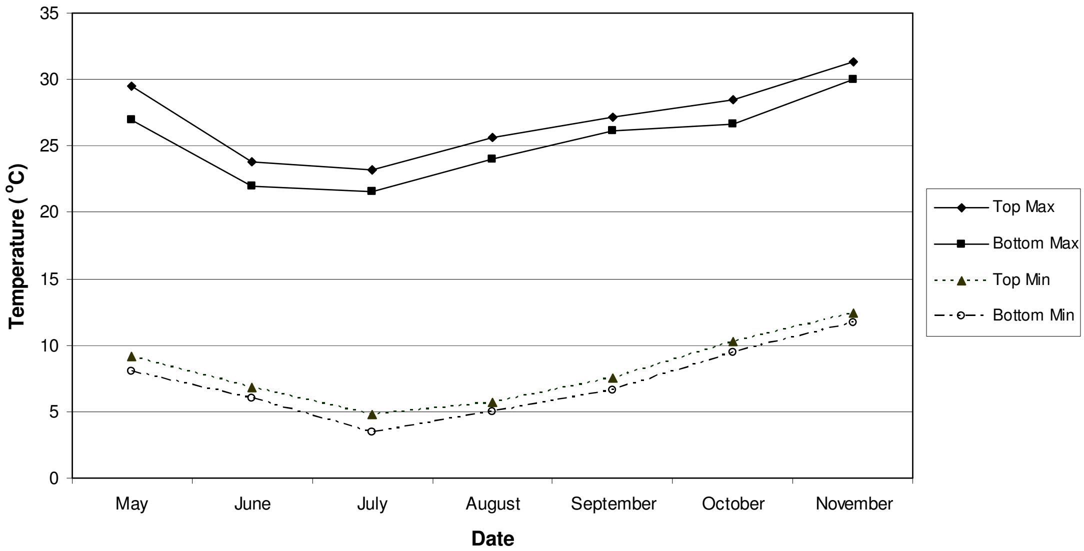

Figure 3.1 Average monthly minimum and maximum temperatures as measured on ground level (Bottom) and 1.8 m above ground level (Top).

PAR increased (Figure 3.2) from middle July 2007 until the end of November 2007 and was lower inside the greenhouse compared to outside, regardless of the time (10h00, 12h00 or 14h00) measurements were taken. The highest light levels (PAR) inside the greenhouse were measured at 12h00, whereas differences between the 10h00 and 14h00 measurements could only be observed from the middle of October 2007 until the end of November 2007 and were slightly higher at 14h00 (compared to 10h00) during the latter period. Similar trends were observed outside the greenhouse.

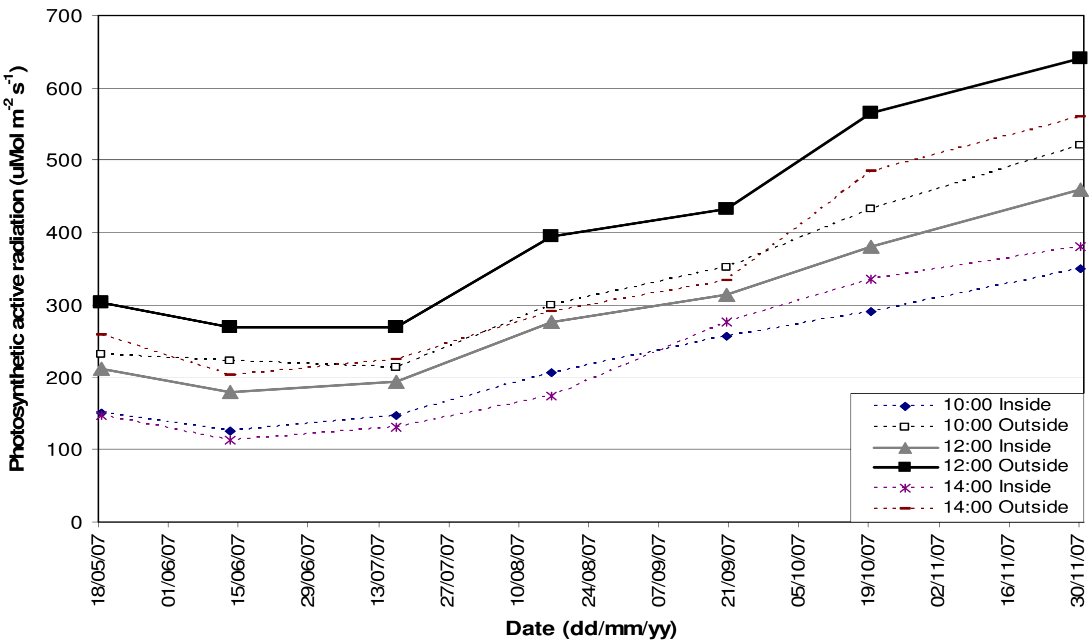

Figure 3.2 PAR changes inside and outside the greenhouse at 10h00, 12h00 and 14h00 as measured randomly over a 14 week period.

PAR measured at 10h00, 12h00 and 14h00 followed the same trend during the trial period and therefore an average was calculated for measurements taken in the two production systems evaluated (Figure 3.3). PAR in the ‘A-shape’ system was higher compared to measurements taken in the vertical system, regardless of planting density. Average PAR inside both production systems was low with a maximum of between ± 200 μMol m^{-2} s^{-1} (vertical system) and ± 300 μMol m^{-2} s^{-1} (‘A-shape’ system). In this study, a 20% shade treatment will let 80% light through. Thus, with PAR levels of 200 μMol m^{-2} s^{-1}, plants will receive 160 μMol m^{-2} s^{-1} and with PAR levels of 300 μMol m^{-2} s^{-1}, plants will receive 240 μMol m^{-2} s^{-1}.

According to Morgan (2006), strawberry plants become light saturated around 800 to 1200 μMol m^{-2} s^{-1} (photosynthetic photon flux) at a temperature of 25°C. Below 700 μMol m^{-2} s^{-1} photosynthetic rates are greatly reduced. The polyethylene cover reduced the photosynthetic photon flux and possibly reduced the yield potential of the production systems evaluated.

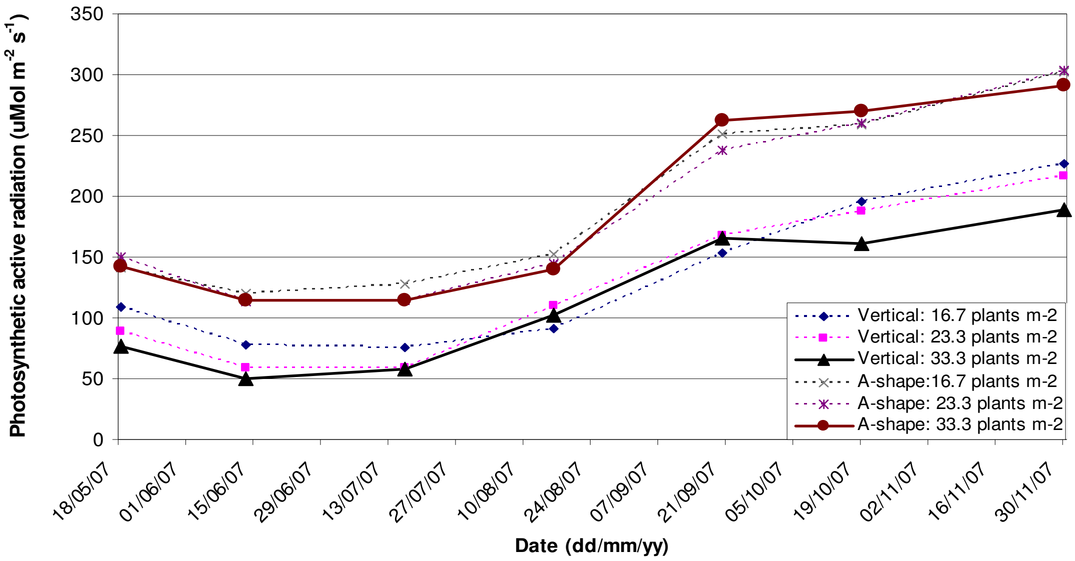

Figure 3.3 PAR inside each production system at different planting densities as measured randomly over a 14 week period.

Two flowers plant^{-1} were selected and marked on the day of anthesis, the first flower at the beginning of the flowering stage and one 4 - 6 weeks later. The number of days from anthesis to harvest (Ant-H) was recorded for each marked fruit. Fruits in the first data set took longer to develop, but the same trend was observed in both data sets. Therefore, an average between the two data sets was calculated for each plant to determine possible differences due to the treatments applied.

Strawberries were harvested when the fruit reached a full red colour (Appendix A, Plate 7.4) and the following data was recorded:

- Total fruit weight at each harvest, before the fruits were sorted into the following categories: >20 g fruit^{-1} (A), 14-20 g fruit^{-1} (B), 9-14 g fruit^{-1} (C), 5-9 g fruit^{-1} (D), <5 g fruit^{-1} (E) and malformed. Number of fruits in each category was counted and fresh weight was measured. Each category was then calculated as a percentage of the total production. Yield loss due to malformation (%YLM) was also calculated at the end of the trial.

- Percentage soluble solids (^{o}Brix), total soluble solids (TSS) and fruit firmness (kPa) were taken for each harvested fruit. The average percentage soluble solids content of fruits (%SS) and total soluble solids produced (TSS) plant^{-1} were then calculated at the end of the trial.

- All the leaves were removed on the last day of harvest and the total number of leaves plant^{-1}, as well as leaf fresh weight (LW) plant^{-1} was calculated.

- Total yield plant^{-1} and number of fruits plant^{-1} were also recorded during a 14 week harvest period (22 August to 30 November 2007) and the yield m^{-2} was calculated to compare the production systems, planting densities and shading treatments.

Results and Discussion

Table 3.1 Analyses of variance (ANOVA) of plant growth and fruiting responses as affected by shading (C), planting density (D) and production system (S)

	Pr > F						
	Shading(C)	Density(D)	System (S)	C*D	C*S	D*S	C*D*S
Yield plant^{-1}	0.0002	<0.0001	0.0093	0.5171	0.3565	0.0264	0.3388
Yield m^{-2}	0.0005	<0.0001	0.0615	0.6214	0.5984	0.0886	0.3665
Ant-H (days)	0.0464	0.0535	0.0005	0.0957	0.3578	0.0270	0.5618
Fruits plant^{-1}	0.0057	<0.0001	0.1381	0.4622	0.2858	0.0640	0.5747
Fruit size	0.0521	0.2787	0.0318	0.4994	0.6212	0.5810	0.3956
%YLM	0.0229	0.2090	0.6952	0.5133	0.7342	0.1968	0.7966
%SS	0.3277	0.6559	0.0017	0.9634	0.6676	0.9163	0.3332
TSS plant^{-1}	0.0002	0.0002	0.0010	0.5303	0.6870	0.0253	0.5969
Leaves plant^{-1}	0.3100	0.0002	0.3401	0.6042	0.3410	0.0910	0.1048
LW plant^{-1}	0.4776	<0.0001	<0.0001	0.8902	0.0990	0.0024	0.0383

Ant-H = number of days from anthesis to harvest

%YLM = percentage yield loss due to malformation

%SS = average soluble solids content of fruits

TSS plant^{-1} = total soluble solids plant^{-1}

LW plant^{-1} = total leaf fresh weight plant^{-1}

Shading (C) significantly affected (P0.05) both the yield plant^{-1} and yield m^{-2}, as well as number of days from anthesis until fruit harvest (Ant-H), number of fruits plant^{-1}, percentage yield loss due to malformation (%YLM) and total soluble solids production (TSS) plant^{-1} (Table 3.1).

Yield plant^{-1}, yield m^{-2}, fruits plant^{-1}, TSS plant^{-1}, total leaf weight (LW) plant^{-1} and the number of leaves plant^{-1} were significantly affected (P0.05) by different planting density (D) treatments (Table 3.1).

Production system (S) had a significant effect (P0.05) on the yield plant^{-1}, number of days from Ant-H, fruit size, soluble solids content of fruits (%SS), TSS plant^{-1} and the LW plant^{-1} (Table 3.1).

Shading did not interact with planting density or production system, but the following factors were significantly affected (P0.05) by a D*S interaction: yield plant^{-1}, number of days from Ant-H, TSS plant^{-1} and LW plant^{-1} (Table 3.1). LW plant^{-1} was the only parameter that showed a significant C*D*S interaction, because it is difficult to find any scientific explanation why only this parameter showed such a response, it is regarded as an experimental error and will therefore be ignored (Table 3.1; Appendix A, Figure 7.1).

Fruit firmness was not affected by production system evaluated, planting density, shading or any interactions between these factors. Reasons for this will be discussed in Chapter 5.

Yield plant^{-1}

Table 3.2 The effect of shading, planting density and production system on the yield plant^{-1} and yield m^{-2}

Factor		Yield plant^{-1} (g)	Yield m^{-2} (g)
	0	283.59c	6717.78c
Shading (%)	20	257.22b	6068.09b
	50	222.04a	5269.80a
	16.7	286.52c	4784.83a
Density (plants m^{-2})	23.3	259.13b	6037.69b
	33.3	217.21a	7233.15c
Vertical system		240.41a	5776.88a
‘A-shape’ system		268.16b	6260.24a

Means followed by the same letter in a block are not significantly different at P=0.05

Yield plant^{-1} decreased significantly (Tables 3.1 and 3.2) as the percentage shading was increased from 0% to 20% and from 20% to 50%. With no shading (0%), an average yield of 283.95 g was produced per plant, while plants subjected to 20% and 50% shading produced on average only 257.22 g and 222.04 g respectively. Awang & Atherton (1995) also reported a yield decline for plants subjected to shading. The observed yield decrease due to shading treatments applied was lower than expected, 20% and 50% shading treatments only caused a 9.2% and 21.7% decrease in yield respectively. One of the reasons for this low yield decline might be due to the mobilization of carbohydrates from other sources. According to Morgan (2006), only 25% of the carbohydrates required for the first 7 days of fruit growth are supplied by current photo assimilates The rest is mobilized from other organs like the roots and crowns. Plants in this trial were left unshaded until the first flower buds were visible, thus plants had ± 3 months to build up carbohydrate reserves. This might have accounted for the higher than expected yields produced by shaded plants.

Yield plant^{-1} was also significantly decreased (Table 3.1) with an increase in planting density, with a highest mean of 286.52 g plant^{-1} (Table 3.2) at a planting density of 16.7 plants m^{-2} and a lowest of 217.21 g plant^{-1} at a planting density of

33.3 plants m^{-2}. Dijkstra *et al.* (1993) and Paranjpe *et al.* (2003) also reported a decline in yield $plant^{-1}$ with an increase in planting density.

Although plants in the 'A-shape' production system produced significantly higher yields $plant^{-1}$ (268.16 g) compared to the 240.41 g $plant^{-1}$ produced in the vertical system (Table 3.2), the significant interaction (Table 3.1) between planting density and production system indicated that the yield response to increasing planting densities differed between production systems. Figure 3.4 clearly illustrates a larger yield reduction with an increase in planting density for the 'A-shape' system compared to the vertical system. Higher PAR was measured (Figure 3.3) inside the 'A-shape' system compared to the vertical system. Therefore, higher yields were expected in the 'A-shape' system, which was observed at low (16.7 plants m^{-2}) and medium (23.3 plants m^{-2}) planting densities, but not at the highest planting density (33.3 plants m^{-2}).

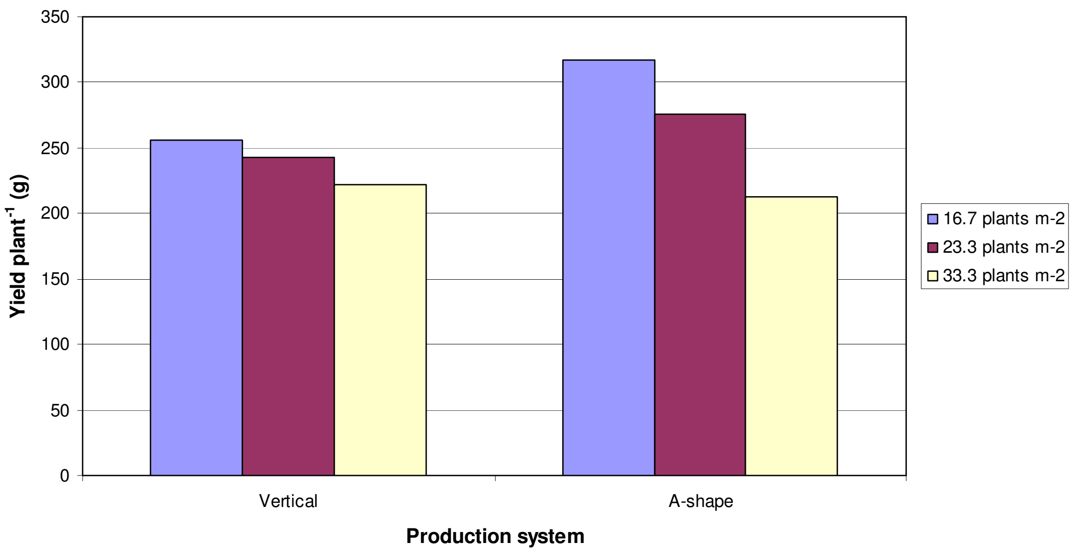

Figure 3.4 The effect of planting density on the yield $plant^{-1}$ in two production systems (LSD = 34.69).

Average yield of unshaded plants at a medium (23.3 plants m^{-2}) planting density was 298.08 g ('A-shape' system) and 309.51 g (vertical system) respectively (data not shown). Paraskevopoulou-Paroussi & Paroussis (1995) reported that plants in a soilless vertical bag system produced 315 g $plant^{-1}$ at a planting density of

24 plants m^{-2}, but the harvest period was much longer (± 7 months). According to Linsley-Noakes *et al*. (2006), an average yield of 200 g $plant^{-1}$ can be produced at planting densities of 50 plants m^{-2}.

Yield m^{-2}

Total yield m^{-2} during the 14 week harvest period, as in the case of yield $plant^{-1}$, decreased significantly (Table 3.1) from 6717.78 g m^{-2} to 5269 g m^{-2} when the percentage shading increased from 0% to 50% (Table 3.2). Yield m^{-2} was also significantly reduced when the plants were subjected to 20% shading (6068.09 g m^{-2}) compared to unshaded (0%) plants.

In contrast to yield $plant^{-1}$, yield m^{-2} increased significantly from a mean of 4784.83 g m^{-2} with a planting density of 16.7 plants m^{-2} to a mean of 7233.15 g m^{-2} with a planting density of 33.3 plants m^{-2} (Table 3.2). Compared to the 16.7 plants m^{-2} density, a significant increase in yield m^{-2} was also recorded with an increase in planting density to 23.3 plants m^{-2} (6037.69 g). According to Morgan (2006), increasing the planting density has the potential to significantly increase the yield m^{-2}, which was clearly observed in this study.

No significant difference in mean yield m^{-2} due to the production systems evaluated were found, but yields obtained with the 'A-shape' system tended to be higher due to higher light levels in the latter system, as was also shown for yield $plant^{-1}$.

From the above, it became clear that light intensity and planting density are very important factors which affect strawberry yields in greenhouse production systems at mean light levels (PAR) of between 50 µMol m^{-2} s^{-1} and 300 µMol m^{-2} s^{-1} during the flowering and fruiting period. Highest total yields (14 week harvest period) of 7.76 kg m^{-2} (vertical system) and 8.06 kg m^{-2} ('A-shape' system) were thus produced by unshaded plots at a planting density of 33.3 plants m^{-2}. These higher yields were the result of a higher yield level throughout the 14 week harvest period (Figure 3.5). The difference in cumulative yield m^{-2} between the highest (33.3 plants m^{-2}) and lowest (16.7 plants m^{-2}) planting densities therefore increased over the 14 week harvest period. After a harvest period of 7 weeks the cumulative yield at a planting density of 33.3 plants m^{-2} was ± 1.3 kg m^{-2} higher compared to the cumulative yield at a planting density of 16.7 plants m^{-2}, this difference increased to ± 2.8 kg m^{-2} after a 14 week harvest period. Planting density therefore seems to affect production peaks and the advantage of higher plant densities increased with time during the harvest period.

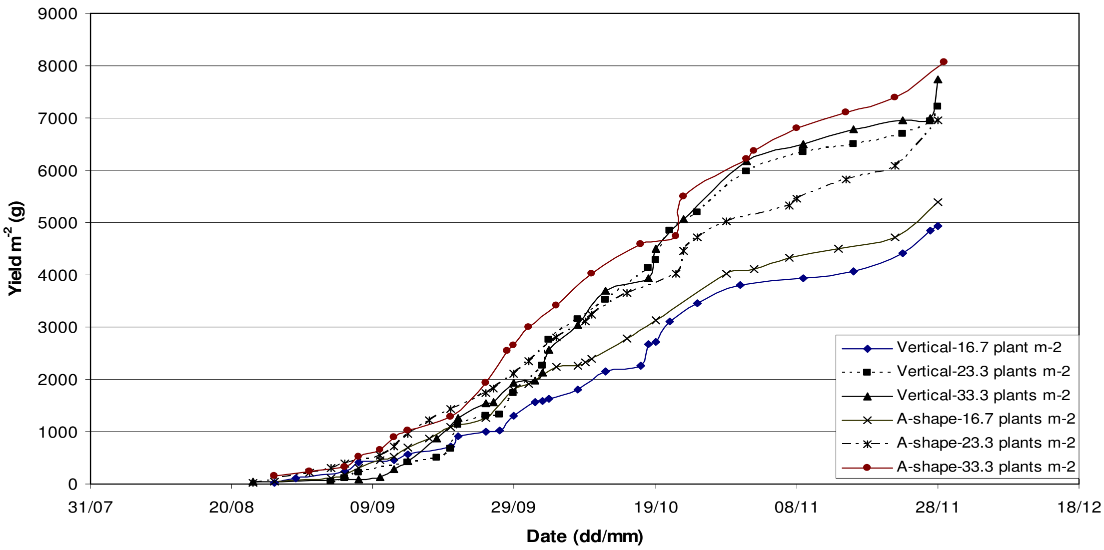

Figure 3.5 Cumulative yield m^{-2} of unshaded plants in the vertical- and A-shape system at three different planting densities.

Yields obtained in this trial were similar to that reported by Paraskevopoulou-Paroussi & Paroussis (1995), even though the harvest period was much longer in the latter report. According to Linsley-Noakes *et al.* (2006), yield can be as high as 10 kg m^{-2} with planting densities of 50 plants m^{-2}, but lower planting densities were recommended. On the other hand, trials in Egypt have shown that an 'A-shape' NFT (nutrient film technique) system can produce yields of 14 kg m^{-2} at planting densities of 28.6 plants m^{-2} (El-Behairy *et al.*, 2001), but it is not clear whether it was the use of an 'A-shape' production system that had this significant affect on yield m^{-2}.

Days from anthesis to harvest (Ant-H)

Table 3.3 The effect of shading, planting density and production system on the days from anthesis to harvest (Ant-H), fruits plant^{-1}, average fruit size, percentage yield loss due to malformation (%YLM), average soluble solids content (%SS) and total soluble solids (TSS) plant^{-1}

Factors		Ant-H (days)	Fruits plant^{-1}	Fruit size (g)	%YLM	%SS	TSS plant^{-1} (g)
	0	42.02a	21.23b	13.41a	14.00a	8.55a	24.24b
Shading(%)	20	44.08ab	19.55ab	13.19a	17.91ab	8.55a	22.02b
	50	44.78b	17.67a	12.55a	20.94b	8.36a	18.61a
Density	16.7	43.28a	21.78b	13.15a	16.47a	8.48a	24.36c
(plants m^{-2})	23.3	45.17a	20.25b	12.73a	20.04a	8.43a	21.88b
	33.3	42.43a	16.42a	13.27a	16.34a	8.56a	18.62a
Vertical system		45.46b	18.88a	12.73a	17.25a	8.28a	19.91a
'A-shape' system		41.80a	20.09a	13.37b	17.99a	8.70b	23.33b

Means followed by the same letter in a block do not differ significantly at P=0.05

Shading had a significant effect (Table 3.1) on the number of days from anthesis to harvest and increased significantly from a mean of 42.02 days to a mean of 44.78 days as the percentage shading was increased from 0% to 50% (Table 3.3). With 20% shading it took fruits an average of 44.08 days to develop from anthesis to harvest, but this did not differ significantly from fruits of unshaded plants. Miura *et al*. (1993) also reported that fruits subjected to shading took longer to reach the full red stage compared to unshaded fruits.

Planting density did not affect the number of days from anthesis to harvest (Tables 3.1 and 3.3), but a significant difference (Table 3.1) was observed between the two production systems evaluated (Table 3.3). Fruits produced in the 'A-shape' system took an average of 41.80 days to develop, whereas fruits produced in the vertical system took 45.46 days to develop from anthesis to harvest. As was illustrated in Figure 3.3, light levels (PAR) were not so much affected by different planting densities, but were much lower inside the vertical system compared to the 'A-shape' system. This observation support results obtained from shading treatments, as well as a report by Miura *et al.* (1993), which stated that shading (low light intensity) can increase the number of days from anthesis to harvest (or the full red stage).

A significant interaction (Table 3.1) between planting density and production system however showed that the difference between the two systems with regard to fruit development (number of days from anthesis to harvest), decreased with an increase in planting density (Figure 3.6). At a planting density of 16.7 plants m^{-2}, fruits in the vertical system took significantly longer (46.87 days) to develop compared to fruits in the 'A-shape' system (39.70 days). Similar, but not significant, tendencies were also observed at higher planting densities. Fruits in the vertical system required 46.57 days (23.3 plants m^{-2}) and 42.93 days (33.3 plants m^{-2}) to develop from anthesis to harvest, whereas fruits in the 'A-shape' system took 43.77 days (23.3 plants m^{-2}) and 41.93 days (33.3 plants m^{-2}) to develop.

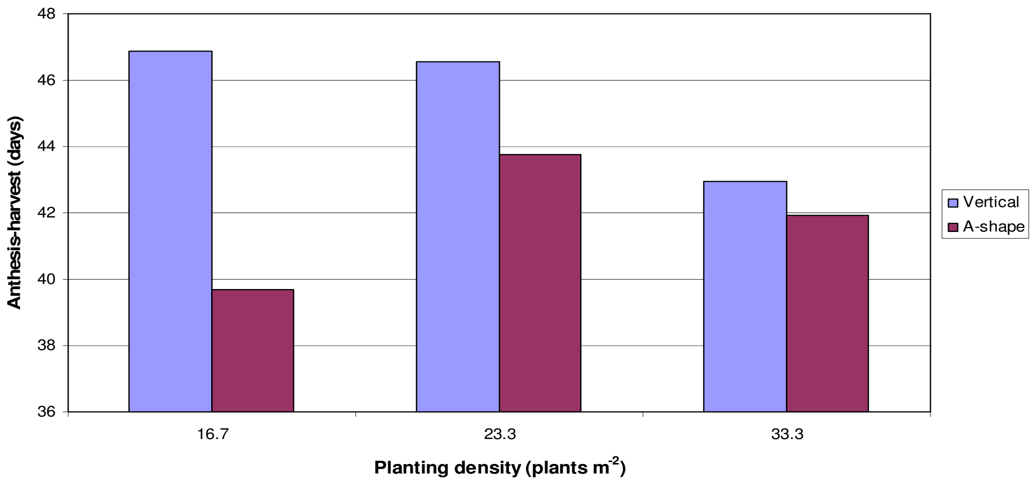

Figure 3.6 Effect of production system on the number of days from anthesis to harvest at three different planting densities (LSD=3.16).

Fruits plant^{-1}

The number of fruits produced per plant decreased significantly (Table 3.1) as the percentage shading was increased from 0% to 50% (Table 3.3). Unshaded plants produced on average 21.23 fruits compared to the 17.67 fruits produced by plants subjected to 50% shading. Plants subjected to 20% shading did not differ significantly with either of the 0% and 50% treatments and produced 19.55 fruits plant^{-1}. This downward trend in the number of fruits plant^{-1} with an increase in shading was similar to that reported by Awang & Atherton (1995).

An increase in planting density from 16.7 to 33.3 plants m^{-2} significantly decreased (Table 3.1) the number of fruits produced plant^{-1} (Table 3.3), but no significant difference was recorded between the low (16.7 plants m^{-2}) and medium (23.3 plants m^{-2}) planting densities. At the lowest planting density (16.7 plants m^{-2}), 21.78 fruits were produced on average per plant, followed by 20.25 and 16.42 fruits produced at planting densities of 23.3 and 33.3 plants m^{-2} respectively. Similar results were observed in a report by Paranjpe *et al.* (2003). In the latter report the yield plant^{-1} decreased as the planting density increased, but the average fruit size was not affected, thus the number of fruits plant^{-1} decreased with an increase in planting density.

Although the 'A-shape' system produced slightly more fruits (20.09 fruits plant^{-1}) compared to the vertical system (18.88 fruits plant^{-1}), these differences were not significant and production system therefore did not affect the number of fruits produced per plant.

Fruit size

Shading did not have a significant effect (Table 3.1) on the average fruit size, even though a slight decrease in fruit size was observed (Table 3.3) with an increase in shading from 0% to 50%. Average fruit size of unshaded plants was found to be 13.41 g compared to 12.55 g for plants subjected to 50% shading. Fruits of plants subjected to 20% shading had an average weight of 13.19 g fruit^{-1}. Miura *et al*. (1993) reported that strawberry fruits under a black net with a 60% light transmittance were smaller compared to fruits of unshaded plants. According to Morgan (2006), any conditions that limit photosynthesis, such as limited leaf area and low light intensities, can have a negative effect on fruit size.

Average fruit size was not affected (Tables 3.1 and 3.3) by different planting density treatments. This result was consistent with a report by Paranjpe *et al.* (2003) which stated that an increase in planting density from 10.8 plants m^{-2} to 22 plants m^{-2} had no affect on the average fruit size. On the other hand, Dijkstra *et al*. (1993) reported that an increase in planting density can have a negative effect on fruit size. Yield is the product of a combination of characters, such as number of fruits plant^{-1} and fruit size (Hancock, 1999). Even though fruit size was not affected by planting density, the number of fruits plant^{-1} decreased with an increase in planting density, therefore the overall product (yield) was influenced negatively by an increase in planting densities.

Average fruit size was significantly affected (Table 3.1) by the production systems evaluated. Fruits produced in the 'A-shape' system had an average size of 13.37 g compared to an average of 12.73 g in the vertical system (Table 3.3). As was mentioned earlier, PAR was lower in the vertical system compared to the 'A-shape' system, therefore the average fruit size was smaller in the vertical system. A report by El-Behairy *et al*. (2001) has shown that the average fruit size of 'Chandler' strawberries produced in an 'A-shape' NFT system was 12.74 g. This result compared well with average fruit size produced in the vertical system, but was lower compared to average fruit size in the 'A-shape' system.

According to Morgan (2006), the fruit size of 'Chandler' strawberries can vary from small to very large, but tend to produce a larger number of smaller fruits after several weeks of cropping.

Table 3.4 Percentage of total yield in each category for two production systems

System	Category				
	A(>20 g fruit^{-1})	B(14-20 g fruit^{-1})	C (9-14 g fruit^{-1})	D (5-9 g fruit^{-1})	E (<5 g fruit^{-1})
Vertical	16.69%	27.18%	28.45%	10.00%	0.43%
A-shape	20.27%	28.23%	26.29%	6.95%	0.27%

The vertical system produced the highest percentage (28.45%) of the total production in category C(9-14 g fruit^{-1}) (Table 3.4), followed by 27.18% in category B(14-20 g fruit^{-1}) and 16.69% in category A(>20 g fruit^{-1}). The 'A-shape' system produced 28.23% of the total production in category B, 26.29% in category C and 20.27% in category A. Only 6.95% of the total production in the 'A-shape' system was produced in category D(5-9 g fruit^{-1}), compared to 10.00% in the vertical system. The vertical and 'A-shape' systems produced 0.43% and 0.27% of the total production in category E(<5 g fruit^{-1}) respectively. Overall, bigger fruits are preferred, but the size depends on the market and probably the time of year. Smaller fruits might be more acceptable during out of season production.

Percentage yield loss due to malformation (%YLM)

Malformation was significantly increased (Table 3.1) with an increase in shading. Only a 14% yield loss was observed (Table 3.3) in unshaded blocks due to malformation, whereas yield loss was increased to 20.94% in blocks subjected to 50% shading. Blocks subjected to 20% shading did not differ significantly with either of the 0% and 50% treatments and 17.91% of the total yield was lost due to malformation. According to Voyiatzis & Paraskevopoulou-Paroussi (2002), malformed fruit, as a result of stamen sterility and poor pollen quality, can have a negative effect on strawberry production. Low light intensity shortly before and during flowering is regarded to be one of the main reasons of anther and pollen degeneration (Smeets, 1976; Smeets, 1980). Consequently, shading probably had a negative effect on pollen quality, thus malformation of fruits increased as shading was increased from 0% to 50%. Strawberry flowers are mostly self pollinated, but in a greenhouse pollination needs to be carried out by either introducing hives of bees or by artificial methods (Morgan, 2006). In this study pollination was assisted by air blowing plants two times a week, but lower percentages of malformation might have been possible with the introduction of bee hives.

Planting density did not affect the malformation of fruits (Tables 3.1 and 3.3). Paranjpe *et al.* (2003) also reported that malformation was not significantly increased by increasing planting densities.

Higher percentage of malformation was expected in the vertical system (Tables 3.1 and 3.3) compared to the 'A-shape' system due to lower light conditions, but no difference was observed between the two production systems.

Average soluble solids content of fruits (%SS)

Different levels of planting density and shading did not affect the average soluble solids content of fruits (Table 3.1), but the production systems evaluated had a significant effect. Shading did not affect (Table 3.3) the soluble solids content of fruits, as was also reported by Awang & Atherton (1995). They showed that shading did not affect the soluble solids content of fruits at an EC of 2.6 mS cm^{-1} and only started to have an effect at higher EC levels. Morgan (2006) on the other hand, reported that plants need good light levels for sugar production and that strawberries often suffer from a lack of sweetness under low winter light conditions. According to Miura *et al*. (1993), shaded fruits had lower levels of fructose, glucose and sucrose compared to unshaded fruits. Carlen *et al*. (2007) reported that ^{o}Brix (percentage soluble solids) is strongly related to the leaf:fruit ratio (cm^2 g^{-1}) and that an increase in leaf:fruit ratio can increase the percentage soluble solids in fruits.

As was mentioned earlier, plants in this trial were left unshaded until the first flower buds were visible, therefore plants had about 3 months to build up carbohydrate reserves. According to Morgan (2006), carbohydrates can be mobilized from other organs, for that reason it might be possible that shaded plants mobilized more carbohydrates from other organs like the roots and crowns for the production of soluble solids. Therefore, shading did not affect the average soluble solids content of fruits and only had a negative effect on the yield produced per plant.

The average soluble solids content of fruits was not affected (Table 3.3) by different planting densities. This might be due to the fact that similar light levels (PAR) were measured at different planting densities in a production system.

Fruits produced (Table 3.3) in the 'A-shape' system had an average soluble solids content of 8.70% compared to an average of 8.28% in the vertical system. Morgan (2006) reported that good light levels are necessary for sugar production in fruits. As was illustrated in Figure 3.3, light levels (PAR) were higher in the 'A-shape' system compared to the vertical system, which might account for the higher percentage of soluble solids produced by fruits in the 'A-shape' system. Figure 3.7 clearly illustrates that fruits in the 'A-shape' system produced on average a higher percentage of soluble solids compared to fruits in the vertical system, regardless of planting density.

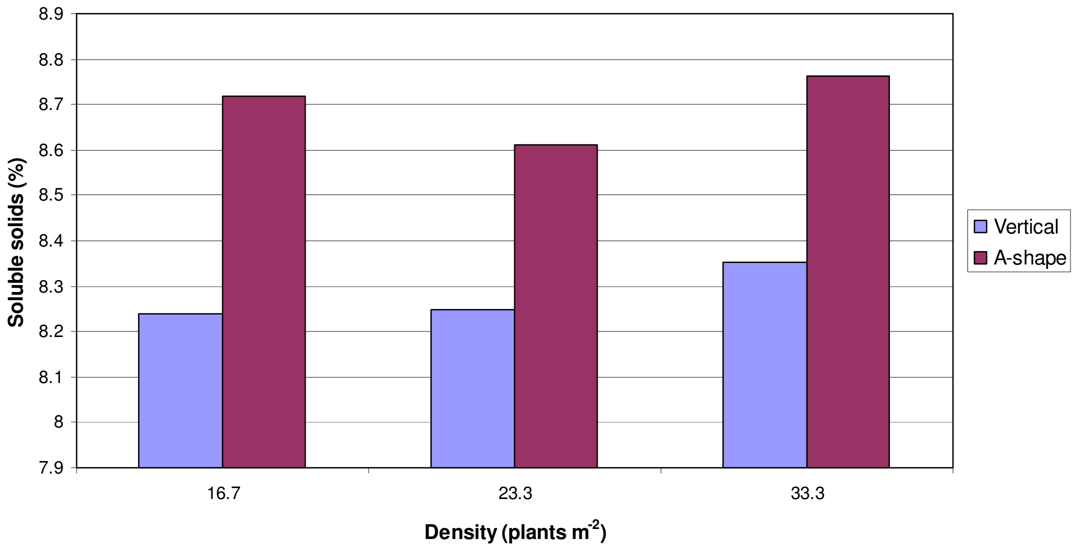

Figure 3.7 The effect of production system on the average soluble solids content of fruits at three different planting densities (LSD=0.41).

The average sugar levels of strawberry fruits are between a ^{o}Brix of 8 and 10%, which gives acceptable flavour (Hancock, 1999), therefore acceptable sugar levels were produced by fruits in both production systems regardless of planting density or shading.

Total soluble solids (TSS) plant^{-1}

Shading significantly decreased (Tables 3.1 and 3.3) the total soluble solids produced per plant. Unshaded plants produced the most soluble solids (24.24 g plant^{-1}) followed by plants subjected to 20% shading (22.02 g plant^{-1}), even though the two treatments did not differ significantly. Plants subjected to 50% shading only produced 18.61 g soluble solids plant^{-1}, which was significantly lower compared to both the 0% and 20% shade treatments. This trend was due to a decrease in yield plant^{-1} with an increase in shade level, while soluble solids fruit^{-1} was not affected by shading.

An increase in planting density had a significant effect (Table 3.1) on the total soluble solids produced plant^{-1} and was significantly decreased (Table 3.3) from low (16.7 plants m^{-2}) to medium (23.3 plants m^{-2}) planting densities and also from medium to high (33.3 plants m^{-2}) planting densities. Plants subjected to planting densities of 16.7, 23.3 and 33.3 plants m^{-2} produced 24.36 g, 21.88 g and 18.62 g soluble solids plant^{-1} respectively. This result was also due to different yield levels while soluble solids production fruit^{-1} was not affected by planting density.

Table 3.5 The effect of a D*S interaction on the total soluble solids production plant^{-1}

System (S)	Density (D) (plants m^{-2})	Total soluble solids plant^{-1} (g)
	16.7	21.15ab
Vertical	23.3	19.97a
	33.3	18.61a
	16.7	27.58c
‘A-shape’	23.3	23.79b
	33.3	18.63a

Means followed by the same letter in a column do not differ significantly at P=0.05

Plants in the 'A-shape' system produced significantly more (Table 3.3) soluble solids plant^{-1} (23.33 g) compared to plants in the vertical system (19.91 g), but the significant interaction (Tables 3.1 and 3.5) between plant density and production system indicated that the 'A-shape' system only produced more soluble solids plant^{-1} at low (16.7 plants m^{-2}) and medium (23.3 plants m^{-2}) planting densities. At a planting density of 33.3 plants m^{-2} no difference with regard to total soluble solids production plant^{-1} was observed between the two production systems. Total soluble solids production in the 'A-shape' system was affected by an increase in planting density and decreased significantly from low (16.7 plants m^{-2}) to medium (23.3 plants m^{-2}) and from medium to high (33.3 plants m^{-2}) planting densities. In the vertical system total soluble solids production plant^{-1} was not affected by planting density.

Leaves plant^{-1}

Table 3.6 The effect of shading, planting density and production system on the number of leaves plant^{-1} and total leaf weight plant^{-1}

Factors		Leaves plant^{-1}	Total leaf weight plant^{-1} (g)
	0	21.02a	29.46a
Shading(%)	20	19.70a	28.73a
	50	19.27a	27.98a
	16.7	23.08c	32.86c
Density (plants m^{-2})	23.3	19.88b	29.73b
	33.3	17.02a	23.59a
Vertical system		19.53a	25.98a
'A-shape' system		20.46a	31.47b

Means followed by the same letter in a block do not differ significantly at P=0.05

Shading and production system did not affect (Tables 3.1 and 3.6) the number of leaves plant^{-1} even though shading tended to decrease the number of leaves plant^{-1} slightly from 21.02 (unshaded) to 19.27 (50% shading). This was in contrast to Awang & Atherton (1995) who reported that shading significantly decreased the number of leaves plant^{-1}. As was mentioned earlier, plants were not subjected to shading the entire trial period, which might account for the small difference between shaded and unshaded plants with regard to number of leaves plant^{-1}.

Number of leaves plant^{-1} decreased significantly from low (16.7 plants m^{-2}) to medium (23.3 plants m^{-2}) planting densities and from medium to high (33.3 plants m^{-2}) planting densities. At the lowest planting density (16.7 plants m^{-2}) plants had 23.08 leaves on average, followed by 19.88 and 17.02 leaves at planting densities of 23.3 and 33.3 plants m^{-2} respectively. This might be a hormonal effect to decrease intra plant shading due to lower light levels as planting density increased. All leaves sprout from crowns (shortened stems) in the strawberry plant. Thus, another explanation might be that plants at higher planting densities produced less crowns due to lower light levels and therefore less leaves were produced.

Total leaf weight (LW) plant^{-1}

A slight downward trend (Table 3.6) in the leaf weight plant^{-1} with an increase in shading was observed, but this result was not significant (Table 3.1). Awang & Atherton (1995) reported that shading significantly decreased total leaf growth, but plants in the latter report were subjected to shading the entire growth period.

Planting density affected (Table 3.1) the total leaf weight plant^{-1}, which was significantly (Table 3.6) higher (32.86 g) at a planting density of 16.7 plants m^{-2} compared to the leaf weight (29.73 g) at a planting density of 23.3 plants m^{-2}. Plants subjected to a planting density of 33.3 plants m^{-2} produced the lowest total leaf weight plant^{-1} (23.59 g), which was significantly lower compared to the leaf weight at low and medium planting densities. PAR measured inside a production system did not differ significantly, regardless of planting density, but an increase in planting density had a negative effect on yield plant^{-1}, fruits plant^{-1}, number of leaves plant^{-1} and total leaf weight plant^{-1}. Therefore, inter plant factors such as inter plant shading might have accounted for the negative effect observed with an increase in planting density.

Table 3.7 The effect of a D*S interaction on the total leaf weight plant^{-1}

System (S)	Density (D) (plants m^{-2})	Total leaf weight plant^{-1} (g)
Vertical	16.7	28.43b
	23.3	25.84ab
	33.3	23.67a
A-shape	16.7	37.28d
	23.3	33.62c
	33.3	23.50a

Means followed by the same letter in a column do not differ significantly at P=0.05

Plants in the 'A-shape' system produced significantly more (Tables 3.1 and 3.6) leaf weight plant^{-1} (31.47 g) compared to plants in the vertical system (25.98 g), but the significant interaction (Tables 3.1 and 3.7) between planting density and production system indicated that the 'A-shape' system only produced more leaf weight at low (16.7 plants m^{-2}) and medium (23.3 plants m^{-2}) planting densities. At a planting density of 33.3 plants m^{-2} no significant difference, with regard to leaf weight plant^{-1}, was observed between the two production systems. This tendency for higher leaf weight plant^{-1} in the 'A-shape' system might be due to higher light levels (PAR) inside this system, even though it was not reflected in the results of the highest (33.3 plants m^{-2}) planting density. A larger leaf weight reduction was observed with increasing plant density in the 'A-shape' system compared to the vertical system. This result followed the same trend as was observed with yield plant^{-1}, therefore plants with higher total leaf weight produced on average a higher yield.

Conclusion

Shading had a negative effect on production. Fruits that were subjected to shading also took longer to develop and less fruits were produced by shaded plants. Shading also tended to decrease the average fruit size, but this result was not significant. Malformation of fruits was increased by shading. In this study the average soluble solids content of fruits was not affected by shading, but the TSS production plant^{-1} decreased with an increase in shading. Shading also tended to decrease the number of leaves plant^{-1} and leaf fresh weight plant^{-1}.

In the 'A-shape' system, an increase in planting density significantly decreased the yield plant^{-1}, whereas only a slight reduction was observed in the vertical system. In both systems the yield m^{-2} was increased with an increase in planting density. The advantage of using higher planting densities was clearly illustrated in this study. Average fruit size was not affected, but the number of fruits plant^{-1} decreased with an increase in planting density. In the 'A-shape' system, TSS production plant^{-1} decreased with an increase in planting density, but the average soluble solids content of fruits was not affected. Leaf fresh weight plant^{-1} and number of leaves plant^{-1} also decreased with an increase in planting density.

Light levels (PAR) measured in the 'A-shape' system were higher compared to measurements taken in the vertical system. Plants in the 'A-shape' system produced better yields and more leaf fresh weight at low and medium planting densities, compared to the vertical system. Fruits tended to develop faster in the 'A-shape' system, regardless of planting density. Fruits in the 'A-shape' system were also slightly bigger and had higher sugar levels compared to fruits in the vertical system, but fruits in both systems produced acceptable sugar levels. Overall, the 'A-shape' system performed better compared to the vertical system, but more studies are necessary to increase the performance at higher planting densities.

References

AWANG, Y.B. & ATHERTON, J.G., 1995. Growth and fruiting responses of strawberry plants grown on rockwool to shading and salinity. *Scientia Horticulturae* 62, 25-31.

CARLEN, C., POTEL, A.M. & ANCAY, A., 2007. Influence of leaf/fruit ratio of strawberry plants on the sensory quality of their fruits. *Acta Horticulturae* 761, 121-126.

DIJKSTRA, J., DE BRUIJN, J., SCHOLTENS, A. & WIJSMULLER, J.M., 1993. Effect of planting distance and peat volume on strawberry production in bag and bucket culture. *Acta Horticulturae* 348, 180-187.

DURNER, E.F., 1999. Winter greenhouse strawberry production using conditioned plug plants. *Hortscience* 34(4), 615-616.

EL-BEHAIRY U.A., EL-SHINAWY, M.Z., MEDANY, M.A. & ABOU-HADAD, A.F., 2001. Utilization of 'A-shape' system of nutrient film technique (NFT) as a method of producing some vegetable crops intensively. *Acta Horticulturae* 559(2), 581-586.

HANCOCK, J.F., 1999. Strawberries. Crop production science in horticulture. CABI Publishing, Oxon, UK.

LINSLEY-NOAKES, G., WILKEN, L. & DE VILLIERS, S., 2006. High density, vertical hydroponics growing system for strawberries. *Acta Horticulturae* 708, 365-370.

MIURA, H., YOSHIDA, M. & YAMASAKI, A., 1993. Effect of light intensity on growth and ripening of strawberry fruit. *Acta Horticulturae* 348, 393-394.

MORGAN, L., 2006. Hydroponic strawberry production. A technical guide to the hydroponic production of strawberries. Suntec (NZ) Ltd, Tokomaru, New Zealand.

PARANJPE, A., CANTLIFFE, D.J., LAMB, E.M., STOFELLA, P.J. & POWELL, C., 2003. Increasing winter strawberry production in North-Central Florida using passive ventilated greenhouses and high plant densities. *Acta Horticulturae* 626, 269-276.

PARASKEVOPOULOU-PAROUSSI, G. & PAROUSSIS, E., 1995. Precocity, plant productivity and fruit quality of strawberry plants grown in soil and soilless culture. *Acta Horticulturae* 408, 109-117.

SMEETS, L., 1976. Effect of light intensity during flowering on stamen development in the strawberry cultivar 'Glasa'. *Scientia Horticulturae* 4, 255-260.

SMEETS, L., 1980. Effect of light intensity during flowering on stamen development in the strawberry cultivars 'Karina' and 'Sivetta'. *Scientia Horticulturae* 12, 343-346.

STATISTICA, 2007. Data analysis software system, Version 8.0, Statsoft Inc., www.statsoft.com.

STEINER, A.A., 1984. The universal nutrient solution. *Proceedings of the International Society for Soilless Culture.* Pp. 633-649.

VOYIATZIS, D.G. & PARASKEVOPOULOU-PAROUSSI, G., 2002. The effect of photoperiod and gibberillic acid on strawberry pollen germination and stamen growth. *Acta Horticulturae* 567, 257-260.

CHAPTER 4

THE EFFECT OF PLANTING DENSITY AND SHADING ON THE GROWTH AND FRUITING RESPONSES OF HYDROPONICALLY GROWN 'CHANDLER' STRAWBERRY PLANTS IN A CONVENTIONAL DOUBLE ROW SYSTEM

Introduction

Hydroponic strawberry crops are usually grown at higher planting densities than those produced in the field. Traditionally, hydroponic strawberry plants have been grown at low average planting densities of 5 to 6 plants m^{-2}, but yield m^{-2} can be increased by as much as 50% by using planting densities of up to 17 plants m^{-2}. Planting densities of between 3 and 12 plants m^{-2} have shown that lower planting densities can increase individual plant yield, but do not compensate for lower yields m^{-2} (Morgan, 2006). According to Hancock (1999), the average planting density for conventional hydroponic strawberry production is 12 plants m^{-2}.

Strawberry plants have a reasonably high light requirement for good yields and high quality fruit (Morgan, 2006). According to Awang & Atherton (1995), low irradiance tends to direct plants towards excessive vegetative growth and this may delay the reproductive development. Shading can also have a strong inhibitory effect on floral development. It can reduce the number of inflorescences per plant, as well as the number of flowers and fruits per inflorescence. Fruit yield under shaded conditions can also be lower (Awang & Atherton, 1995). On the other hand, overhead shading can be used to prevent high temperature damage in strawberry crops (Morgan, 2006).

The main aim of this study was to determine the vegetative growth (leaves $plant^{-1}$ and leaf fresh weight $plant^{-1}$) and fruiting potential (yield, sugar level, size etc.) of strawberry plants in a conventional double row system at three different levels of planting density and shading treatments. The secondary aim, which will be discussed in Chapter 5, was to use this data as a basis for comparison with the two vertical production systems described in Chapter 3.

Materials and Methods

Locality

The experiment was conducted in a greenhouse at the Department of Agronomy, University of Stellenbosch, South Africa during the period of April 2007 to November 2007 (late autumn to early summer). The plastic cladded greenhouse, fitted with a wet-wall and fan cooling system, was constructed in an east-west orientation due to strong mountain winds.

Cultivation Practices

Field runners of the strawberry cultivar 'Chandler' obtained from Môrester farm, Op-die-berg, South Africa on 25 April 2007 were planted on 26 April 2007 in 800 ml black plastic pots. Two drainage holes were made about 1 cm above the base of each pot (opposite sides of the pot). The pots were filled with a coir (coco peat) medium a week before planting and irrigated with 100 ml municipal water day^{-1} to remove excess salts and to ensure the medium was moist on the day of planting.

The conventional double row system consisted of pots that were placed on the greenhouse floor in double rows (Appendix A, Plate 7.3). Plants in each conventional double row system had the same in-row and between-row spacing. Rows were orientated in a north-south direction and a 1 m spacing was maintained between all adjacent double row systems.

Pots were initially irrigated with a standard Steiner nutrient solution (Steiner, 1984) at an EC of 1 mS cm^{-1}, but the EC was raised to 2 mS cm^{-1}, one week after planting. The nutrient solution was stored in a 1500 litre plastic tank and Netafim drippers (pressure compensated, non-leakage), with a capacity of 2.0 L hr^{-1}, were used to supply each pot with nutrient solution through spaghetti tubing. Application frequency and amount per irrigation were adjusted with temperature changes during the experimental period (increases in plant size and therefore water usage) to ensure a 30% drainage at all time.

Treatments

Plants used in the conventional system were subjected to three planting densities (3.3, 5.6 and 10 plants m^{-2}). The system was also subjected to 20% shading, 50% shading and a control (no shading) to study the effect of lower light levels on fruiting and growth responses of strawberry plants. All plants were left unshaded until the first flower buds were visible upon which different levels of shading were applied randomly. White shade net was used in both 20% and 50% shading treatments.

Experimental design

A split plot analysis was done with planting density as the main block factor and shading as the sub block factor. Two blocks (replicates) were used in total and four plants represented an experimental unit. Data was analyzed using STATISTICA version 8.0 (Statsoft 2007). Fisher's protected Least Significant Difference (FPLSD) was calculated at a 5% level to compare the treatment means.

Data collected

Thermometers were set to record minimum and maximum temperatures (Table 4.1) during a 24 hour period and were reset at 10h00 on a daily basis. Temperatures were taken at ground level. Photosynthetic active radiation (PAR) was measured inside and outside the greenhouse at 10h00, 12h00 and 14h00 on selected cloudless days. Measurements were taken at a height of ± 1 m above ground level (Figure 4.2).

Figures 4.1 and 4.2 clearly illustrate that temperatures increased with an increase in PAR from a mean monthly maximum temperature of 21.6°C during July (± 2 months after planting) to a mean monthly maximum temperature of 30.0°C during November. Temperatures at ground level exceeded 26°C from the beginning of September 2007. Average temperatures exceeded 26°C during most of the harvest period (22 August to 30 November 2007). Elevated temperatures can have a negative effect on fruit size and quality (Hancock, 1999). Optimal temperatures for leaf and fruit growth are between 15 and 26°C (Morgan, 2006), therefore temperature probably had a negative effect on plant and fruit growth from the beginning of September 2007 until the end of the trial (30 November 2007).

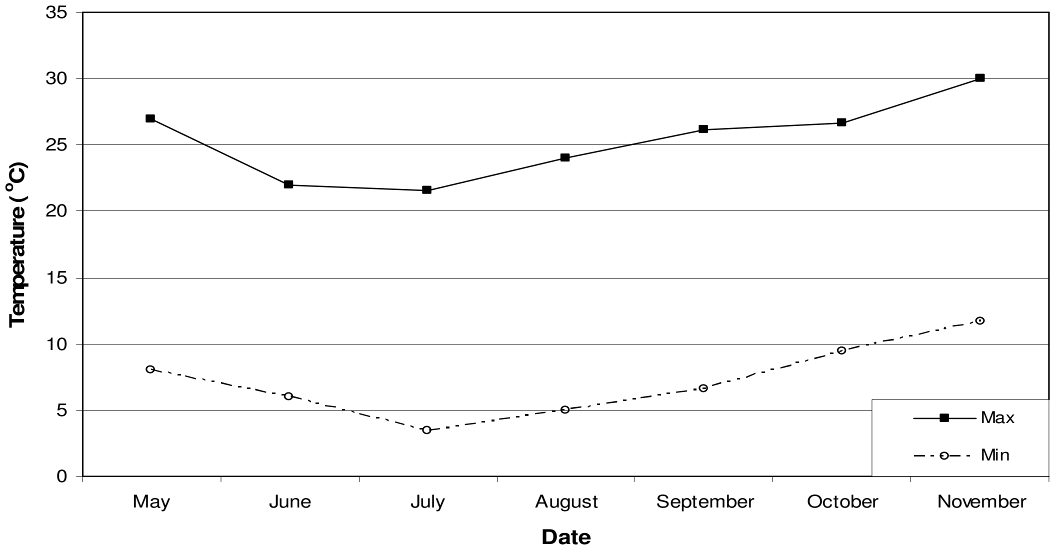

Figure 4.1 Average monthly minimum and maximum temperatures as measured on ground level.

Light levels (PAR) increased (Figure 4.2) from middle July 2007 until the end of November 2007, but PAR inside the greenhouse (Figure 4.2) was much lower compared to PAR outside regardless of the time of measurement. According to Morgan (2006), strawberry plants become light saturated around 800 to 1200 µMol m^{-2} s^{-1} (photosynthetic photon flux) at a temperature of 25°C. Below 700 µMol m^{-2} s^{-1} photosynthetic rates are greatly reduced. The polyethylene cover reduced the photosynthetic photon flux and probably reduced the yield potential of the production systems evaluated.

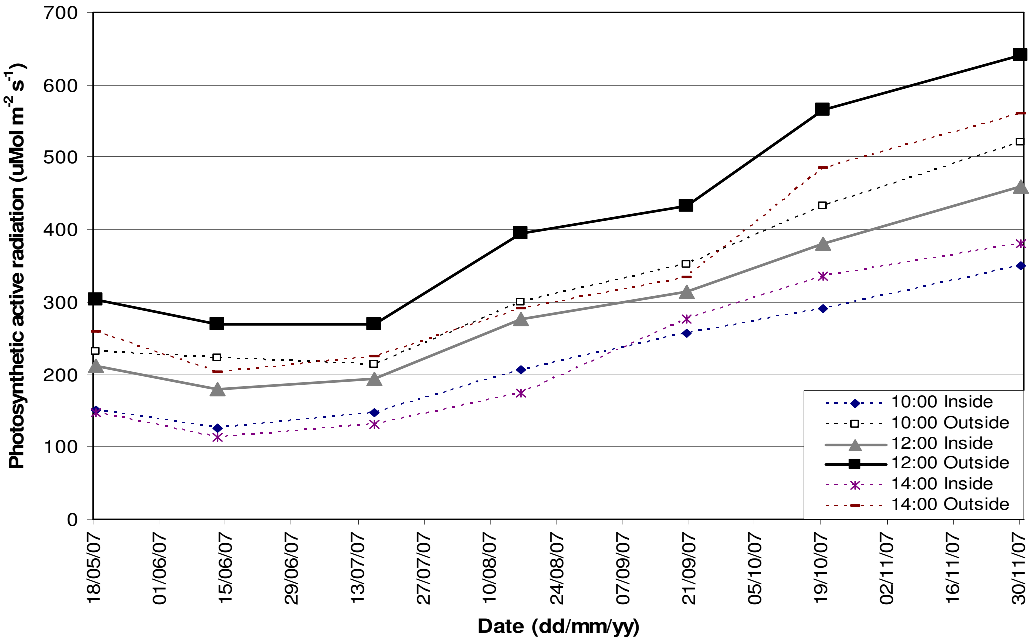

Figure 4.2 PAR changes inside and outside the greenhouse at 10h00, 12h00 and 14h00 as measured randomly over a 14 week period.

Two flowers plant^{-1} were selected and marked on the day of anthesis, the first flower at the beginning of the flowering stage and one 4 - 6 weeks later. The number of days from anthesis to harvest (Ant-H) was recorded for each marked fruit. Fruits in the first data set took longer to develop, but the same trend was observed in both data sets. Therefore, an average between the two data sets was calculated for each plant to determine possible differences due to treatments applied.

Strawberries were harvested when the fruit reached a full red colour (Appendix A, Plate 7.4) and the following data was recorded:

- Total fruit weight at each harvest, before the fruits were sorted into the following categories: >20 g fruit^{-1} (A), 14-20 g fruit^{-1} (B), 9-14 g fruit^{-1} (C), 5-9 g fruit^{-1} (D), <5 g fruit^{-1} (E) and malformed. Number of fruits in each category was counted and fresh weight was measured. Each category was then calculated as a percentage of the total production. Yield loss due to malformation (%YLM) was also calculated at the end of the trial.

- Percentage soluble solids (^{o}Brix), total soluble solids (TSS) and fruit firmness (kPa) were taken for each harvested fruit. The average percentage soluble solids content of fruits (%SS) and total soluble solids produced (TSS) plant^{-1} were then calculated at the end of the trial.

- All the leaves were removed on the last day of harvest and the total number of leaves plant^{-1}, as well as leaf fresh weight (LW) plant^{-1} was calculated.

- Total yield plant^{-1} and number of fruits plant^{-1} were also recorded during a 14 week harvest period (22 August to 30 November 2007) and the fruit yield m^{-2} was calculated to compare the planting density and shading treatments.

Results and Discussion

Table 4.1 Analyses of variance (ANOVA) of plant growth and fruiting responses as affected by shading (C) and planting density (D)

	Pr > F		
	Shading (C)	Density (D)	C*D
Yield plant^{-1}	0.0101	0.0587	0.1259
Yield m^{-2}	0.0126	<0.0001	0.0499
Ant-H (days)	0.6024	0.4588	0.3565
Fruits plant^{-1}	0.0168	0.0001	0.0077
Fruit size	0.2017	<0.0001	0.3361
%YLM	0.0496	0.0733	0.3886
%SS	0.0005	<0.0001	0.3829
TSS plant^{-1}	0.0006	0.0029	0.1955
Leaves plant^{-1}	0.0080	0.8264	0.0728
LW plant^{-1}	0.0006	0.0868	0.3054

Ant-H = number of days from anthesis to harvest
%YLM = percentage yield loss due to malformation
%SS = average soluble solids content of fruits
TSS plant^{-1} = total soluble solids plant^{-1}
LW plant^{-1} = total leaf fresh weight plant^{-1}

Shading (C) significantly affected (P0.05) both the yield plant^{-1} and yield m^{-2}, as well as the number of fruits plant^{-1}, percentage yield loss due to malformation (%YLM), soluble solids content of fruits (%SS), total soluble solids production (TSS) plant^{-1}, number of leaves plant^{-1} and total leaf fresh weight (LW) plant^{-1} (Table 4.1).

Yield m^{-2}, fruits plant^{-1}, average fruit size, %SS and TSS plant^{-1} were significantly affected (P0.05) by different planting density (D) treatments (Table 4.1).

Yield m^{-2} and fruits plant^{-1} were significantly affected (P0.05) by an interaction between shading and planting density (Table 4.1).

Fruit firmness was not affected by planting density, shading or an interaction between these two factors. Reasons for this will be discussed in Chapter 5.

Yield plant^{-1}

Table 4.2 The effect of shading and plant density on the yield plant^{-1} and yield m^{-2}

Factor		Yield plant^{-1} (g)	Yield m^{-2} (g)
	0	510.73ab	3134.56a
Shading(%)	20	554.94b	3455.05b
	50	471.38a	2979.76a
	3.3	503.37a	1661.11a
Density (plants m^{-2})	5.6	548.28ab	3070.39b
	10	485.39a	4837.88c

Means followed by the same letter in a block do not differ significantly at P=0.05

Shading had a significant effect (Table 4.1) on the yield plant^{-1}. A slight yield increase (Table 4.2) from 510.73 g to 554.94 g plant^{-1} was observed as the percentage shading increased from 0% to 20%, but yield plant^{-1} decreased significantly as the percentage shading increased from 20% to 50% (471.38 g plant^{-1}). No significant difference was observed between the 0% and 50% shade treatments, even though 50% shading tended to have a negative effect on the yield plant^{-1}. According to Austin *et al*. (1960), fruit temperature can exceed air temperature by as much as 8^{o}C on a sunny day. High temperatures can have a negative effect on fruit size, fruit set and overall yield (Hancock, 1999). According to Morgan (2006), overhead shading can be used to prevent high temperature damage in strawberry plants. At a shading level of 20% the yield plant^{-1} was slightly increased, probably due to lower surface temperatures of leaves and fruits. On the other hand, 50% shading tended to have a negative effect on the yield plant^{-1}, most likely due to lower light levels (PAR), despite the fact that plants and fruits subjected to 50% shading probably had the lowest surface temperature.

Planting density had no significant effect (Table 4.1) on the yield plant^{-1}, but the same trend as found with shading was observed. Yield increased (Table 4.2) from 503.37 g plant^{-1} to 548.28 g plant^{-1} as the planting density increased from 3.3 to 5.6 plants m^{-2}, but a further increase from 5.6 to 10 plants m^{-2} resulted in a decrease in yield to 485.39 g plant^{-1}. Plants subjected to a planting density of 3.3 plants m^{-2} were more exposed to direct sunlight compared to plants subjected to higher planting densities. Fruits of these plants were also more exposed and therefore had higher surface temperatures. These elevated temperatures probably had a negative effect on fruit size or fruit set and therefore overall yield. At the highest planting density (10 plants m^{-2}), adjacent plants had to compete for direct sunlight. This might have caused the slight reduction in yield compared to plants at medium planting densities (5.6 plants m^{-2}).

Yield m^{-2}

Yield m^{-2} was significantly increased (Tables 4.1 and 4.2) from 1661.11 g m^{-2} to 3070.39 g m^{-2} as the planting density increased from 3.3 to 5.6 plants m^{-2}. In contrast with yield plant^{-1}, yield m^{-2} increased to 4837.88 g m^{-2} as the planting density increased from 5.6 to 10 plants m^{-2}.

As with yield plant^{-1}, yield m^{-2} was significantly affected by shading (Table 4.1). Unshaded plants (3134.56 g m^{-2}) produced on average a significantly lower yield m^{-2} (Table 4.2) compared to plants subjected to 20% shading (3455.05 g m^{-2}), but yield m^{-2} decreased significantly as the percentage shading was increased from 20% to 50% (2979.76 g m^{-2}). No significant difference was observed between the 0% and 50% treatments.

Table 4.3 The effect of a D*C interaction on the yield m^{-2}

Density (D)	Shading (C) (%)	Yield m^{-2} (g)
3.3 plants m^{-2}	0	1598.27a
	20	1913.38a
	50	1471.68a
5.6 plants m^{-2}	0	3341.03b
	20	3052.28b
	50	2817.85b
10 plants m^{-2}	0	4464.38c
	20	5399.50d
	50	4649.75c

Means followed by the same letter in a column do not differ significantly at P=0.05

From Table 4.3 however, it is clear that yield m^{-2} was significantly affected by shading at high planting densities of 10 plants m^{-2} only. At this planting density (10 plants m^{-2}) yield was increased from 4464.38 g m^{-2} to 5399.50 g m^{-2} with 20% shading in comparison with no shading. Similar tendencies, although not significant, were observed at a low planting density (3.3 plants m^{-2}). At a medium planting density (5.6 plants m^{-2}), yield m^{-2} was not affected by different shading treatments, but a downward trend from 3341.03 g to 2817.85 g m^{-2} was observed as the percentage shading increased from 0% to 50%. As can be seen in table 4.3, it is clear that an increase in planting density significantly increased the yield m^{-2} regardless of the level of shading used in this study.

Figures 4.3, 4.4 and 4.5 clearly illustrate that shading of up to 50% did not have a large affect on the cumulative yield level and the same patterns were observed for each planting density regardless of the level of shading. 20% shading only increased the yield at a planting density of 10 plants m^{-2} (Figure 4.5). This yield increase was due to a slightly higher yield level between 21 September 2007 and 12 October 2007 and did not escalate over time.

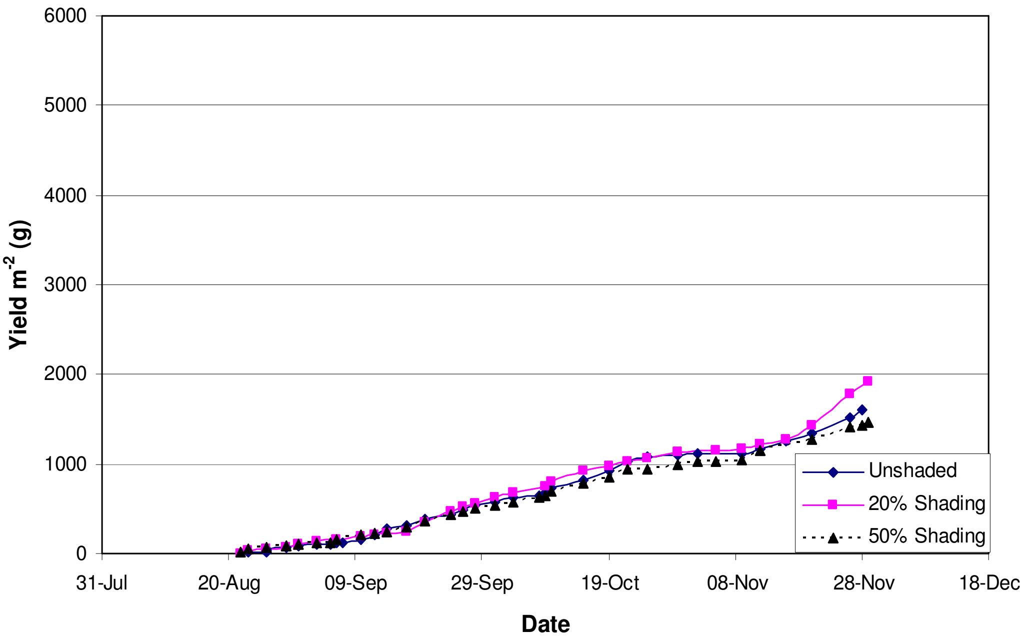

Figure 4.3 Cumulative yield m^{-2} of plants subjected to three different levels of shading at a planting density of 3.3 plants m^{-2}.

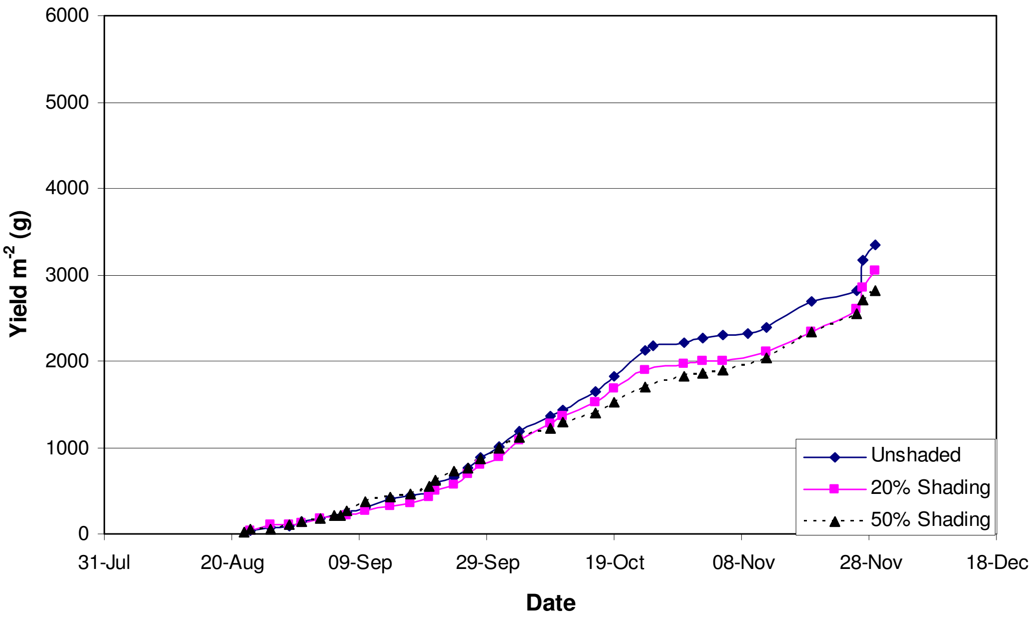

Figure 4.4 Cumulative yield m^{-2} of plants subjected to three different levels of shading at a planting density of 5.6 plants m^{-2}.

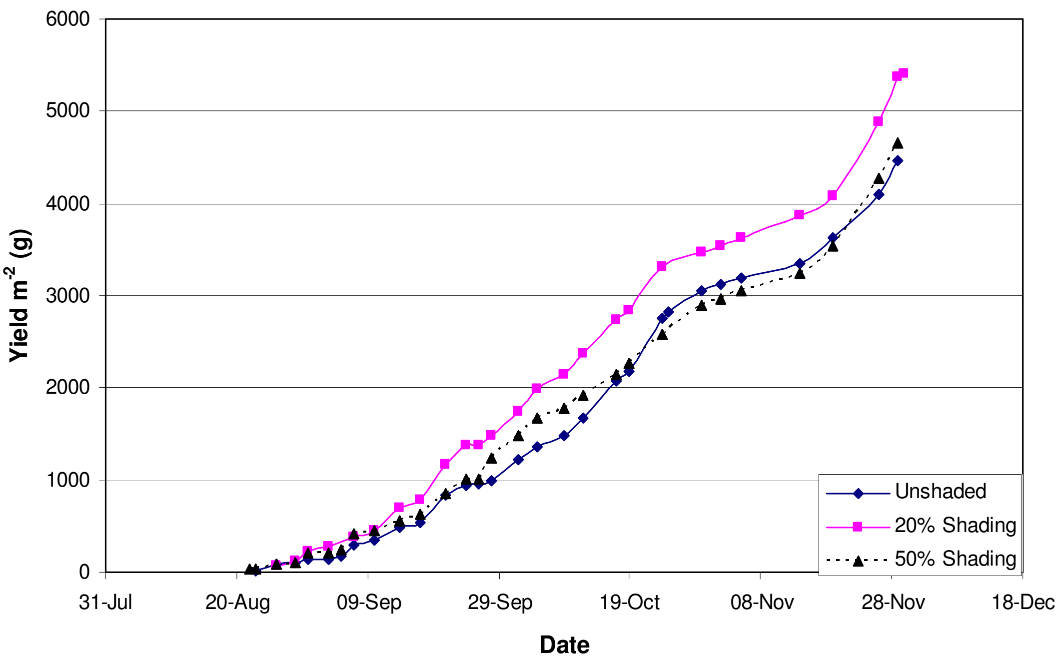

Figure 4.5 Cumulative yield m^{-2} of plants subjected to three different levels of shading at a planting density of 10 plants m^{-2}.

Due to the fact that 20% shading only increased the yield at the highest planting density (10 plants m^{-2}) and that similar cumulative yield patterns were observed regardless of the amount of shading, the cumulative yield of unshaded plots at planting densities of 3.3, 5.6 and 10 plants m^{-2} were compared in Figure 4.6. The highest total yield (Figure 4.6) during the 14 week harvest period was produced by plots subjected to a planting density of 10 plants m^{-2}. This higher yield was due to an escalating yield level throughout the 14 week harvest period. The difference in cumulative yield m^{-2} between the highest (10 plants m^{-2}) and lowest (3.3 plants m^{-2}) planting densities increased over the 14 week harvest period. After a 7 week harvest period the cumulative yield at the highest planting density (10 plants m^{-2}) was ± 0.8 kg m^{-2} higher than the cumulative yield at a planting density of 3.3 plants m^{-2}. This difference increased to ± 2.6 kg m^{-2} after 14 weeks of harvest. This result clearly illustrates that total yield can be increased by using higher planting densities in a conventional system and that the advantage of this higher planting densities also increased during the harvest period.

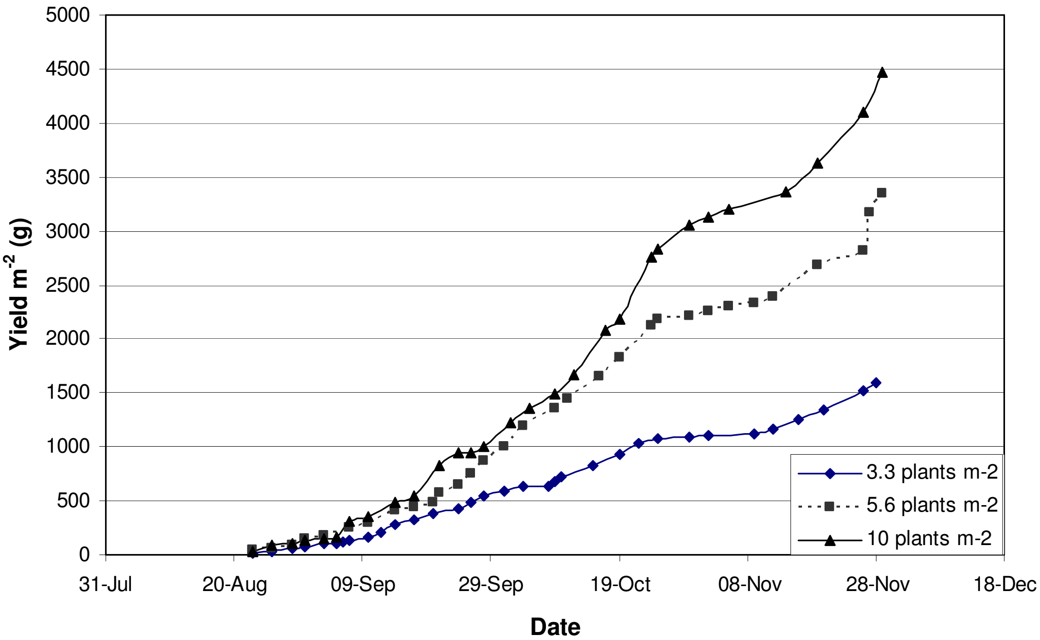

Figure 4.6 Cumulative yield m^{-2} of unshaded plants in the conventional system at three different planting densities.

Days from anthesis to harvest (Ant-H)

Table 4.4 The effect of shading and planting density on the number of days from anthesis to harvest (Ant-H), fruits plant^{-1}, fruit size, percentage yield loss due to malformation (%YLM), average soluble solids content of fruits (%SS) and total soluble solids (TSS) plant^{-1}

Factors		Ant-H (days)	Fruits plant^{-1}	Fruit size (g)	%YLM	%SS	TSS plant^{-1} (g)
	0	35.63a	34.46a	14.95a	3.90a	9.67b	49.39b
Shading(%)	20	36.83a	37.88b	14.72a	4.10a	9.62b	53.39b
	50	36.50a	33.25a	14.27a	8.45b	9.14a	43.08a
Density	3.3	35.50a	36.79b	13.64a	4.74ab	9.81b	49.38b
(plants m^{-2})	5.6	36.42a	37.88b	14.53b	3.58ab	9.61b	52.69b
	10	37.04a	30.92a	15.76c	8.10b	9.01a	43.73a

Means followed by the same letter in a block do not differ significantly at P=0.05

Shading had no significant effect (Table 4.1) on the number of days from anthesis to harvest even though unshaded fruits developed on average ± 1 day faster (Table 4.4) compared to shaded fruits. Miura *et al*. (1993) reported that fruits subjected to shading took longer to reach the full red stage compared to unshaded fruits.

Planting density also had no significant effect (Table 4.1) on the number of days from anthesis to harvest, but fruits at the lowest planting density (3.3 plants m^{-2}) developed on average ± 1 day faster (Table 4.4) compared to fruits at the medium planting density (5.6 plants m^{-2}). Fruits at the medium planting density also developed on average about half a day faster compared to fruits at the highest planting density (10 plants m^{-2}). This slightly delayed development with increasing plant densities might be due to inter plant shading. According to Hancock (1999), high temperatures increase the rate of fruit development. Fruits produced at lower planting densities were more exposed to direct sunlight, therefore the rate of fruit development probably decreased as planting density increased.

Fruits plant^{-1}

Shading had a significant effect (Table 4.1) on the number of fruits plant^{-1}. Plants subjected to 20% shading produced significantly more (Table 4.4) fruits (37.88) compared to 0% (34.46) and 50% (33.25) shade treatments, but no difference was observed between the latter two shade treatments. According to Awang & Atherton (1995), the number of fruits plant^{-1} decreased with an increase in shading. In this study 20% shading had a positive effect on the number of fruits plant^{-1}, but was not affected by 50% shading. This trend was probably observed due to a temperature effect, as was mentioned earlier. Elevated temperatures can reduce fruit set, but 20% shading most likely reduced the surface temperature of plants and fruits and therefore had a positive effect on fruit set. On the other hand, 50% shading might have decreased surface temperature, but photosynthesis was affected negatively. Therefore, no difference was observed between fruit set of unshaded plants and plants subjected to 50% shading.

Significantly more fruits were produced per plant at low (3.3 plants m^{-2}) and medium (5.6 plants m^{-2}) planting densities compared to high planting densities (10 plants m^{-2}) (Tables 4.1 and 4.4). At a high planting density only 30.92 fruits were produced per plant compared to 36.79 and 37.88 fruits plant^{-1} at low and medium planting densities respectively.

Table 4.5 The effect of a D*C interaction on the number of fruits plant^{-1}

Density (D) (plants m^{-2})	Shading (C) (%)	Fruits plant^{-1}
3.3	0	33.63bc
	20	42.00d
	50	34.75bc
5.6	0	42.00d
	20	36.75cd
	50	34.88bc
10	0	27.75a
	20	34.88bc
	50	30.13ab

Means followed by the same letter in a column do not differ significantly at P=0.05

A significant interaction (Table 4.1) between planting density and shading was observed with regard to the number of fruits plant^{-1}. At low (3.3 plants m^{-2}) and high (10 plants m^{-2}) planting densities an increase in shading from 0% to 20% significantly increased (Table 4.5) the number of fruits plant^{-1}. At a low planting density the number of fruits plant^{-1} increased from 33.63 (unshaded) to 42.00 (20% shading), whereas at a high planting density an increase from 27.75 (unshaded) to 34.88 (20% shading) fruits plant^{-1} was observed. A further increase in shading from 20% to 50% decreased the number of fruits plant^{-1} at both low and high planting densities. A different trend was observed at a medium (5.6 plants m^{-2}) planting density, because the number of fruits plant^{-1} decreased from 42.00 to 34.88 as the shading increased from 0% to 50%. This tendancy of 20% shading to increase the number of fruits plant^{-1} might be due to slightly lower plant temperatures under the net. According to Morgan (2006), high temperatures can have a negative effect on fruit set.

Fruit size

Average fruit size was not significantly affected by shading (Table 4.1). With no shading (0%), the average fruit size was 14.95 g, while plants subjected to 20% and 50% shading produced fruits with an average size of 14.72 g and 14.27 g respectively (Table 4.4). Miura *et al*. (1993) reported that strawberry plants under a black net with a 60% light transmittance were smaller compared to fruits of unshaded plants.

An increase in planting density significantly increased the average fruit size from 13.64 g to 14.53 g as the planting density increased from 3.3 to 5.6 plants m^{-2} (Table 4.1 and 4.4). Plants subjected to a planting density of 10 plants m^{-2} produced fruits with an average fruit size of 15.76 g which was significantly larger compared to fruits at lower planting densities. Dijkstra *et al*. (1993) reported that an increase in planting density can have a negative effect on fruit size. On the other hand, elevated temperatures can also have a negative effect on fruit size (Hancock, 1999). Fruits at lower planting densities were more exposed to direct sunlight. Therefore, the increased surface temperature of fruits at lower planting densities probably had a negative effect on fruit size. On the other hand, significantly less fruits were produced at the highest planting density (10 plants m^{-2}) and this might have caused a slight increase in average fruit size.

Table 4.6 Percentage of total yield in each category at three planting densities

Density	Category				
(plants m^{-2})	A(>20 g $fruit^{-1}$)	B(14-20 g $fruit^{-1}$)	C(9-14 g $fruit^{-1}$)	D(5-9 g $fruit^{-1}$)	E(<5 g $fruit^{-1}$)
3.3	22.68%	31.93%	31.40%	8.70%	0.55%
5.6	25.85%	35.20%	28.61%	6.59%	0.17%
10	30.90%	36.84%	20.20%	3.94%	0.02%

Table 4.6 clearly illustrates that the percentage of yield in category A(>20 g $fruit^{-1}$) and B(14-20 g $fruit^{-1}$) increased as the planting density increased from 3.3 to 10 plants m^{-2}. The contrary was observed for category C(9-14 g $fruit^{-1}$), D(5-9 g $fruit^{-1}$) and E(<5 g $fruit^{-1}$) production. At a planting density of 3.3 plants m^{-2} only 22.68% of the total production was produced in category A compared to 25.85% and 30.90% at planting densities of 5.6 and 10 plants m^{-2} respectively. The same trend was observed for category B production, which increased from 31.93% to 36.84% with an increase in planting density from 3.3 to 10 plants m^{-2}. Category C production decreased from 31.40% to 20.20%, whereas category D and E production decreased from 8.70% to 3.94% and from 0.55% to 0.02% respectively, as the planting density increased from 3.3 to 10 plants m^{-2}. Category B production contributed the most to the total yield, even though category C production was only 0.53% lower compared to category B production at a planting density of 3.3 plants m^{-2}. Overall, bigger fruits are preferred, but the size depends on the market and probably the time of year. Smaller fruits might be more acceptable during out of season production.

Percentage yield loss due to malformation (%YLM)

Percentage yield loss due to malformation increased (Table 4.1 and 4.4) as the percentage shading increased from 0% to 50%. No significant difference was observed between unshaded (3.90%) treatments and 20% (4.10%) shading treatments, but 50% shading significantly increased malformation to 8.45%. Low light intensity shortly before and during flowering is considered one of the main reasons for anther and pollen degeneration (Smeets, 1976; Smeets, 1980) and therefore an increase in malformation (Voyiatzis & Paraskevopoulou-Paroussi, 2002).

Planting density did not have a significant effect (Table 4.1) on malformation, even though malformation tended to increase (Table 4.4) at a planting density of 10 plants m^{-2} (8.10%). Paranjpe *et al.* (2003) also reported that malformation was not significantly increased by an increase in planting density in a single layer system.

Average soluble solids content of fruits (%SS)

Shading significantly (Table 4.1) decreased the soluble solids content of fruits. Unshaded plants produced the highest percentage soluble solids (9.67%), followed by plants subjected to 20% shading (9.62%) (Table 4.4). These two treatments did not differ significantly. Plants subjected to 50% shading produced 9.14% soluble solids, which was significantly lower compared to both the 0% and 20% shade treatments. Morgan (2006) reported that low light levels can have a negative effect on sugar production. According to Miura *et al.* (1993), shaded fruits had lower levels of fructose, glucose and sucrose compared to unshaded fruits. On the other hand, Awang & Atherton (1995) reported that soluble solids concentration was not affected by shading at EC levels of 2.6 mS cm^{-1} and only start to have an effect at higher EC levels.

Planting density had a significant affect on the average soluble solids content of fruits (Tables 4.1 and 4.4). Plants subjected to planting densities of 3.3, 5.6 and 10 plants m^{-2} produced fruits with an average of 9.81%, 9.61% and 9.01% soluble solids respectively. A clear downward trend was observed, but only at a planting density of 10 plants m^{-2} the average soluble solids content of fruits was significantly decreased. All treatments produced acceptable sugar levels.

Total soluble solids (TSS) plant^{-1}

Total soluble solids plant^{-1} was only significantly affected by 50% shading (Tables 4.1 and 4.4). This result was observed due to the fact that 50% shading decreased both the yield plant^{-1} and the percentage soluble solids fruit^{-1}. Unshaded plants produced 49.39 g soluble solids plant^{-1}, followed by 53.39 g and 43.08 g produced by plants subjected to 20% and 50% shading respectively. Plants subjected to 20% shading tended to produce more soluble solids plant^{-1} compared to unshaded plants. This result was observed due to a slightly higher yield level from plants subjected to 20% shading.

The same trend as with shading was observed with regard to planting density. Only the highest planting density (10 plants m^{-2}) significantly decreased the total soluble solids $plant^{-1}$ (Tables 4.1 and 4.4). At a planting density of 3.3 plants m^{-2}, 49.38 g soluble solids was produced per plant, followed by 52.69 g and 43.73 g at planting densities of 5.6 and 10 plants m^{-2} respectively. Total soluble solids $plant^{-1}$ tended to be higher at a planting density of 5.6 plants m^{-2} compared to 3.3 plants m^{-2}. This result was observed due to a slightly higher yield $plant^{-1}$ at a planting density of 5.6 plants m^{-2}.

Leaves plant^{-1}

Table 4.7 The effect of shading and planting density on the number of leaves $plant^{-1}$ and total leaf weight $plant^{-1}$

Factors		Leaves $plant^{-1}$	Total leaf weight $plant^{-1}$ (g)
	0	27.79a	56.65a
Shading(%)	20	34.00b	78.78b
	50	28.13a	60.43a
	3.3	30.67a	62.96a
Density (plants m^{-2})	5.6	29.33a	60.22a
	10	29.92a	72.68a

Means followed by the same letter in a block do not differ significantly at P=0.05

Number of leaves $plant^{-1}$ was significantly increased by 20% shading (Tables 4.1 and 4.7), but 50% shading had no effect. Plants subjected to 20% shading had 34 leaves on average, whereas unshaded plants and plants subjected to 50% shading only had an average of 27.79 and 28.13 leaves $plant^{-1}$ respectively. The same trend was observed with yield and number of fruits $plant^{-1}$. Planting density did not affect the number of leaves $plant^{-1}$ (Table 4.1).

Total leaf weight (LW) plant^{-1}

Total leaf weight plant^{-1} was also significantly increased by 20% shading (78.78 g plant^{-1}) (Tables 4.1 and 4.7), but no difference was observed between unshaded plants (56.65 g plant^{-1}) and plants subjected to 50% shading (60.43 g plant^{-1}). The 20% shade cover might have prevented high temperature damage in the plants. Therefore, the number of leaves plant^{-1} and the leaf fresh weight plant^{-1} were higher compared to unshaded plants. On the other hand, 50% shading probably decreased plant surface temperature, but also photosynthetic rates and therefore did not differ compared to the control (unshaded plants).

Planting density did not affect the total leaf weight plant^{-1} (Table 4.1), but leaf weight tended to be higher at a planting density of 10 plants m^{-2} compared to leaf weight at planting densities of 3.3 and 5.6 plants m^{-2} (Table 4.7). Yield plant^{-1} was slightly lower at a planting density of 10 plants m^{-2}, whereas the leaf fresh weight tended to be higher compared to the other plant densities. Inter plant shading might have increased the competition between adjacent plants and therefore slightly more energy was used for vegetative growth compared to fruit growth.

Conclusion

Although not significant, plants subjected to 20% shading tended to produce on average higher yields plant^{-1}. These plants also produced more fruits, leaves and leaf fresh weight. Maximum temperatures exceeded 25^{o}C for most of the harvest period, but 20% shading probably decreased the surface temperature of plants and therefore had a positive effect on overall growth. The yield, number of leaves plant^{-1} and total leaf weight plant^{-1} were not affected by a 50% shade treatment, but a tendency to reduce the yield was observed. Shading did not affect the rate of fruit development, even though shaded fruits took slightly longer to reach the full red stage. Fruit size was also not significantly affected by shading, but the average fruit size slightly decreased with an increase in shading. Plants subjected to 50% shading produced significantly more malformed fruits. These plants also produced fruits with lower levels of soluble solids compared to fruits subjected to 0% and 20% shading. Overall, 50% shading only had a minor negative affect on the yield and fruit quality. In this study 20% shading tended to have a positive effect on yield. Fruit quality of plants subjected to 20% shading was also good. Therefore, 20% shade net might be used to overcome the negative effect of elevated temperatures in areas where high light levels prevail.

Yield m^{-2} increased with an increase in planting density. Consequently, the total yield was significantly increased by using higher planting densities in a conventional double row system. Planting density did not affect the rate of fruit development, even though fruits took slightly longer to reach the full red stage with an increase in planting density. At the highest planting density (10 plants m^{-2}) the number of fruits $plant^{-1}$, average soluble solids content of fruits and total soluble solids production $plant^{-1}$ were lower compared to the other planting densities. On the other hand, fruit size was significantly increased by an increase in planting density, probably due to better shading of fruits from direct sunlight. Even though plants subjected to the highest planting density (10 plants m^{-2}) tended to produce more malformed fruits, the yield m^{-2} was the highest and fruit quality was also good. Therefore, in this study, higher planting densities had a positive effect on strawberry production.

References

AUSTIN, M.E., SHUTAK, V.G. AND CHRISTOPHER, E.P., 1960. Color changes in harvested strawberry fruits. *Proceedings of the American Society for Horticultural Science* 75, 382-386.

AWANG, Y.B. & ATHERTON, J.G., 1995. Growth and fruiting responses of strawberry plants grown on rockwool to shading and salinity. *Scientia Horticulturae* 62, 25-31.

DIJKSTRA, J., DE BRUIJN, J., SCHOLTENS, A. & WIJSMULLER, J.M., 1993. Effect of planting distance and peat volume on strawberry production in bag and bucket culture. *Acta Horticulturae* 348, 180-187.

HANCOCK, J.F., 1999. Strawberries. Crop production science in horticulture. CABI Publishing, Oxon, UK.

MIURA, H., YOSHIDA, M. & YAMASAKI, A., 1993. Effect of light intensity on growth and ripening of strawberry fruit. *Acta Horticulturae* 348, 393-394.

MORGAN, L., 2006. Hydroponic strawberry production. A technical guide to the hydroponic production of strawberries. Suntec (NZ) Ltd, Tokomaru, New Zealand.

PARANJPE, A., CANTLIFFE, D.J., LAMB, E.M., STOFELLA, P.J. & POWELL, C., 2003. Increasing winter strawberry production in North-Central Florida using passive ventilated greenhouses and high plant densities. *Acta Horticulturae* 626, 269-276.

SMEETS, L., 1976. Effect of light intensity during flowering on stamen development in the strawberry cultivar ‘Glasa’. *Scientia Horticulturae* 4, 255-260.

SMEETS, L., 1980. Effect of light intensity during flowering on stamen development in the strawberry cultivars ‘Karina’ and ‘Sivetta’. *Scientia Horticulturae* 12, 343-346.

STATISTICA, 2007. Data analysis software system, Version 8.0, Statsoft Inc., www.statsoft.com.

STEINER, A.A., 1984. The universal nutrient solution. *Proceedings of the International Society for Soilless Culture*. Pp. 633-649.

VOYIATZIS, D.G. & PARASKEVOPOULOU-PAROUSSI, G., 2002. The effect of photoperiod and gibberillic acid on strawberry pollen germination and stamen growth. *Acta Horticulturae* 567, 257-260.

CHAPTER 5

A COMPARISON BETWEEN YIELD, GROWTH AND QUALITY FACTORS OF UNSHADED 'CHANDLER' STRAWBERRY PLANTS GROWN HYDROPONICALLY IN THREE DIFFERENT PRODUCTION SYSTEMS

Introduction

Greenhouse structures are expensive and therefore it is important to utilize greenhouse space efficiently, but it is also important to find the correct balance between planting density, production system, marketable yield and fruit quality. The main aim of using a vertical production system is to increase the yield per unit area inside a greenhouse (Linsley-Noakes *et al*., 2006). It is therefore important that a comparison is made between the conventional system and vertical production systems used in this study.

Planting densities used in the conventional production system were lower compared to the vertical production system and for this reason no statistical comparison could be made between the conventional and vertical production systems. This chapter will therefore only compare and discuss different trends with regard to yield, growth and quality factors of strawberry plants grown in a conventional double row-, a vertical- and an 'A'-shape' production system. To do this, only data of unshaded plots at the highest planting density in each production system were used. This was done to compare the efficiency or maximum potential of production systems used in this study.

Results and discussion

Table 5.1 Effect of different production systems on yield, growth and quality factors of strawberry plants and fruits

Factors	Production system		
	Conventional(10 plants m^{-2})	'A-shape'(33.3 plants m^{-2})	Vertical(33.3 plants m^{-2})
Yield $plant^{-1}$ (g)	446.44	241.74	233.00
Yield m^{-2} (g)	4464.38	8058.00	7766.67
Ant-H (days)	34.88	42.80	43.20
Fruits $plant^{-1}$	27.75	17.20	18.00
Fruit size (g)	16.09	14.05	12.94
%YLM	5.65	13.06	13.01
% SS	9.26	8.73	8.42
TSS $plant^{-1}$ (g)	41.34	21.10	19.62
Leaves $plant^{-1}$	30.50	19.10	19.60
LW $plant^{-1}$ (g)	67.18	26.76	26.74

Ant-H = number of days from anthesis to harvest
%YLM = percentage yield loss due to malformation
%SS = average soluble solids content of fruits
TSS $plant^{-1}$ = total soluble solids $plant^{-1}$
LW $plant^{-1}$ = total leaf fresh weight $plant^{-1}$

Yield

Yield $plant^{-1}$ was ± 1.9 times higher (Table 5.1) in the conventional system (446.44 g $plant^{-1}$) compared to the vertical- and 'A-shape' production systems, which produced yields of 233.00 g $plant^{-1}$ and 241.74 g $plant^{-1}$ respectively during a 14 week harvest period. Planting density in the vertical- and 'A-shape' systems (33.3 plants m^{-2}) were 3.3 times higher compared to the planting density used in the conventional system (10 plants m^{-2}). In the conventional system yields of 4464.38 g m^{-2} was produced compared to 7766.67 g m^{-2} and 8058 g m^{-2} in the vertical and 'A-shape' systems respectively. Yield m^{-2} therefore tended to increase with the use of vertical production systems, regardless of the lower yield $plant^{-1}$ in the latter systems. Similar results were reported by Paraskevopoulou-Paroussi & Paroussis (1995). Yield loss due to malformation tended to be higher in the vertical production systems, with an average of about 13% compared to only 5.65% in the conventional system. Malformation can be decreased by introducing hives of bees in the greenhouse, by artificial pollination or by removing small malformed fruits as soon as possible (Morgan, 2006). Plants in all three systems produced less than 0.5% of the total yield as fruits smaller than 5 g. For this reason only malformed fruits will be regarded as unmarketable yield during this discussion. Plants in the conventional system produced 4212.14 g m^{-2} as marketable yield compared to 6756.23 g m^{-2} and 7005.63 g m^{-2} as marketable yield in the vertical and 'A-shape' systems respectively. Figure 5.1 clearly illustrates that the higher planting densities in the vertical production systems tended to increase the yield m^{-2}. This higher yield was due to an escalating yield level throughout the 14 week harvest period. The vertical production systems reached a cumulative yield of about 4.5 kg m^{-2} after 8 weeks of harvest, whereas the conventional system could only reach a similar cumulative yield after a 14 week harvest period.

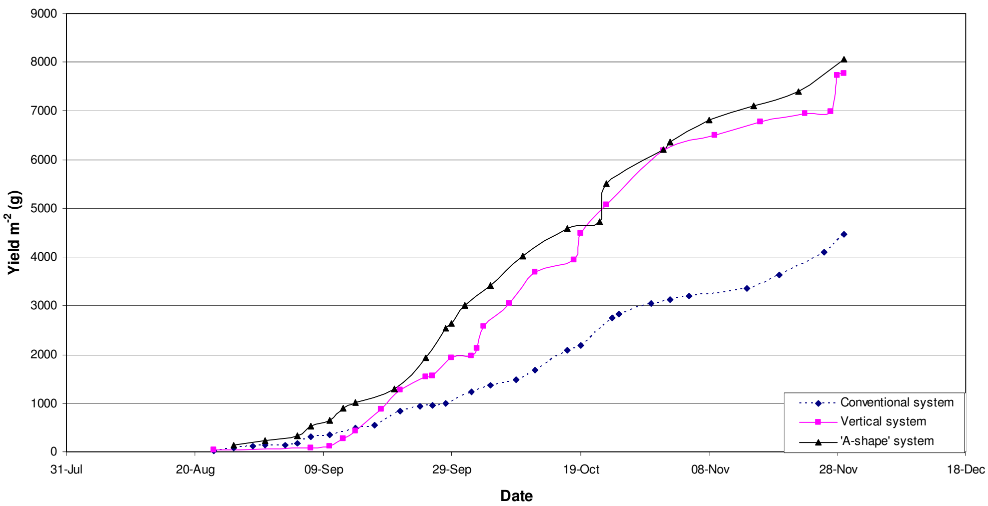

Figure 5.1 Cumulative yield m^{-2} of plants subjected to three different production systems.

Fruit quality

Fruit quality of strawberries produced in the conventional system tended to be slightly better, with an average fruit size of 16.09 g compared to 14.05 g and 12.94 g in the 'A-shape'- and vertical system respectively. Average soluble solids content (%SS) of fruits produced in the conventional system was also slightly higher (9.26%) compared to the %SS of fruits in the vertical system (8.42%) and 'A-shape' system (8.73%). Strawberries were picked at the full red stage and plants in all three production systems produced fruits with good skin colour development, even though skin colour was not measured as a quality factor. The only difference observed with regard to colour development was that fruits produced in the conventional system needed 34.88 days to develop from anthesis to harvest (full red stage), whereas fruits produced in the vertical and 'A-shape' systems needed 43.20 days and 42.80 days respectively. Therefore, fruits in the conventional system ripened about one week faster compared to fruits in the vertical and 'A-shape' systems. Malformation in the vertical and 'A-shape' systems was much higher compared to malformation in the conventional system and therefore had a negative effect on overall fruit quality. As was mentioned in Chapter 3 and 4, fruit firmness was not affected by the production system used, planting density, shading or any interactions between these factors. The mean value for fruit firmness was 24.98 kPa. According to Paraskevopoulou-Paroussi & Paroussis (1995), fruit firmness is cultivar dependent and is not affected by cultivation techniques.

Growth

Plants in the conventional system produced on average, 27.75 fruits plant^{-1}, whereas plants in the vertical and 'A-shape' systems produced 17.20 and 18.00 fruits plant^{-1} respectively. Plants in the conventional system produced ± 2 times more soluble solids (TSS) plant^{-1} (41.34 g plant^{-1}) compared to the vertical system (19.62 g plant^{-1}) and 'A-shape' system (21.10 g plant^{-1}). Number of leaves plant^{-1} was higher in the conventional system (30.50 leaves plant^{-1}) compared to the vertical system (19.60 leaves plant^{-1}) and 'A-shape' system (19.10 leaves plant^{-1}). The same trend was observed with regard to total leaf fresh weight plant^{-1} (LW plant^{-1}). Plants in the conventional system produced 67.18 g LW plant^{-1}, whereas plants in the vertical and 'A-shape' systems produced only 26.74 g and 26.76 g LW plant^{-1} respectively.

Conclusion

Higher yields m^{-2} were obtained in the 'A-shape' and vertical production systems. Fruit quality was slightly better in the conventional system, but fruits in the 'A-shape' and vertical production systems had acceptable fruit size and sugar levels. Yield loss due to malformation was much lower in the conventional system. Therefore, the marketable yields of the 'A-shape' and vertical systems can be further increased by decreasing malformation. Plants in the conventional system produced more fruits and leaves plant^{-1}. Leaf fresh weight plant^{-1} was also much higher in the conventional system compared to the 'A-shape' and vertical systems.

Before setting up a vertical production system, it will be important to calculate the fixed cost (initial investment) of a greenhouse with a conventional production system, as well as a greenhouse with a vertical production system. Costs and productivity potential of different vertical production systems must also be taken into account to select the most suitable vertical production system.

References

LINSLEY-NOAKES, G., WILKEN, L. & DE VILLIERS, S., 2006. High density, vertical hydroponics growing system for strawberries. *Acta Horticulturae* 708, 365-370.

MORGAN, L., 2006. Hydroponic strawberry production. A technical guide to the hydroponic production of strawberries. Suntec (NZ) Ltd, Tokomaru, New Zealand.

PARASKEVOPOULOU-PAROUSSI, G. & PAROUSSIS, E., 1995. Precocity, plant productivity and fruit quality of strawberry plants grown in soil and soilless culture. *Acta Horticulturae* 408, 109-117.

CHAPTER 6
GENERAL CONCLUSIONS

Conventional production systems limit strawberry production to a single layer and therefore planting density can only be increased to a certain extent. Greenhouse structures are expensive to set up. Therefore, it is important to utilize the volume of a greenhouse. Vertical production systems increase the utilization of greenhouse space due to fact that much higher planting densities are possible, but these higher planting densities can have a negative effect on production and fruit quality due to lower light levels compared to conventional systems. Therefore, planting density and light intensity are important factors in strawberry production.

Two experiments were conducted in a plastic cladded greenhouse with a wet-wall and fan cooling system, at the Department of Agronomy, University of Stellenbosch, South Africa during the period of April 2007 to November 2007 (late autumn to early summer). Mean daily maximum temperatures exceeded 26 ^{o}C during most of the 14 week harvest period (22 August to 30 November 2007), while photosynthetic active radiation (PAR) measured at 12:00 on selected cloudless days inside the greenhouse increased from about 200 µMol m^{-2} s^{-1} to about 460 µMol m^{-2} s^{-1} during this period. The objective of the first experiment was to determine the effect of two different vertical production systems (vertical system and 'A-shape' system), subjected to three planting densities (16.7, 23.3 and 33.3 plants m^{-2}), as well as three levels of shading (0%, 20% and 50%) on selected yield, quality and growth factors. The objective of the second experiment was to determine the effect of three planting densities (3.3, 5.6 and 10 plants m^{-2}) and three levels of shading (0%, 20% and 50%) on the same factors (yield, quality and growth) in a conventional production system. The second experiment also served as a basis for comparison with the two vertical production systems with regard to yield, quality and growth. To do this comparison, data of unshaded plots at the highest planting density in each production system were used.

All plants were initially irrigated with a standard Steiner nutrient solution (Steiner, 1984) at an EC of 1 mS cm^{-1}, but was increased to 2 mS cm^{-1} one week after planting. Temperatures inside the greenhouse were measured daily. Photosynthetic active radiation (PAR) was measured inside and outside the greenhouse, as well as inside the vertical production systems on randomly selected days. Strawberries were harvested when the fruits reached a full red colour and the weight, ^{o}Brix and firmness (kPa) were taken for each harvested fruit. Number of leaves plant^{-1} and leaf fresh weight (LW) plant^{-1} were recorded on the last day of harvest.

In the first experiment photosynthetic active radiation (PAR) measured in the ‘A-shape’ system was higher compared to measurements in the vertical system regardless of planting density. Plants in the ‘A-shape’ system tended to produce higher yields than plants in the vertical system. Quality (fruit size and soluble solids content) of fruits in the ‘A-shape’ system was better compared to the vertical system. Plants in the ‘A-shape’ system also produced more leaf fresh weight compared to plants in the vertical system. An increase in planting density decreased the yield plant^{-1}, however the yield m^{-2} was significantly increased. Planting density did not affect the average fruit size or soluble solids content of fruits, but LW plant^{-1} decreased with an increase in planting density. An increase in shading decreased the yield significantly. Shading did not affect fruit size and soluble solids content, even though shading tended to have a negative effect on fruit size. Yield loss due to malformation of fruits (%YLM) was only increased by increasing the level of shading. Total leaf fresh weight plant^{-1} was not affected by shading.

In the second experiment yield plant^{-1} was not affected by planting density, but tended to decrease at the highest planting density (10 plants m^{-2}). Yield m^{-2}, as well as fruit size increased with an increase in planting density. Average soluble solids content of fruits was significantly reduced by a planting density of 10 plants m^{-2}. A shading level of 20% tended to increase the yield. Fruit quality (fruit size and soluble solids content of fruits) was decreased by 50% shading, whereas %YLM was increased. The total leaf fresh weight plant^{-1} was increased by 20% shading. In this experiment it was also clear that higher planting densities had a positive effect on yield m^{-2}. Under elevated temperature conditions, higher planting densities might increase fruit size due to better shading of fruits. In a conventional system, 20% shade cover for plants under elevated temperature conditions might be able to increase yield and vegetative growth, without reducing fruit quality or increasing yield loss.

A comparison between the three production systems (conventional-, vertical- and 'A-shape' system), at the highest planting density of each system, have shown that the yield plant^{-1} was higher in the conventional system compared to the vertical and 'A-shape' systems, but yield m^{-2} was much lower. Fruit quality was slightly better in the conventional system. Total leaf fresh weight plant^{-1} was also higher in the conventional system. Yield loss due to malformation of fruits was much higher in the vertical and 'A-shape' systems. Overall, the yield and quality of strawberries produced in the vertical and 'A-shape' systems were good.

From this study it is clear that the 'A-shape' system is the most promising of the three production systems evaluated. Yield, quality and growth factors of strawberry plants grown in vertical production systems were influenced by different planting density and shading treatments. Light levels play an important role in strawberry production. Therefore, vertical production systems should only be used in regions with good light levels, as well as an adequate amount of cloudless days. As was seen with both vertical production systems, an increase in the number of gutters per row (plants m^{-2}) decreased the yield plant^{-1}. The main reason for this yield reduction might be due to a lower degree of light penetration through the system due to closer gutter spacing. Therefore, more studies can be done by using the same number of gutters as with the lowest planting density (16.7 plants m^{-2}) in the vertical production systems, but with more plants per gutter. Therefore, light penetration through the system can be increased without a reduction in planting density. More studies can also be done to decrease fruit malformation in the vertical production systems, this might be done by introducing hives of bees in the greenhouse, artificial methods (air blast pollinators) or by removing malformed fruits as soon as they are evident.

References

STEINER, A.A., 1984. The universal nutrient solution. *Proceedings of the International Society for Soilless Culture.* Pp. 633-649.

CHAPTER 7

APPENDIX A

Plate 7.1 Vertical system before planting (top) and 5 weeks after planting (bottom).

Plate 7.2 ‘A-shape’ system before planting (top) and 5 weeks after planting (bottom).

Plate 7.3 Plants grown in the conventional production system.

Plate 7.4 Full red colour at which fruits were harvested.

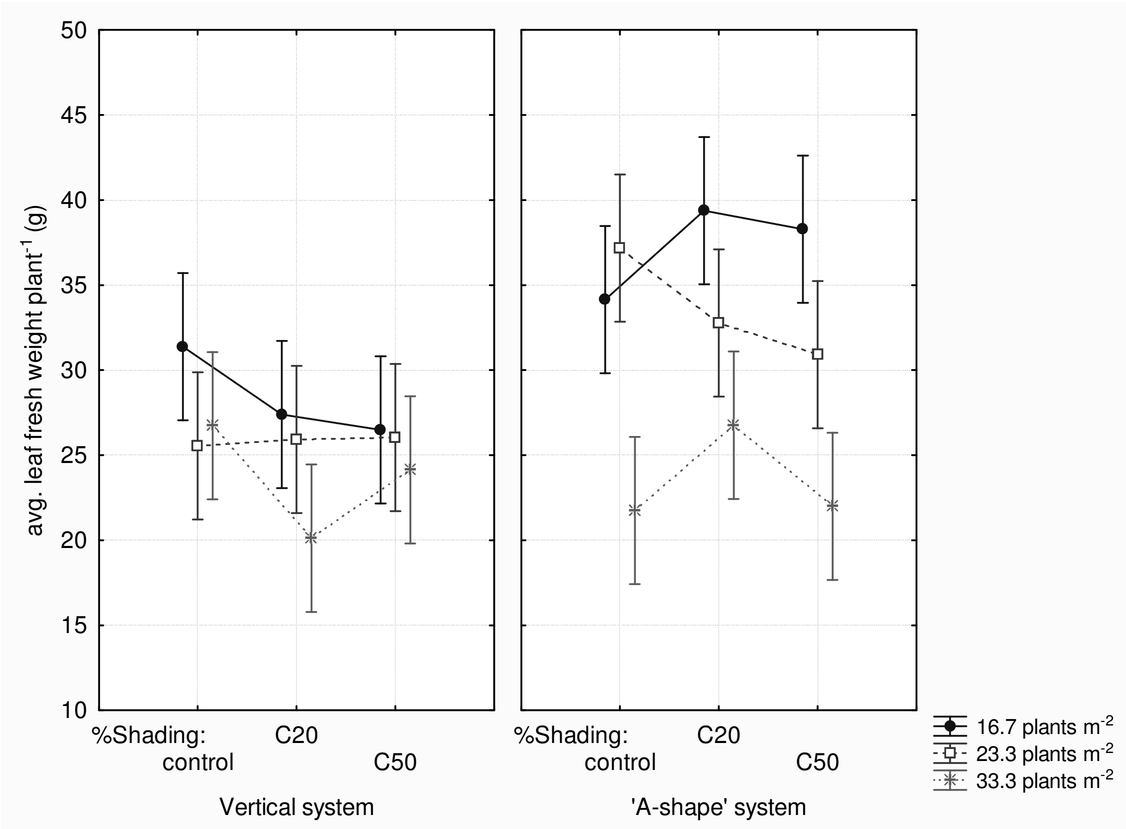

Figure 7.1 Average leaf fresh weight plant^{-1} as influenced by an interaction between production system, planting density and shading.