Fertigation of Bell Pepper (*Capsicum annuum* L.) in a Soil-less Greenhouse System: Effects of Fertiliser Formulation and Irrigation Frequency

By

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Declaration

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This is to certify that:

(i) the thesis comprises only of my original work towards the PhD except where indicated;
(ii) due acknowledgement has been made in the text to all other materials used; and
(iii) the thesis is about 71,000 words in length (all inclusive).

Mohamad Zamri Sabli
March 2012

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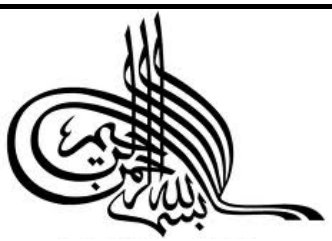
In the name of God, Most Gracious, Most Merciful

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Abstract

Increasing costs and more limited availability of water and fertiliser, coupled with mounting concern over nutrient leaching damaging the environment has led to greater interest in improved methods of managing these inputs. Greenhouse horticulture could, until recently, be characterised by large fertiliser inputs and low fertiliser use efficiency. Adoption of fertigation (application of fertilisers through irrigation water) within greenhouse production systems brings the potential for close control of both water and fertiliser applications. It is claimed that timing, amounts and ratios of fertilisers applied are easily controlled leading to optimisation of yield and product quality. However efficient operation of fertigation systems is hampered by lack of data on optimum consumption rates of essential nutrients by important crops as functions of time. The biological, chemical and physical database on fertigation is still very limited and simple extrapolation of the data to different climatic and substrate conditions may lead to operational errors.

The aim of this research study was to evaluate the effects of varying fertiliser concentration and irrigation frequency on growth and yield of greenhouse bell pepper (*Capsicum annuum* L.) grown in rockwool using a fertigation system. A study on responses to varying nitrogen and potassium concentrations at different growth stages showed that increasing N from 126mg l^{-1} to 265mg l^{-1} and 385mg l^{-1} and increasing K from 106 mg l^{-1} to 214mg l^{-1} and 321mg l^{-1} increased fruit yield significantly over the control. Higher yield was associated with higher leaf area and total dry matter production, better quality fruits and better nutrient uptake. Indications were that recommended doses of nutrients in soil-less culture should change according to the growth stage of the crop with the fertigation program being adjusted during the growing season to suit plant development.

In another experiment, effects of varying nitrogen and potassium rates and ratios on growth, yield, and the incidence of blossom - end rot (BER), leaf chlorophyll content,

photosynthetic aspects and NPK uptake was investigated. Phosphorus concentration (55mg l^{-1}) was kept constant whilst N:K ratio varied. Increasing the NPK concentration from low concentration (44-55-71 mg l^{-1}) to high concentration (126-55-106 mg l^{-1}) significantly increased growth and yield with no further increases up to 500-55-625 mg l^{-1}. Plants subjected to high NPK concentration in the second and third stage had more fruits with BER. The implications are that nutrient management must avoid too low and too high fertiliser concentrations and carefully manage electrical conductivity (EC) of nutrient solution in order to achieve high yield and quality whilst reducing nutrient leaching to the environment.

The ability of fertigation systems to increase irrigation frequency affords a major advantage to crop production. As no research had examined effects of irrigation frequency at different growth stages an experiment was made to quantify the potential benefits of more frequent irrigation. With 20 irrigation events day^{-1} throughout the season, yield increased significantly by 22% over the control (5 irrigation events day^{-1} throughout the season). Higher yield was associated with taller and thicker plants, higher leaf area, greater total dry matter production, bigger fruits and better NPK uptake. The difference in growth and yield over the control could be attributed to differences in leaf phosphorus concentration, indicating the main effect of fertigation frequency was related to improved phosphorus mobilisation and uptake. Increasing the daily fertigation frequency from five to twenty irrigation events day^{-1} significantly reduced BER incidence.

A final experiment examined effects of defoliation (removal of older, lower leaves) which may influence nutrient use efficiency and dry matter production and partitioning. There were four treatments: two irrigation schedules (5 and 10 irrigation events per day) and two defoliation strategies (0% defoliation and 20% of lower leaves removed). Defoliated plants reduced yield compared to non-defoliated plants irrespective of fertigation frequency because of less leaf area, lower total dry matter production and lower NPK uptake. Clearly, defoliation caused by leaf eating insects, disease or deliberate removal by the grower should be avoided or yield is likely to suffer.

Structure of the Thesis

The thesis is presented as follows:

- Chapter one (1) is the general introduction of the thesis.
- Chapter two (2) consists of the literature review and an overview of previous work done by earlier researchers in the area of fertigation.
- Chapter three (3) describes the general materials and method employed in the study.
- Chapters four (4) to six (6) represent the different set of experiments designed to achieve the set of objective(s).
- Chapter seven (7) is the conclusion and recommendation for further studies. This chapter is followed by appendices and detailed references of cited literature.

Abbreviations

EC	Electrical conductivity
TDM	Total dry matter
cm	Centimetre(s)
mm	Millimetre(s)
SPAD	Soil-Plant Analyses Development (SPAD) unit of Minolta Camera
%	Percent
DAT	Days after transplanting
mg l^{-1}	Milligram per litre
µg l^{-1}	Microgram per litre
ppm	Parts per million
^{o}C	Degree Celsius
g	Gram(s)
kg	Kilogram(s)
mg	Milligram(s)
L	Litre(s)
ml	Millilitre(s)
v/v	volume/volume
hr	Hour(s)
min	Minute(s)
s	Second(s)
no.	Number(s)
N	Nitrogen
P	Phosphorus
P_2O_5	Phosphorus pentoxide
K	Potassium
K_2O	Potassium oxide
WUE	Water use efficiency
FUE	Fertiliser use efficiency

SLA	Specific leaf area (leaf area (cm^2)/ leaf dry biomass (g) is the ratio of leaf area to leaf plant dry biomass and thus a measure of leaf thickness
LWR	Leaf weight ratio (g/g) is the ratio of leaf dry biomass to total plant dry biomass and thus a measure of the proportion of the plant dry biomass residing in the leaf material.
HI	Harvest index (HI) was calculated by dividing the oven dried mass of mature fruit by above-ground dry weight. It is expressed in percentage.
IRGA	Infrared gas analyser
TSS	Total soluble solids

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Chapter 1
General Introduction

1.1 Introduction

This chapter provides the background information and sets the framework for the experiments as reported in Chapter 4-6. Also included are the objectives, research questions and finally, an overall overview of the thesis. It puts the research into general context by introducing the challenges of global food production to meet the world's population demands and also those of optimising the efficiency of intensive protected horticultural cropping systems. Attention is also given to Brunei's horticulture production where food security and self-sufficiency challenges have prompted needs to advance its systems and become more intensive whilst sustainable.

Agriculture and horticulture are terms used throughout the thesis. In the context of this thesis, horticulture refers to high value 'vegetable' crops grown intensively, either in the field or in a protected environment where several crops are grown in a single season or a crop is grown for an extended period of time over the season. On the other hand, agricultural crops are generally grown on a bigger scale in the field, have a lower financial output/ha and their performance is generally less controllable by management than horticultural crops.

In intensive horticulture different terminology is applied to techniques or processes that are essentially the same and vice versa. Hydroponics can be defined the process of growing plants without soil, in beds of sand, gravel, or similar supporting material flooded with nutrient solutions (Hornby, 2010). Devries (2003) defines hydroponic plant culture as "one in which all nutrients are supplied to the plant through the irrigation water, with the growing substrate being soil-less". Soil-less culture is a generic name for all the methods of growing crops either in any medium, except soil, or without medium. Thus, hydroponics is but one type of soil-less culture. However Jones (2005) defined hydroponics as a method of growing crops in a liquid medium. It refers to a technique in which plants roots are suspended in either a static, continuously

aerated nutrient solution or a continuous flow or mist of nutrient solution. The growing of plants in substrate (e.g. sand, gravel, perlite, rockwool, coir) and periodically watered with a nutrient solution should be referred to as soil-less culture but not necessarily hydroponic (Jones, 2005).

The introduction of soil-less culture on commercial scale was motivated by a potential increased crop productivity and efficiency (Raviv and Lieth, 2008). Technical innovations in fertilisation and irrigation resulted in adoption of fertigation technologies wherein completely soluble fertilisers are dissolved in irrigation water so as to deliver to plants the nutrients they need for optimal growth (Van Os et al., 2008). Drip irrigation is currently the most common irrigation approach in soil-less culture in greenhouses (Van Os et al., 2008). Irrigation water serves two main functions: it provides a vital resource for growth and also as a transport system for nutrients. Irrigation practices where both of these functions are actively combined in one system through the use of completely soluble fertilisers are called fertigation (Van Os et al., 2008).

Therefore, growing of crops using soil-less substrate with drip irrigation may be referred to as soil-less culture (Raviv and Lieth, 2008), or hydroponics with substrate (Devries, 2003) or soil-less fertigation (Bar-Yosef, 2008). For the purpose of this study the term soil-less fertigation is used by the author.

1.2 Rationale, Motivation and Problem Identification

The huge increase in global food production in recent decades has been attributed to two basic agriculture procurements: irrigation and fertilisation (Silber, 2005). While the former is less costly than the latter at present, the time is not far off when water availability is going to become scarce and costlier because of increased industrialisation and intensive horticulture resulting from the increasing food and fibre needs of the increasing population of the world. In fact only 2.5% of the world's water is fresh, capable of serving the various needs of man, including horticulture (Papadopoulos, 1993). Currently only around 17% of the world cultivated area is irrigated yet this land accounts for more than 40% of the world food production (Papadopoulos, 1993). By superimposing the FAO's (2008) hunger map on the aridity index map (Figure 1.1), it is clear that in many regions of the world, a large population suffers hunger mainly due to

water scarcity.

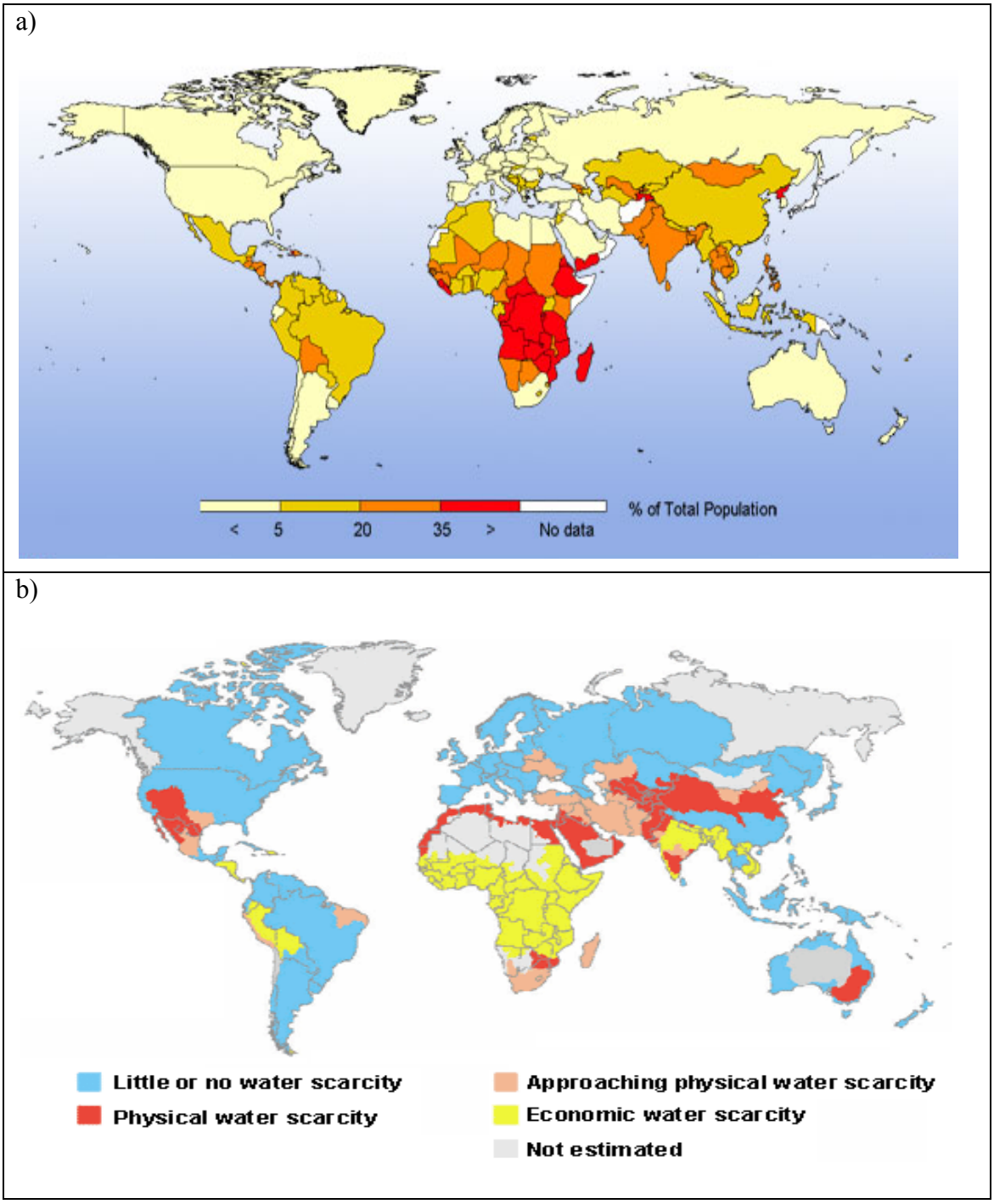


Figure 1.1 (a)Percentage of undernourished population around the globe; (b) Aridity index around the globe (FAO, 2008)

One of the main challenges for global horticulture is to produce adequate quantities of affordable food. Soil-less fertigation production systems may be part of the solution to the problems created by the lack of water and fertile soils. The fact that a relatively

small cultivated area can provide for a large population can stimulate this development. It is, therefore, imperative that the available water and fertiliser are utilised with care and more efficiently for crop production. The bulk of efforts of research have been directed towards quantifying savings of water and increasing crop yield. However, savings in fertiliser consumption using drip irrigation are few and far between (Chawla and Narda, 2001).

In modern greenhouse horticulture, the nutrients (fertilisers) are commonly supplied with the irrigation water to the plants, which is termed as fertigation (Bar-Yosef, 1999). Hence, the excess nutrient solution that drains out of the root zone after each irrigation cycle, termed as drainage solution or leachate, contains considerable amount of nutrients such as nitrates and phosphates and is, therefore, considered an environmental pollution (Raviv and Lieth, 2008). Fertigation allows the application of nutrients exactly and uniformly on the wetted root zone, where active roots are concentrated (Bar-Yosef, 1999) and has the flexibility in timing fertiliser application in relation to crop demand based on development and growth stage of crops (Papadopoulos, 1984). These remarkably increases fertiliser and water use efficiency which not only reduces the production costs but also lessen the potential of environmental pollution as a result of fertiliser leaching.

Previous studies have shown that water-use as well as fertiliser-use efficiency of soil-less fertigation plant production is higher than that of soil-grown plants (Raviv and Lieth, 2008), more food can be produced with such systems with less water and fertiliser. The science of plant production in soil-less fertigation system is still young, and although much work has been done, many questions still remained unanswered.

The challenge of producing enough food with less fertiliser and water whilst having minimal impact on environmental pollution is a global challenge. It is particularly important to the author's home country, Brunei, which imports most of its food requirement as local production is not able to meet local demand.

Agriculture was once an important economic activity in Brunei, but now constitutes a tiny and dwindling fraction of the Gross Domestic Product (Britannica, 2008). Today Brunei Darussalam depends mainly on the production of oil and liquefied natural gas

for its economy. The natural resources are however non-replaceable. The Government of Brunei is taking positive steps to improve agriculture and reduce the country's dependence on oil and gas based industry. This was reflected in his Majesty's the Sultan of Brunei speech (Ishak and Yunus, 2008):

> The attitude of completely relying on dollars to fill stomachs is no longer relevant with the emergence of this crisis (food shortage and increase in food commodities worldwide) ... it is proper for us to have a strategic plan and a national agricultural policy, which amongst other things, make the guarantee of national food security one of its priorities (p.1).

His Majesty has also pointed out agriculture as an effective method to tackle or overcome poverty in the country (Kon, 2008). As a result, the agricultural sector was given priority in the 9th National Development Plan (NDP), which ran from 2007 to 2010 whereby about £50 million were injected to spur agricultural development (Brunei Department of Agriculture). It planned programmes that diversify Brunei's economy through the agricultural-based sector. In line with the development in agricultural sectors, an official agricultural policy was introduced in 1995. The aim of this policy was to provide services in agricultural sectors in order to make Brunei self-sufficient. One of the goals was to encourage farming as a profession through education and technology (Department of Agriculture, 2007).

National agricultural research programmes provide the base for expert services to review, plan, organise and implement activities to generate suitable and adapted technology for rapid agricultural development. Since education, science and technology are vital elements for agricultural growth and development, Brunei Darussalam needs educated and professional farmers and trained local manpower to work with maximal efficiency in agricultural areas. At present Brunei Darussalam lacks this expertise and, as a result, high levels of horticultural development in the country are not being achieved.

The author believes that Brunei's horticultural sectors have a lot to offer to improve and diversify the country's economic output and employment. However this must be done through thorough planning. To start with, it must begin with the introduction of latest

technology such as soil-less fertigation system, an issue which is not being addressed properly at the moment. At present, agricultural activities are miniscule and if Brunei is to address the issues related to food security and self-sufficiency, it needs to begin by looking at its horticultural undertakings especially in regard with the latest technology.

These reasons are the main motivation for the author to initiate the study. The outcome of the study should be able to contribute to an increased understanding of fertiliser use of bell pepper in hydroponics medium grown in greenhouse condition. Clearly this has universal application, but the implication of the current study towards horticultural production in Brunei will be discussed towards the end of the thesis.

1.3 Soil-less culture and justification for using rockwool in the study

Soil-less production system may increase productivity and help to meet consumer demands for high-value food. The major shift away to substrate cultivation was the proliferation of soil-borne pathogens and lack of suitable soils (Raviv and Lieth, 2008). Soil was replaced with alternatives since they are virtually free of pests and diseases because of their manufacturing processes. A number of media (called artificial media or mixtures) have been used as substrates for soil-less culture, of which the most popular are: rockwool, peat, perlite, vermiculite, coir, sawdust, bark chips, sand, gravel, pumice, polyurethane mats, water and mixtures of the above (Jones, 2005).

For these reasons, the trend of growing plants in media, instead of soil has become widespread throughout the world (Raviv et al., 2002). Most media-grown plants are grown in greenhouses under supposedly near-optimal production conditions. However, an inherent drawback of soil-less culture is that the root volume is restricted which has several important effects, especially limited supply of nutrients (Bar-Tal, 1999). It also increases root-to-root competition since there are more roots per unit volume of medium (Raviv et al., 2002).

Rockwool is a chemically inert substrate, obtained from diabase, a volcanic rock, and has a porosity of about 96% (Jones, 2005). The use of rockwool as a growing media was invented in Denmark in 1960s (De Rijck and Schrevens, 1998). Rockwool is chemically inert, making it possible to correctly supply nutrients and control of the root environment (Jones, 2005). Rockwool is by far the most important inert medium in

horticulture because of the extent to which it is used commercially around the world and because of the wealth of information available from experienced growers and plant scientists (Raviv and Lieth, 2008).

It is probably the most widely used hydroponics growing medium in use in the world today for the production of tomato, bell pepper and cucumber accounting for more than 95 per cent of all greenhouse vegetable production (Jones, 2005). It is favoured because of its ability to simultaneously hold a large quantity of water (good water holding capacity) and air (good aeration) (Raviv and Lieth, 2008). Its composition and texture is also well-suited to aiding in plant stability (Sonneveld, 2002). It also provides other feasible conditions to support better crop growth, leading to consistency in plant production and yield, which is an important consideration for commercial growers (Jones, 2005).

Whilst some substrates such as sawdust or coir are less expensive than rockwool, rockwool slabs can be pasteurised and reused for up to three years (Portree, 1996). However, the disposal of used rockwool is a major problem because it is less biodegradable than organic materials (Spillane, 2002). Rockwool however can be recycled in the form of slag; a single cubic metre of slag can be turned into over 35 cubic metres of rockwool (Jones, 2005).

1.4 Objectives

The experiments presented in this thesis aim to contribute and enhance the understanding of improved use fertiliser of bell pepper in soil-less production systems and provide information on the fertiliser concentration (N and K rates) and irrigation frequency to meet the plant's requirement at different growth stages. The specific objectives of the study can be summarised as below:

i. To quantify the response of bell pepper production to different nitrogen (N) and potassium (K) levels;
ii. To evaluate the effect of fertigation frequency on bell pepper growth and yield;
iii. To assess the effect of leaf removal (defoliation) on bell pepper growth and yield:
iv. To develop an understanding of the effect of fertiliser concentration, fertigation frequency, and defoliation on the production response of bell pepper production.

In other words, to critically evaluate the process that might account for an increase/decrease in bell production with varying fertiliser concentration and fertigation frequency as well as leaf removal (defoliation); and

v. Investigate any likely effects of fertiliser concentration, fertigation frequency and defoliation on the incidence of blossom-end rot (BER) in bell pepper.

1.5 Research questions

The research questions for the study were:

1. Are there differences in the production of bell pepper (*Capsicum annuum* L.) under different nitrogen (N) and potassium (K) concentration (126-106; 256-214; and 385-321mg l^{-1}) fertigated into drip irrigation water according to different growth stages?
2. What are the effects of too high and too low nitrogen (N) and potassium (K) concentration (42-71; 126-106; and 500-625mg l^{-1}) fertigated into drip irrigation water according to different growth stages on the growth, yield and incidence of BER in greenhouse bell pepper (*Capsicum annuum* L.)?
3. What are the effects of different fertigation frequency (5, 10 and 20 irrigation events day^{-1}) on growth, yield and incidence of BER in bell pepper (*Capsicum annuum* L.) with fertigation regimes in a greenhouse?
4. What are the effects of defoliation (0% and 20% defoliation) under different fertigation frequency (5 and 10 irrigation events day^{-1}) on bell pepper (*Capsicum annuum* L.)?
5. Are there differences in production of bell pepper (*Capsicum annuum* L.) with different season growing conditions (summer-autumn and spring-summer)?
6. Are there differences in the effects of different varieties (California Wonder and Ferrari) on the production of bell pepper (*Capsicum annuum* L.) with fertigation regimes in greenhouse conditions?

1.6 Overview of the Thesis

The thesis consolidates the research on two broad fronts: (i) bell pepper performance with different concentration of nitrogen and potassium; and (ii) bell pepper performance with different fertigation frequency, focusing towards the above mentioned aims and objectives. The various studies that address these themes are presented in subsequent chapters (Chapter 4, 5 and 6 respectively).

The following chapter (Chapter 2) presents a comprehensive literature review pertinent to the research reported in this thesis. The detailed information related to nutrients requirements in crops plants; and fertigation frequency is presented. The growth responses of bell pepper to nitrogen (N) and potassium (K) and fertigation frequencies arising from applications made according to plant growth stage, and the consequences for fertiliser use on plant production are discussed and reviewed in this chapter. Chapter 3 deals with materials and methods employed in the research presented in the study.

Nitrogen (N) and potassium (K) are among the elements that affect the yield and quality of vegetables grown in soil-less cultivation. The effect of varying N and K rates at different plant growth stages was evaluated to overcome inefficient use of fertiliser (Chapter 4 of this thesis). Chapter 5 describes the detail of further evaluation of the effects of fertiliser concentration – effects of higher and lower fertiliser concentration (N and K rates) on bell pepper production. Fertigation frequency and fertiliser application seem to be powerful means to improve the quality of plants. A greenhouse experiment conducted to evaluate the effect of varying frequencies across plant's growth stages is presented in Chapter 6 of this thesis.

Finally, the conclusions and recommendations that were made in Chapters 4-6 are summarized in Chapter 7. This thesis study contributes to better understanding of improved use of fertiliser potentially of great benefit in bell production with fertigation in a soil-less system.

Chapter 2
Review of Literature

2.1 Introduction

For many years, the main goal of applying fertilisers was to provide nutrients to plants to increase or sustain crop yield. Thus, improving fertiliser use in terms of nutrients uptake and crop yield is crucial. However, fertilisers can harm the environment if misused. To ensure that proper use of fertiliser is beneficial to both crop production and the environment, it is important to find ways to achieve the goal of fertiliser use, i.e. improving fertiliser use and minimising environmental impacts. The purpose of this chapter is to examine literature reports which are pertinent to the experiments undertaken by the author.

This chapter is organised and presented on three major thematic areas: (i) bell pepper; (ii) management of irrigation and fertiliser; and (iii) irrigation frequency The first provides a general overview of bell pepper including, occurrence of blossom-end rot (BER), effects of leaf removal (defoliation), seasonal conditions, and electrical conductivity (EC) of nutrient solution on growth and yield. The second includes management of irrigation water and fertiliser feed, mineral nutrient requirements in crop plants; nutrient response curve; nutrient requirement and growth stages; nutrient requirement of substrate grown plants; N (nitrogen) – P (phosphorus) – K (potassium) functions in bell pepper; role of N and K in bell pepper; N and K scheduling; N-P-K nutrient uptake curves; nutrient and dry weight accumulation; and nutrient, photosynthesis and leaf chlorophyll. The third and final theme reviews the irrigation frequency on the matters pertaining to impact of fertigation frequency; irrigation frequency and water saving; effects of irrigation frequency on plant growth and yield; nutrient availability and uptake by plants affected by irrigation frequency; effects of irrigation frequency on root growth and root/shoot ratio; effects of irrigation frequency on yield and growth aspects; and effects of irrigation frequency on blossom end rot (BER) incidence

2.2 Bell Pepper

2.2.1 Bell pepper production

Bell peppers (*Capsicum annuum* L.) (family: *Solanaceae* ; sub-family of *Solanoideae*) originate from Central and South America where numerous species were used before Columbus landed on the continent (Manrique, 1993). Bell pepper is a short lived perennial plant that grows up two metres high, has pubescent leaves, has two or more greenish-white flowers per node and extremely pungent fruit (Kamaruddin et al., 2001). The plant has a densely branched stem with white flowers bear the fruit which is green when unripe, changing to red, although some varieties may ripen to yellow, purple and brown (Christopher, 1980).

According to Jovicich et al. (2004) bell pepper varieties most commonly used in greenhouse production are hybrids that have bell-shaped or blocky-type fruits, with red, orange or yellow colour when they mature. They suggested that varieties should be selected for a grower's ability to market them as well as pest and disease resistance or tolerance, low susceptibility to fruit disorders, and yield and quality performance. The red and yellow varieties produced fruit yields of 0.07 to 0.09 kg m^{-2}, the orange cultivars had yields of 0.06 to 0.08 kg m^{-2} (Jovicich et al., 2004).

Bell pepper requires a very warm sunny position and fertile well-drained soil. It prefers a light sandy soil that is slightly acidic but can tolerates a pH in the range of 4 to 8 (Grubben and Mohamed, 2004). Plants can tolerate a small amount of frost but bell pepper does not normally do well outdoors in an average British summer and so it is usually grown in a greenhouse (Protabase, 2008). Optimal temperature for growth and production are between 18^{o}C and 30^{o}C while the seeds germinate best at 25-30^{o}C (Grubben and Mohamed, 2004). Flowering is delayed if day temperatures drop below 25^{o}C and flower buds abort if night temperatures are too high i.e. above 32^{o}C (Protabase, 2008).

Seeds will germinate 6-21 days after sowing and continuous flowering starts 60-90 days after sowing (Protabase, 2008). Bell pepper flowers are self pollinated, but the use of bumblebees inside the greenhouse help to ensure the set of high quality fruits, especially during the cool season when pollen viability is lower (Calpas, 2002). In the bud stage the stigma is receptive, but the pollen is not yet mature, so hand pollination is easy.

Under normal circumstances 40-50% of the flowers set fruit. Fruit begin to mature 4-5 weeks after flowering, and can be picked every 5-7 days (Protabase, 2008).

The fruits are ready for harvest 2-3 months after transplanting, depending on the fruit maturity desired (Protabase, 2008). Bell peppers are harvested at the green mature stage or at full maturity, depending on demand and utilization (Protabase, 2008). Green fruits are sufficiently mature for harvest when firm, if gently squeezed, make a characteristic popping sound (Grubben and Mohamed, 2004).

Bell pepper growth can be divided into three general periods namely (1) vegetative growth (from planting to first flowering); (2) flowering (from flowering to fruit set); and (3) fruit development (fruit ripening to harvest) (Hoyos and Rodriguez-Delfin, 2007). The duration of each stage may vary according to growing period, variety characteristics and climatic conditions (HAIFA, 2011). The different growth stages in bell pepper would have unique nutritional needs, consequently requiring different fertilisation regimes.

2.2.2 Blossom-end rot (BER) in bell pepper

If Ca is deficient in developing fruits, an irreversible condition known as blossom-end rot (BER) will develop (Taylor et al., 2004). The general estimates of the economic loss of bell pepper due to BER is in the range of 20-40% (Silber, 2008) which is significant.

Blossom end rot (BER) is one of the main mineral disorders affecting tomato and bell pepper which reduces marketable yield (Bar-Tal and Aloni, 2005). Over the years, BER occurrence has been related to calcium deficiency in fruit and in the defective tissue; it has been reduced translocation of calcium to the fruit tip under stress condition and is therefore referred to as a "calcium-related disorder" (Ho et al., 1993, Ho and White, 2005). The majority of the studies have identified a localised Ca deficiency in the distal fruit tissue as the primary cause of BER (Ho and White, 2005).

However, in many studies no correlation was found between BER and Ca concentration in the fruit which seems to contradict some other views, and Saure (2001) concluded that calcium deficiency per se may not be the only detrimental factor, and that additional "metabolic stress factors" might be involved.

Research has also shown that Ca in solution competes with potassium (K), magnesium (Mg) and ammonium-nitrogen (NH_4-N) for uptake in the plant (Bar-Tal et al., 2001a). Although no established guidelines exist to determine what proportions of these nutrients in nutrient supply or plant tissue are appropriate, it is known that excessive shoot growth resulting from over fertilisation of N and K during early bloom and fruiting stages is a major contributor to BER in developing fruit (Bar-Tal et al., 2001a). At early bloom stage for bell pepper and tomato, leaf N and K analysis should both be within 4.0 to 6.0 % (Bar-Tal et al., 2001b). Levels higher than these may indicate excess fertilizer.

Some researchers found that irrigation with saline water enhanced the occurrence of BER (Ehret and Ho, 1986, Adams and Holder, 1992). It was also found to increase when electrical conductivity (EC) increased above 1.0dS m^{-1} (Aktas et al., 2005) and caused substantial increase in percentage of BER-affected fruits especially when the temperature increased (Bar-Tal et al., 2003). The increase in the occurrence of BER-affected fruits under irrigation with saline water and high EC has been related to reduce Ca uptake (Sonneveld and Voogt, 2009) and its transport to the fruits (Adams and Holder, 1992). However, Aktas et al (2005) found that irrigation with saline water that contained high Ca concentration had no effect on the concentration of Ca in the BER-free fruits at their initial stage.

Some researchers believe the relative humidity and transpirational rates of tomato and pepper are the real keys to understanding what factors trigger BER in fruiting vegetables. (Saure, 2001). Some studies have shown that the incidence of BER in tomato is lower under high daytime relative humidity (RH) than under low RH (Bertin et al., 2000). However, the opposite effect was found by Tadesse et al (2001) who reported that increasing the RH of the air close to the fruit enhanced the incidence of BER in bell pepper.

Fluctuations of moisture may trigger BER due to irregular transpiration rates, affecting the quantities and timing of water and Ca moving up the xylem. Conversely, during hot, dry weather when transpiration is occurring at a much faster rate, developing vegetative parts such as growing leaves and stems become greater sinks for Ca than developing fruits (Taylor et al., 2004). Lastly, as the waxy outer layer of bell pepper fruit develops,

the fruit's transpiration rate decreases because water movement through the epidermal cells and evaporation into the outside air become difficult (Taylor et al., 2004). The resulting decrease of Ca that flows into those young fruit tissues via xylem transport is believed to contribute to the onset of BER. Some research findings have quantified a decrease of BER incidence with increased irrigation rates (Silber et al., 2005).

It was clear that BER is both such a general and major concern in the production of bell pepper that investigation of the role of fertiliser concentrations (N and K rates) and irrigation frequency in the development of BER in fruits was appropriate as part of the studies undertaken.

2.2.3 Effect of leaf removal (defoliation)

Bell pepper growth and yield may be affected by defoliation. Previous reports (Aung and Kelly, 1966, Hussey, 1963) have documented the effect of removal on the production of new leaves. Aung and Kelly (1966) observed an increase in the size of relative mature leaves when tomato plants had been partially defoliated of immature leaves. They suggested that tomato plant can compensate for loss of leaves and maintain equilibrium in the plant canopy by increasing the development of remaining leaves. However, the report was unclear as to whether axillary or main leaves were removed. A study by Decoteau (1990) showed that the removal of main leaves by 36% did not stimulate additional axillary leaf development, however removal of axillary leaves by 27% stimulated an increase in the size of main leaves by 33%.

Removal of leaves from tomato plant canopy had been previously shown to affect flowering and fruiting (Decoteau, 1990). The stimulation of flowering following removal of young leaves may result from the release of an inhibitory factor originating from the young developing leaves and/or greater supply of assimilates made available as a consequence of the removal of these leaves (Decoteau, 1990). Ramirez et al (1988) and Adeniyi and Ayandiji (2011) however have shown that defoliation resulted in yield reduction. The reduction in yield was attributed to the reduced leaf area per fruit (source) which has been found to be a limiting factor for fruit growth (sink). Both studies had the implication on the effect of leaves damaged as a result of pests and diseases.

2.2.4 Effect of seasonal conditions

Growth and yield of bell pepper may also be affected by the season in which they are grown. Higher yield in the hotter long days season (spring-summer) over those grown in cooler short days season (summer-autumn) have been reported by various studies (Al-Jaloud and Ongkingco, 1999, Xu et al., 2001). The higher yield of bell pepper in the spring to summer cropping season has been attributed to better temperature conditions and solar radiation (Adams, 2002, Rouphael and Colla, 2005). The higher solar radiation due to high level of natural light and long photoperiod was presumably responsible for the increased photosynthesis in the spring-summer with respect to the summer-autumn season. The driving force behind the growth rate is the radiation and therefore, the daily uptake varies strongly with the radiation input. Thus, the daily uptake is much higher in summer time than in winter time (Sonneveld and Voogt, 2009).

The total nutrient uptake of the crop fluctuates strongly with climatic parameters (solar radiation and air temperature) (Sonneveld, 2002). This is understandable because the radiation input is the driving force behind the growth, and in consequence the uptake of the nutrients. The total nutrient uptake is strongly enhanced by stronger natural radiation or supplemental light (Ryan et al., 1992). These results are in line with those of Adams (1993) and He et al (1999) who observed that the uptake of nutrients of plants generally increases as the light intensity and air temperature rise.

Xu et al (2001) reported that the total uptake of N by bell pepper plant in the summer season was about 2.2-2.8 times higher than that in the winter season when the same concentration of N was applied in the nutrient solution. While Rouphael and Colla (2005) reported that during spring-summer season the growing medium electrical conductivity (EC) increases much more rapidly than during the summer to autumn season. The implication is that at higher temperature and solar radiation (spring-summer season), less concentrated fertiliser solutions should be used to maintain the EC of the growing medium at the desired level to prevent yield reductions.

2.3 Management of irrigation and fertiliser feed

This section provides information about management of irrigation and fertiliser, nutrient requirements in crop plants in general and application of this information in soil-less

fertigation and greenhouse conditions. Previous studies pertinent to the development of the knowledge of nutrient requirement of crop plants, in terms of bell pepper performance are reviewed and presented in this section.

In soil-less fertigation production systems the application of water is integrated with the application of fertiliser feed (Calpas, 2002). The management of fertiliser application to the plants is therefore integrated with the management of watering. The management of watering and nutrition is focused on the optimal delivery of water and nutrients over the various growth stages of the plant in order to maximise yield.

2.3.1 Irrigation Water

Plants are comprised of 80 to 90 % water and the availability of adequate quality water is very important to successful crop production (Taiz and Zeiger, 2010). The quality of water is determined by the concentration of soluble salts in solution (Salisbury and Ross, 1978).

Substantial quantities of nutrients present in the irrigation water and affects the composition of nutrient solutions (Sonneveld and Voogt, 2009). Therefore water quality should be tested before use (Jones, 2005). Composition characteristics of water suitable for use hydroponically have been suggested by Calpas (2002) as presented in Table 2.1 which also details the pH and electrical conductivity (EC). pH has a major effect on the solubility and plant availability of nutrients (Styer and Koranski, 1997). The optimum pH of a feed solution, with respect to the availability of nutrients to plants, is in the range of 5.5 and 6.0 (Calpas, 2002).

2.3.2 Mineral nutrition of plants

According to Hanan (1998) the essentiality of a nutrient is based on the element's requirement for the plant to survive and reproduce – often so called "critical" level or range. In order to support optimum growth, development and yield of the crop, the fertiliser feed solution has to continuously meet the nutritional requirements of the plants (Hanan, 1998). Table 2.2 shows the mineral elements that are considered essential for plant growth (Calpas, 2002). The essential elements can be grouped into two categories reflecting the quantities of the nutrients required by plants. Macro nutrients are required by plants in larger quantities, when compared to the amounts of

micro nutrients required for growth (Salisbury and Ross, 1978). Table 2.3 shows the summary of the main functions of these nutrients.

The availability of the nutrient elements to plants is generally based on the existence of the nutrient as a charged particle, either a charged atom or charged molecule (Calpas, 2002). An atom or molecule that carries an electric charge is called an ion, and positively charged ions are called cations, while negatively charged ions are called anions (Boikess and Edelson, 1981). Plants are able to acquire the essential mineral elements via the root system utilising the chemical properties of the ions, particularly that to acquire negatively charged anions, the plants roots have sites that are positively charged (Calpas, 2002). The plant is also able to attract positively charged cations to negatively charged sites on the roots (Calpas, 2002).

Table 2.1 The maximum desirable concentration salt ions in fertigation water for greenhouse crops production (Calpas, 2002)

Element	**Maximum desirable (mg $l^{-1)}$**	**Element**	**Maximum desirable (mg l^{-1})**
Nitrogen (NO_3-N)	5	Sodium (Na^{2+})	30
Phosphorus (H_2SO_4-P)	5	Iron (Fe^{3+})	5
Potassium (K^+)	5	Boron (B)	0.5
Calcium (Ca^{2+})	120	Zinc (Zn^{2+})	0.5
Magnesium (Mg^{2+})	25	Manganese (Mn^{2+})	1.0
Chloride (Cl^-)	100	Copper (Cu)	0.2
Sulphate (SO_4^-)	200	Molybdenum (Mo)	0.02
Bicarbonate (HCO_3^-)	60	Fluoride (F^-)	1

The required nutrient levels or target nutrient level of the various elements is often expressed as desired milligram per litre (mg l^{-1}), in the final nutrient solution. The recommended nutrient fertiliser feed targets for greenhouse bell peppers grown in soil-less substrate (Calpas, 2002) are listed in Table 2.4. Modern nutrient solutions for soilless culture mostly contain more or less all nutrients necessary for plant growth (Sonneveld and Voogt, 2009).

Table 2.2 The essential mineral for plants (Calpas, 2002)

Element	Symbol	Type	Available to plants	Symptoms of deficiency
Nitrogen	N	Macronutrient	NO_3^- NH_4^+	Plant light green, lower (older) leaves yellow
Phosphorus	P	Macronutrient	$H_2PO_4^-$ HPO_4^{2-}	Plant dark green turning purple
Potassium	K	Macronutrient	K^+	Yellowish green margins on older leaves
Magnesium	Mg	Macronutrient	Mg^{2+}	Chlorosis between the veins on older leaves first, turning to necrotic spots, flecked appearance at first
Calcium	Ca	Macronutrient	Ca^{2+}	Young leaves of terminal bud dying back at tips and margins. Blossom end rot of fruit (tomato and pepper)
Sulphur	S	Macronutrient	SO_4^{2-}	Leaves light green in colour
Iron	Fe	Micronutrient	Fe^{2-} Fe^{3-}	Yellowing between veins on young leaves (interveinal chlorosis), netted pattern.
Manganese	Mn	Micronutrient	Mn^{2+}	Interveinal chlorosis, netted pattern
Boron	B	Micronutrient	H_3BO_4	Leaves of terminal bud becoming light green at bases, eventually dying. Plants “brittle”.
Copper	Cu	Micronutrient	Cu^{2+} Cu^+	Young leaves dropping, wilted appearance.
Zinc	Zn	Micronutrient	Zn^{2+}	Interveinal chlorosis of older leaves
Molybdenum	Mo	Micronutrient	MoO_4^-	Lower leaves pale, developing a scorched appearance

Table 2.3 Summary of main functions of plant nutrients (Salisbury and Ross, 1978)

Nutrient	Functions
Nitrogen (N)	Synthesis of proteins (growth and yield).
Phosphorus (P)	Cellular division and formation of energetic structures.
Potassium (K)	Transport of sugars, stomata control, cofactor of many enzymes, reduces susceptibility to plant diseases and a-biotic stresses, counteracts salinity
Calcium (Ca)	A major building blocks in cell walls, and reduces susceptibility to diseases.
Sulphur (S)	Synthesis of essential amino acids cystein and methionine.
Magnesium (Mg)	Central part of chlorophyll molecule.
Iron (Fe)	Chlorophyll synthesis.
Manganese (Mn)	Necessary in the photosynthesis process.
Boron (B)	Formation of cell wall. Germination and elongation of pollen tube. Participates in the metabolism and transport of sugars.
Zinc (Zn)	Auxins synthesis.
Copper (Cu)	Influences in the metabolism of nitrogen and carbohydrates.
Molybdenum (Mo)	Component of nitrate-reductase and nitrogenase enzymes.

Table 2.4 Nutrients feed target (mg l^{-1}) for greenhouse bell pepper grown in sawdust (Calpas, 2002)

Nutrient	Target (mg l^{-1})
Nitrogen	200
Phosphorus	55
Potassium	318
Calcium	200
Magnesium	55
Iron	3.00
Manganese	0.50
Copper	0.12
Molybdenum	0.12
Zinc	0.20
Boron	0.90

2.3.3 Nutrient response curve

Maximum crop production is primarily a function of climatic conditions and genetic potential (Raviv and Lieth, 2008). The extent to which this limit can be reached relies directly on the degree and effectiveness of management practices which serve to optimise the plant environment. Fulfilling the crop's water and nutrient requirements are among the most important variables to consider when striving for maximising potential yield. Of the numerous methods available to achieve this goal, fertigation using drip irrigation is the most efficient (Raviv and Lieth, 2008). Various factors are required for plant growth: light, carbon dioxide, water and mineral nutrients. Increasing the supply of any of the factors from the deficiency range increases growth rate and yield, although the response diminishes as the supply of the growth factor is increased (Marschner, 1995).

Figure 2.1 show a general crop yield-response curve to fertiliser application. Generally speaking, higher fertilisation level gives higher yields, but only up to a certain point. Beyond that, addition of fertilisers will not increase yields and may even reduce them as a result of salts accumulation in the root zone which leads to toxicity. According to Marschner (1995) positive yield response curves are the result of different individual processes, such as an increase in leaf area and net photosynthesis per unit area (i.e. effects at the source) or an increase in fruit and seeds number (i.e. effects at the sink).

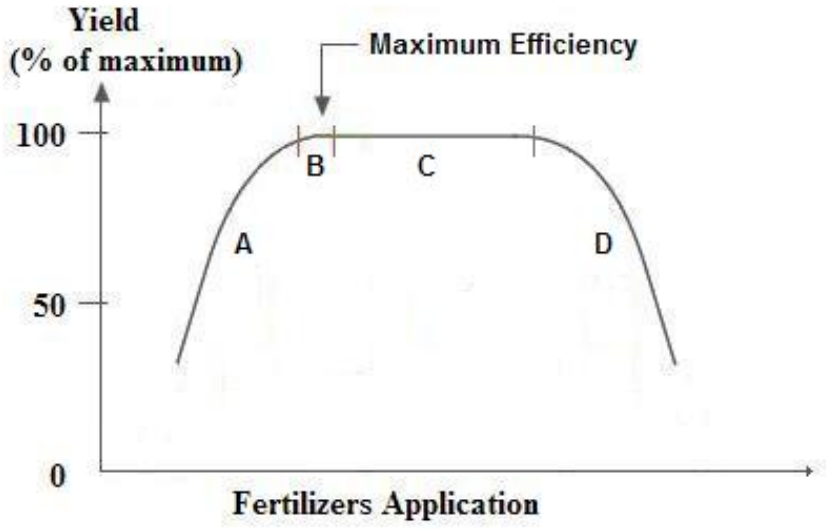


Figure 2.1 A nutrient response curve. At low concentration, small increases in availability results in large changes in growth (A). Further increase in nutrient has smaller effects as nutrient level approaches optimal level (B). At some point additional amounts do not increase growth. This is the range of luxury consumption (C). At high levels, toxicity is reached and growth diminishes (D). (Raviv and Lieth, 2008).

2.3.4 Nutrient requirements and growth stages

A plant differs in its nutrient requirements according to the type, the growth stage and the environmental conditions under which it is grown (Ross, 1998). For fruiting plants, such as bell pepper, the plant goes through an initial vegetative phase, followed by a flowering and fruit set phase and then a fruit development one (Calpas, 2002).

Plant analysis is a useful tool for nutritional diagnostics in plants and allows detection of latent nutrient perturbations, whether deficiencies or excess (Mourao Filho, 2004). This helps maintain efficient use of fertilisers to prevent an excess or luxury uptake. Plant analysis can determine whether during the time of maximum growth plants are provided with all the essential nutrients and to know if one or more of these are restricting the yield. A correct nutritional diagnosis should be considered with the balance of all nutrients implicated in the crop nutrition to allow increases in yield. This is most important that to maintain each nutrient in an adequate concentration (Hoyos and Rodriguez-Delfin, 2007).

The main features of vegetable fruits (in this case, bell pepper) that distinguish them from leafy crops or even flowers are the distinct stages or growth development, starting with the vegetative stage, followed by flowering, anthesis of fruit and fruit development

(Bar-Tal et al., 2003). All these growth stages may require nutrients in different quantities, ratios, and rate of supply. The effects of mineral nutrient supply on fruit yield response curves are often result of sink limitations, imposed by either a deficiency or an excess of mineral nutrients during the critical periods of the plant's development (Bar-Tal et al., 2003). These effects can be either direct (nutrient deficiency) or indirect when they affect the levels of growth regulators (Marschner, 1995).

Yield production in fruit plants is characterised by fruit formation which starts after flowering (Mengel and Kirkby, 2001). At the onset of fruit development, leaves in the direct vicinity of the fruits are the main contributors to fruit growth. The weight and sugar content of different fruits is greater the more leaf material is available to supply the single or the fruit truss (Schaffer et al., 1996). Fruit size and also the number of fruits per plant depend on the earlier nutritional status of the plant (Hochmuth, 2003b).

Indirect effects of nutrition on flower initiation have been reported for various plant fruits. Marschner (1995) summarised the different effects of the short term supply of ammonium (NH_4^+) to the roots of apple. Ammonium was found to more than double both the percentage of buds developing inflorescences and the arginine content in the stem. Arginine is a precursor of polyamines which also accumulate particularly in leaves of plants supplied with high levels of NH_4^+. Ammonium supply also increased the cytokinin concentration in the xylem exudates and the number of flower-bearing lateral branches, whereas the total shoot length was depressed. Therefore, it is assumed that this enhancing effect of NH_4^+ supply on flowering is a result of changes in the phytohormone level in general and of cytokinins in particular.

Phosphorus (P) supply is positively correlated with flower formation in tomato (Marschner, 1995). The positive correlations between the number of flowers and cytokinins level in tomato on the one hand, and between P supply and the cytokinins level on the other, provide additional evidence that cytokinins also contribute to the enhancing effect of P on flower formation (Marschner, 1995).

Yield response curves can differ not only between vegetative and reproductive organs but also between the yield components of harvested products (Figure 2.2). Maximum quality can be obtained either before (Quality 1) or after (Quality 2) the maximum dry

matter yield has been reached, or both the yield and quality can have a synchronous pattern (Quality 3) (Marschner, 1995).

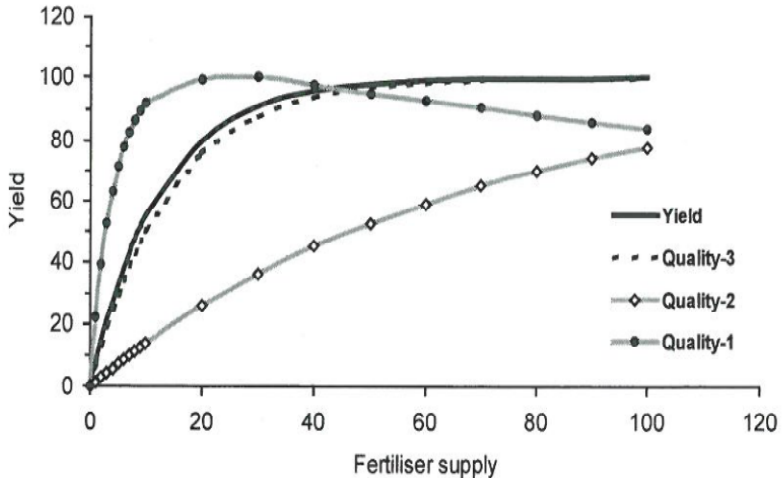


Figure 2.2 Schematic representation of yield response curves harvested products. Yield-quantitative yield (e.g. dry matter per unit area); Quality 1 to Quality 3 – Qualitative yield (e.g. content of sugar, healthy fruits) (Marschner, 1995).

According to Marschner (1995) positive yield response curves for the reproductive organs are the result of either increase in leaf area and net photosynthesis per unit area (i.e. the effects of source) or an increase in fruit and seed number (i.e. effects at sink). Mineral nutrient deficiency can also delay plant development. In cereals, a temporary deficiency of phosphorus (P) or nitrogen (N) during the early growth might reduce final yield as a result of lower number of spikletes per ear or grain per crop. In fruit vegetables, N fertilisation did not influence the flowering and fruiting time of bell pepper but affected fruit set and yield of total marketable fruits (Schon et al., 1994). An increase in soil fertility delayed the flowering and fruit set of bell pepper, but increased total fruit yield (Shrivastava, 1996). Inadequate fertilisation during nursery production of transplants caused a delay in flowering and fruiting time of bell pepper (Bar-Tal et al., 1990).

Xu et al. (2001) found that a low N supply during the short photoperiod progressing from autumn to winter induced early flowering and a high nitrogen (N) supply later in the season is needed for the nutrition of the developing fruits. In the hot and long day summer season, changing the nitrogen (N) distribution during the growing stages

affected the duration of flowering, fruit set ratio and time of fruit development but not the total number of fruits set and total fruit yield (Xu et al., 2001). Aloni et al. (1994) found that a combination of high N with shading enhanced the incidence of 'colour spots' in bell pepper fruit.

Different environmental conditions and the shift from the vegetative to the reproductive stage of growth might alter a plant's requirement for the form of N (Claussen and Lenz, 1995). Yield response curves differ between fruit and leaves as shown for the response of bell pepper to N level and the NH_4^+ / NO_3^- ratio (Bar-Tal et al., 2001b). The optimum ratio of NO_3^--N to NH_4^+-N depends on the growing period (Chance III et al., 1999).

Fruit load in melon plants may cause a reduction in fruit quality especially when several fruits are ripening simultaneously on a single plant. The composition of major nutrients applied to melon plants affects fruit quality (Nerson, 1994). Sugar transport to the developing fruit is high and depends on the rate of photosynthetic activity (Schaffer et al., 1996). Phosphorus and potassium uptake rates are high during the fruit growing period (Bar-Yosef, 1999). Therefore, a low concentration of phosphorus (P) and potassium (K) in the leaves during fruit growth may lower photo assimilate production and its transport from the leaves to the fruits, resulting in poor fruit quality (Bar-Tal et al., 2003).

Ben-Oliel and Kafkafi (2002) concluded that increasing the P concentration during the vegetative stage tended to compensate for the absence of P during fruit development and improved yield and fruit total soluble solid (TSS). The increase in yield and fruit TSS is related to the stem functioning as a store for P, which was later used by the leaves and ensured a proper supply of photo-assimilate to the developing fruits.

2.3.5 Nutrient requirements of substrate grown plants

The basic principles of mineral nutrition of crops have been reviewed by Epstein and Bloom (2005). While the theory of plant nutrition for soil-less grown plants is not different from that for soil-grown plants, some aspects however are different. The main factor that distinguishes between fertilisation of soil-grown from that of soil-less-grown plants is the limited volume of substrate in the latter. Consequently, soil-less culture

methods offer unique benefits such as capabilities to control water availability, pH and nutrient concentrations in the root zone (Silber and Bar-Tal, 2008).

Plants absorb many elements through their roots, however not all are considered to be essential elements. Essential elements can be defined as one that is required for normal life-cycle of a plant and whose role cannot be assumed by another element (Silber and Bar-Tal, 2008). The elements required in largest quantities are the main structural elements which include nitrogen (N) and potassium (K).

Unlike cultivation in soils, in soil-less culture there is a need to supply these essential elements continuously, because of the limited buffer capacity of the medium and its limited supply of nutrients (Savvas, 2001). Many authors and organisations have published recommended tables of solution composition for different crops grown in soil-less culture however the exact amount of nutrient solution varies according to crop, stage of development, environmental conditions and irrigation regime (Silber and Bar-Tal, 2008).

2.3.6 Role of nitrogen and potassium in bell pepper

Nitrogen: Nitrogen is the plant nutrient which most influences growth and development of agricultural crops (Chapin et al., 1987) Yield is closely related to N nutrition. In general, higher production is obtained when N rates in the vicinity of the roots medium are increased, until a level where production per plant responds curvilinear to N rate (Schon et al., 1994). Applying 56 kg N/ha pre-plant followed by 67.2 kg N/ha three times through drip fertigation was found to increase bell pepper yields by 80% over the control and adding more nitrogen did not significantly improve production (Paterson, 1987).

Plants are surrounded by Nitrogen (N) in the atmosphere, but because atmospheric gaseous nitrogen is present as inert nitrogen (N_2) molecules, this nitrogen is not directly available to the plants. Plant available forms of nitrogen (N) are inorganic and include nitrate (NO_3), and ammonium, (NH_4) (Marschner, 1995). Nitrogen is an essential constituent of proteins (RuBisCO) and chlorophyll (Taiz and Zeiger, 2010). Nitrogen is an important component of many important structural, genetic and metabolic compounds in plant cells. It is a major component of chlorophyll (photosynthesis);

amino acids (building blocks of protein such as enzymes); it is also a component of energy-transfer compounds such as ATP (adenosine triphosphate – energy in metabolism) and finally it is a significant component of nucleic acids such as DNA (Marschner, 1995).

Nitrogen is a major constituent of amino acids that play an essential role in plant growth and development. Nitrogen probably has a greatest total influence on plant growth than most other essential elements as within the range from deficiency to excess N level markedly affects plant growth as well as fruit yield and quality (Jones, 2005). Nitrogen is an essential constituent of proteins and chlorophyll and is present in many other compounds of great growth importance such as nucleotides, phosphatides, alkaloids, enzymes, hormones, vitamins etc. It is thus, the very basic constituent of life. It imparts dark green colour to plants and promotes leaf, stem and vegetative growth. It improves quality, succulence of leafy vegetables and fodder crops and governs to a considerable degree, the utilization of potassium, phosphorus and other elements.

Potassium: Although, potassium is not a constituent of any plant structures or compounds, but it plays a part in many important regulatory roles in the plant, i.e. osmo-regulation process, regulation of plant stomata and water use, translocation of sugars and formation of carbohydrates, energy status of the plant, the regulation of enzyme activities, protein synthesis and many other processes needed to sustain plant growth and reproduction (Hsiao and Läuchli, 1986). It is a highly mobile element in the plant and has a specific phenomenon, it is called luxury consumption. In addition, it plays a very important role in plant tolerance of biotic and abiotic stresses (Marschner, 1995). Potassium is also known as the quality nutrient because of its important effects on quality factors (Imas and Bansal, 1999, Lester et al., 2006). With the exception of nitrogen, potassium is required by plants in much greater amounts than all the other nutrients (Tisdale et al., 1985).

Increasing plant vegetative growth, yield as well as fruit quality and chemical composition due to increasing potassium fertilisation levels have been reported by many workers on different crops Nassar et al. (2001) and Fawzy et al. (2005) on bell pepper, Chen Zhen De et al. (1996) and Fawzy et al. (2007*)* on eggplant, Nanadal et al. (1998), Al-Karaki (2000) and Gupta and Sengar (2000) on tomato and Lester et al., (2006) on

muskmelon.

Potassium also has been shown to increase pepper yield (Baghour et al., 2001) and an adequate K content in the cytoplasm is required for N metabolism (Xu et al., 2002). Potassium is essential for maintaining the ion balance in the plants and is believed to be important for carbohydrate synthesis and movement. Potassium is essential for the activation of many enzymes, and the cation, $K^{+,}$ is an important contributor to the osmotic potential of the cells. It is the key element in the function of stomata guard cells, as K deficiency results in the closure of stomata, which in turn reduces transpiration and water uptake by the plant and reduces photosynthesis (Jones, 2005). Potassium is essential for carbohydrate metabolism, synthesis of proteins, chlorophyll regulation of activities of various essential elements, activation of various enzymes, adjustment of stomatal movement and water relations. It imparts increased frost and disease resistance to plants and counteracts the injurious effects of excess nitrogen in plants. Potassium is well known for its role in imparting colour, glossiness and dry matter accumulation in fruits. Hence, a balanced ratio of N and K is important in plant nutrition.

N : K ratio: the relative ratio target in vegetable feed program is about 1:1.5 (Calpas, 2002). Increasing the level of potassium with respect to nitrogen, 1:1.7 will direct the plants to be more generative. The reason for this is that nitrogen promotes vegetative growth while potassium promotes generative growth (Calpas, 2002). Resh (1995) recommends that for the development of tomatoes during the initial vegetative phase the N:K proportion should be 1:5; the intermediate phase during blossoming and fruit set, the N:K ratio should be 1:3; and the mature stage with ripening fruit should have a N:K ratio of 1:1.5.

2.3.7 Nitrogen and potassium scheduling

By fertigation, fertilisers are added in synchronisation with plant needs, which are different for different periods of growth i.e. by fertigation the amount and form of nutrient supply is controlled according to the changing demand for growth stages during the growing season (Rusan, 2004). For example, nitrate : ammonium ratio had a significant impact on the growth and development of the root system. This ratio can be different for different growth and growth stages as well as for different plant species.

This also can also be used to control the quality of agricultural products. For example, providing high rates of nitrate through fertigation can reduce the harmful effects of increased levels of chloride ion concentration (Rusan, 2004).

On the other hand, supplying high rates of nitrate during the last and pre-harvest stages may lead to accumulation of undesirable levels of nitrate in the products, thus reducing their marketability and quality parameters. In addition, by controlling nitrogen fertigation during the last stages of growth one can somewhat control the maturation (Rusan, 2004). High levels of nitrogen are needed in the early stages to stimulate and enhance vegetative growth while high levels of nitrogen should be avoided toward the late and pre-harvest stages to avoid delay in maturation and avoid accumulation of nitrate in the products. Assimilation of nitrogen toward the end of the growing season is significantly reduced and thus most of the nitrate absorbed during these periods tends to accumulate in the products (Rusan, 2004).

Agriculture, in the past dominated mainly by productivity, now also has to consider other objectives like the quality of crop products, the low cost of production and the environmental impact of crops and cropping systems, and hence increased fertiliser use efficiency. Improved fertiliser management has become essential in recent years because of increased levels of nutrient such as nitrate in ground water associated with high rates of fertiliser applied to the crops. The application rates, timing and methods of both fertilisation and irrigation are ways to improve fertiliser management (del Amor, 2007).

During the past 50 years, global fertiliser applications have increased steadily, rising almost 20-fold. Horticultural crop species such as bell pepper are traditionally supplied with high levels of chemical fertilisers, contributing to increased contamination in rivers and lakes. In vegetable crops, the yield response to nitrogen can be dramatic, and the cost of fertiliser often small compared with the cost of lost yield. Therefore, farmers usually over-fertilise with nitrogen rather than risk under-fertilizing and suffering lost revenue (del Amor, 2007). The continuing rise in fertiliser and public awareness that a high contaminants concentration especially nitrate in drinking water is potentially harmful to human health have made the agricultural community very conscious of the need for a more judicious use of fertiliser (Kee Kwong et al., 1999).

Nitrogen and potassium based fertilisers are the most commonly applied nutrients by fertigation for vegetable crops (Calpas, 2002). Some formulations of phosphorus and micro-nutrients can also be used if compatible with irrigation water (pH should be less than 6.5). In addition, because of the precipitation problems, special precautions must be made not to mix P fertilisers with calcium nitrate and iron. To avoid precipitation problems two stock tanks should be used one for calcium nitrate and iron chelate and the other for the remaining fertilisers (Rosen et al., 2004). Suggested N and K fertigation schedules for peppers are provided in Table 2.5. As fruiting begins, the need for potassium increases dramatically.

Tissue analysis can be used to help determine if nutrients are limiting or at an excessive level. Petiole analysis can also be used to help predict the need for nitrogen. The nutrient concentration sufficiency in bell peppers is shown in Table 2.6.

Table 2.5 Suggested N and K fertigation scheduling for bell peppers in ml per 100 linear m of row basis (Rosen et al., 2004)

Days after planting	Daily N	Weekly N	Seasonal N	Daily K_2O	Weekly K_2O	Seasonal K_2O
	ml/100 linear metre of row					
Preplant		7.3			14.7	
0 – 21	0.15	1.1	10.4	0.15	1.1	17.8
22 – 42	0.18	1.3	14.1	0.35	2.5	29.7
43 – 56	0.26	1.8	17.8	0.53	3.7	37.1
57 – 84	0.32	2.2	26.9	0.65	4.6	55.2
84 – 98	0.35	2.5	31.8	0.71	5.0	65.1

Table 2.6 Nutrient concentration sufficiency ranges for bell pepper in petiole (Rosen et al., 2004)

Nutrient	Concentration ranges (%)	Nutrient	mg l^{-1} of dry mater
N	3.5-4.5	Fe	60-300
P	0.30-0.70	B	30-100
K	4.0-5.4	Cu	10-20
Ca	0.4-0.6	Zn	30-100
Mg	0.30-1.50	Mn	26-300
S	-	Mo	-

2.3.8 NPK nutrient uptake curves

There are considerable differences in the shape of nutrient uptake curves among crops. In many cases the uptake curve of a nutrient exhibits sharp changes with the plant's growth stage of development (Bar-Tal et al., 2003). Ignoring the change in uptake rate with time may lead to periods of over- or under- fertilisation. Over-fertilisation may enhance soil salinity and environmental contamination, whereas under-fertilisation may result in nutrient deficiency and yield reduction (Bar-Yosef, 1999). According to Hochmuth (1992) the general uptake curve begins with a small amount of each nutrient, then increases with the rate of application of the nutrient as the crop growth rate and nutrient demand increases. Once the crop has reached maturity, nutrient applications can level off and even decrease slightly toward the end of the cropping period. This uptake curve of nitrogen, phosphorus and potassium in tomatoes and muskmelon (Bar-Yosef, 1999) is shown in Figure 2.3. Similar results were obtained with greenhouse bell pepper (Bar-Tal et al., 2001b).

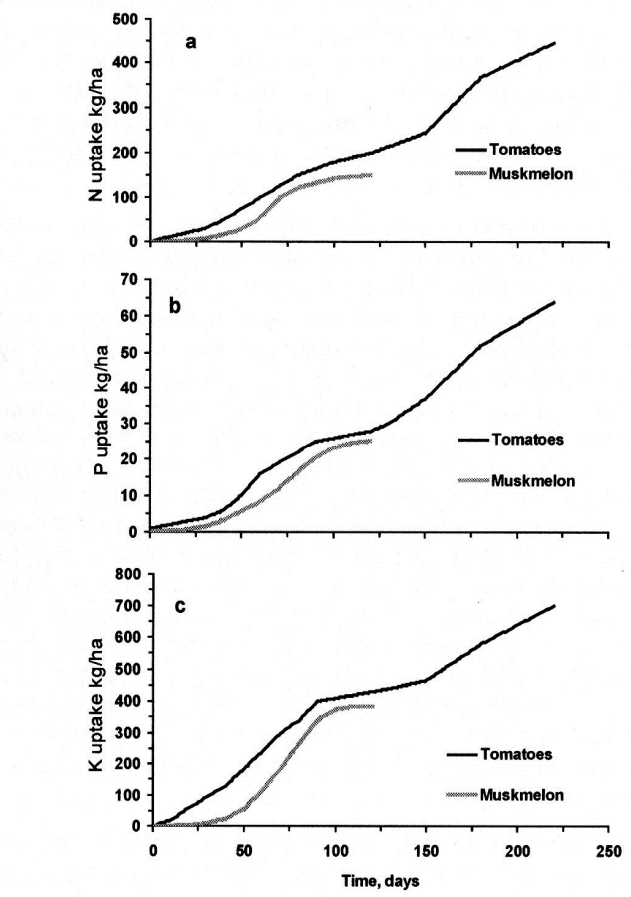


Figure 2.3 Uptake curves of nitrogen (a), phosphorus (b) and potassium (c) of greenhouse-grown tomatoes and muskmelon (Bar-Yosef, 1999)

Extrapolation of known NPK uptake data to environmental conditions different from those specified should be done carefully and treated only as a first approximation (Bar-Yosef, 1999). Xu et al. (2001) reported that the total uptake of N by the bell pepper plant in the summer season was about 2.2-2.8 times higher than that in the winter season when the same concentration of N was applied in the nutrient solution.

2.3.9 Nutrient distribution and transport in plants (Source and sink relations)

Water with its dissolved nutrients moves primarily upward in the plant through the xylem tissue to the site of photosynthesis (Resh, 1995) in response to transpirational losses from the leaves through open stomata (Jones, 2005) The products of photosynthesis (photosynthates) moves from this source of manufacture to other parts of the plant through the phloem tissue (Resh, 1995).

The sources of photosynthates are predominantly mature green leaves although some other organs may contribute and some assimilates are remobilised at a later stage. The photosynthates are transported to sinks where they are metabolised directly or stored (i.e. roots, shoots and fruits) (Marschner, 1995). In young leaves, most or all assimilates produced during photosynthesis (photosynthates) are required for growth and energy supply, therefore in their early growth stages green leaves, also act as a major sink. During its life-cycle each leaf shifts in function from a sink to a source when it is 30-60% fully expanded (Marschner, 1995).With the onset of leaf senescence the rates of photosynthesis and export of sugars from the leaf declines which is associated with an increase in membrane permeability (Marschner, 1995).

The growth rate of sink tissues and organs such as roots, shoots, and fruits can be limited either by supply of photosynthates from the source leaves (source limitation) or by limited capacity of sink to utilise the photosynthates (sink limitation) (Marschner, 1995). Sink-source limitation can be related to low rates of phloem unloading or cell division, a small number of storage cells, low conversion rate of photosynthates (e.g. sugar to starch), or low number of sinks (e.g. grains/ear). Sink-source limitations are characterised by strong genotype/environment interactions and the ratio source size (e.g. leaf area) to sink size (e.g. number of fruits/plant) (Marschner, 1995).

For a given plant species, genotypical differences in sink-source relationships and limitation are often related to differences in the ratio of source size (leaf area) to sink size (e.g. number of fruits per plant) (Marschner, 1995). This was demonstrated with maize subjected to defoliation (Barnett and Pearce, 1983) which reduced the stalk weight as a consequence of the mobilisation of non-structural carbohydrates stored in the stalk. In crop species, where fruits, seeds and tubers represent yield, the effects of mineral nutrient supply on the yield response curve are often a reflection of sink limitations, imposed by either deficiency or an excessive supply of mineral nutrient during certain critical periods of plant development (Marschner, 1995).

Plant growth under various conditions - depends on the acquisition of raw material (carbon fixation and mineral uptake), the allocation of this material over the plant organs, and the impact of environmental stresses. For total biomass production, whilst photosynthetic carbon dioxide fixation is by far the most important process, mineral nutrition, although contributing a much smaller proportion in terms of weight, is also essential for plant growth.

Remobilisation of mineral nutrients occurs simultaneously during the life-cycle of plants (Marschner, 1995). Generally senescence is associated with higher rates of export of mineral nutrients than rates of import, and thus with decreases in net content. During vegetative growth, nutrient supply to the roots is often insufficient, remobilisation of mineral nutrients from mature leaves to areas of new growth is thus of key importance (Marschner, 1995). Deficiency symptoms which predominantly occur in young leaves and apical meristems reflect insufficient remobilisation (Taiz and Zeiger, 2010). Remobilisation of mineral nutrients is particularly important during reproductive growth when fruits are formed. At this growth stage, root activity and uptake generally decrease, mainly as a result of decreasing carbohydrate supply to the roots (‘sink competition’) (Marschner, 1995). As a result, the mineral nutrient content of vegetative parts quite often decline sharply during the reproductive stage.

Remobilisation of mineral nutrients requires several steps: (i) mobilisation within individual leaf cell; (ii) short-distance transport in the symplast to the phloem; (iii) phloem loading; and (iv) phloem transport (Marschner, 1995). Phloem mobility for nitrogen, phosphorus and potassium is generally high (Bar-Tal et al., 2003).

Remobilisation of mineral nutrients is particularly important during reproductive growth when seeds and fruits are formed. At this growth stage, root activity and nutrient activity generally decrease, mainly as a result of decreasing carbohydrate supply to the roots (Morinaga et al., 2003) or other growth regulators (Pressman et al., 1997). Therefore, the mineral nutrient contents of vegetative parts quite often decline sharply during the reproductive stage (Marschner, 1995). During the leaf senescence processes, proteins are degraded and nutrients are remobilised from senescing leaves to other organs (Gregersen et al., 2008).

2.3.10 Nutrients and dry weight accumulation

The demand for nutrients varies widely and dramatically during crop growth. Basically the rate of nutrient requirement at each growth phase is associated with two predominant phases (i) formation of new vegetative plant tissues; and (ii) formation of reproductive organs (flowers, fruits, seeds etc) (Raviv and Lieth, 2008). The nutrient requirements for dry weight (DW) increases are primarily related to the photosynthesis rate, which is affected by various meteorological factors such as photosynthetically active radiation (PAR), air temperature and humidity, wind speed and solar azimuth position (Thornley and Johnson, 1990).

Bell peppers belong to the solanaceous group of vegetables which also include tomato, chilli and eggplants which generally take up large amount of nutrients compared to other horticultural crops (Calpas, 2002) According to Hegde (1997), the amount of nutrients they take up depends on the quantity of fruit and dry matter they produce, which in turn is influenced by a number of genetic and environmental variables. In tomato, dry matter accumulation during the initial 30 days after transplanting (DAT) is low, less than 5% of the total dry matter produced by the end of the growth cycle (Hegde and Srinivas, 1989). Later, there is an almost linear increase in dry matter production up to 90 DAT. It then slows, and during the final stages of the life-cycle there may even be a slight decline in dry matter, due to leaf fall.

In the case of bell pepper, dry matter production continues to the end of the life-cycle (Hegde, 1987). Growth in terms of dry matter production is very slow until 30 DAT. It then picks up between 45 and 105 DAT, later slowing down, mainly due to a reduction in leaf dry matter from leaf fall. In this crop also, nutrient uptake and dry matter

production are closely related. Around 5, 35-40, 75-80 and 90% of total nutrient uptake was achieved by 30, 60, 90 and 105 DAT. Thus, about 40% of nutrient uptake takes place during a period of 30 days, between 60 and 90 DAT (Hegde, 1997). In bell pepper, the greatest requirement for N, P and K is during the period from about 10 days after flowering to about 30 to 33 days from flowering (Hegde, 1986).

2.3.11 Nutrients, photosynthesis and leaf chlorophyll

The rapid photosynthetic rate in crop plants is supported by nitrogen fertilisation which helped the formation of leaves with high chlorophyll content per unit area (Guidi et al., 1997). Chlorophyll concentration (leaf greenness) in corn has been found to be positively correlated with leaf N concentration and N sufficiency (Wood et al., 1992). It follows that leaf chlorophyll concentration reflects relative crop nitrogen (N) status and yield level.

2.3.12 Effect of nutrient concentrations in fertigation recipes

The objective of fertigation is an optimal supply of water and nutrients to crops. The nutrient absorption of different crops is shown in Table 2.7.

Table 2.7 The nutrient absorption of different crops (Sonneveld et al., 1991)

Nutrient elements	mmol/L water absorbed		
	Tomato	Rose	Radish
Potassium (K)	6.3	2.2	4.6
Calcium (Ca)	2.0	0.8	1.5
Magnesium (Mg)	0.6	0.4	0.5
Nitrogen (N)	9.9	5.2	8.6
Phosphorus (P)	1.4	0.4	0.4
Sulphur (S)	1.3	0.5	0.4
Water uptake	650	425	400

Concentrations and ratios of nutrient elements have to be adjusted to the growing stage of crops. Young plants of fruit vegetables crops are often supplied with nutrient solutions of a high electrical conductivity (EC) value to prevent lush growth and improve fruit setting. Table 2.8 shows a tomato recipe placed on plant at different growth stages which is similar to bell pepper (Papadopoulos, 1984).

2.3.13 Electrical conductivity (EC)

Beside the addition of the nutrient elements mentioned previously, the osmotic potential is an important characteristic of nutrient solutions. The osmotic potential of nutrient solutions is mostly measured by the electrical conductivity (EC) and is build up in nutrient solutions by mineral salts (Sonneveld and Voogt, 2009). The EC plays a prominent role in the equilibrium between yield and quality of the harvested produce of many crops grown in substrate and thus a systematic measurement of the EC during crop production is of great importance in order to realise high productions and optimum quality (Sonneveld and Voogt, 2009).

According to Xu et al. (1995) electrical conductivity (EC) is the measurement of a solution's ability to conduct an electric current. For horticultural applications, the unit is often expressed as deci Siemens per metre (dS m^{-1}). Electrolytes dissolved in the water determine how conductive it will be. Therefore EC can be an excellent indicator of: (i) water quality; (ii) soil salinity; and (iii) fertiliser concentration.

The quantity of dissolved solids in parts per million (ppm) or mg l^{-1} by weight is directly proportional to the electrical conductivity decisiemens per meter (dS m^{-1}) per unit volume (Resh, 1995). However, the electrical conductivity (EC) varies not only to the concentration of salt present, but also to the electrical composition of the nutrient solution.

The use of EC measurement is only helpful in checking total salt concentrations in the solution, but the concentrations of individual nutrients will vary considerably from then desired concentration. This is because; this procedure only tells the grower the relative amount of total "salts" in the solution and nothing about each specific nutrient concentration in the solution (Hochmuth, 2008). The true concentration of N, P and K may even be deficient even though the EC is the same as before.

According to Sonneveld and Voogt (2009) the management and control of EC can be achieved through different aspects:

- It is a measure for the availability of nutrients. When the substrate solution does not contain high concentrations of residual salts, a minimum EC is required to supply sufficient nutrients for optimal productions. From this point of view, the

EC for most crops will be at least between 1 and 4 dS m^{-1} dependent on crop and growing conditions.

- Electrical conductivity (EC) is increased above values necessary for maximum productions to control growth and produce quality. Under conditions that plants develop insufficient generative parts a generative development will be stimulated by addition of extra nutrients or by accumulation of residual salts. To control growth and produce quality EC values are required between 2 and 10 dS m^{-1}.
- The use of saline water or by an unbalanced supply of nutrients EC is increased by accumulation of residual salts, which reduces growth and production unnecessary and which can be harmful for the quality when excessive high or low concentrations of nutrients occur. In such cases the measurement of EC offers insufficient information and additional information about the nutrient status is required.

According to Guzman and Olave (2006), maximum production is achieved up to a given threshold of salt concentration for each crop, determined by EC. Beyond this threshold there is a percentage of reduction in yield for each unit increase in electrical conductivity. In soil-less cultivation, this threshold usually is in the range of 2-5 dS m^{-1} (Ling Li et al., 2001). It is well known that high EC reduces yield (Chartzoulakis and Klapaki, 2000). This is as a result of reduced uptake of water into the fruits caused by a high osmotic pressure and as a result the fruit size is smaller (Sonneveld, 1988), although the accumulation of dry matter per fruit is unaffected (Ehret and Ho, 1986).
When irrigation water has an EC>2 dSm^{-1} (high salinity), and the crop is sensitive to salinity, the amount of accompanying ions added with the N or K must be decreased. This practice, according to Imas (1999) will diminish leaf burning caused by Cl excess. Also in greenhouse crops grown in containers with a very restricted root volume, it is very important to select fertilisers with low salt index.

Several studies as cited in Bar-Yosef (1999) indicate that irrigation water with total salt concentration of approximately 2g $litre^{-1}$ can be utilised in drip irrigation without significant yield loss relative to freshwater. The responses of hydroponically grown plants to increasing EC in the nutrient solution due only to the presence of NaCl have

been well documented (Savvas and Lenz, 1996). However, the detrimental effects of salinity on plants may be either indiscriminate (osmotic), if the total salt concentration determines the extent of growth restriction, or ion specific, if the kind of salts being in excess in the nutrient solution is crucial for the plant response (Shannon and Grieve, 1999). Under saline conditions, sodium cations compete with potassium cations for the uptake sites in the roots, and chloride competes for the uptake of nitrate-nitrogen and will reduce yield. This will result in a potassium deficiency in the pepper plants, leading to a low fruit number per plant (Sonneveld and Welles, 1988).

According to Heinen et al (2003) crop growth reduction may occur when the fertigation nutrient solution has both low and high EC. At low EC, not enough nutrients may be available to the roots resulting in a decrease in nutrient uptake, which may reduce crop growth. At high EC, although ample nutrients are available a decrease in water uptake may occur due to osmotic effects, which may result in reduced crop growth. Besides growth and water uptake, the EC of the nutrient solution may affect other variables such as dry matter content (De Koning, 1996) and fruit quality (Mizrahi and Paternak, 1985).

The detrimental effects of high electrical conductivity (EC) on the yield of greenhouse bell pepper are due to a decrease in mean fruit weight whilst the number of fruits per plant is not affected (Adams, 1991, Cuartero and Fernandez-Munoz, 1999, Savvas and Lenz, 2000). The decrease in total yield to high EC was mainly due to a decrease in fruit fresh weight (Sonneveld and Welles, 1988, Adams and Ho, 1989, Willumsen et al., 1996). The differences in the fruit fresh weight between high EC treatment and the control may be attributed to water content as there were no differences in the fruit dry weight (Rubio et al., 2008).

In a study by Savvas et al (2000) at high EC (8 dS m^{-1}), the leaf area and dry weight of leaves and stems per plant were also restricted, and the fruit dry weight was reduced almost as much as the growth of the vegetative organs, whereas the fruit fresh weight was even more severely depressed. Consequently, the detrimental effects of high EC on yield can be attributed to a restriction of water accumulation in the fruit. Therefore the reduction in bell pepper fruit weight with high EC in this study can be attributed to reduced water transport to the fruit, since dry weight was not affected.

Another important aspect of high EC is its effect on the incidence of BER in fruits. High EC caused by nutrient solution content and salinity have been shown to have a strong impact on the incidence of BER (Adams and Holder, 1992, Adams, 2002, Ho et al., 1995, Saure, 2001, Bar-Tal et al., 2003, Ehret and Ho, 1986). The occurrence of BER in pepper was found to increase dramatically when the EC increased above 1.0 dS m^{-1} (Sonneveld, 1979). The sensitivity of crops to high EC and the incidence of BER increases as the environmental conditions enhance transpiration (Adams and Holder, 1992) and it is well known that bell pepper is a salt sensitive plant species (Sonneveld, 1988, Navarro et al., 2002).

The effect of high EC on the incidence of BER has been related to plant water stress (Cerda et al., 1979, Adams and Ho, 1989, Pill and Lambeth, 1980, Shaykewich et al., 1971). The effect of high EC on the incidence of BER has also been related to its effect on calcium (Ca) and water uptake and Ca translocation to the fruits (Bar-Tal et al., 2003). Although the Ca supply to the fruit is considered to be an important factor in the occurrence of BER, efforts to define critical values even to correlate BER incidence with Ca concentration or K:Ca ratio in the fruit have not succeeded (Bar-Tal et al., 2003, Nonami et al., 1995). Saure (2001) suggested that BER is caused by different environmental and growth stress condition rather than Ca supply.

Table 2.8 Nutrient concentration at different growth stage for tomato/bell pepper (Papadopoulos, 1984)

Growth stage	Fertiliser	Application rate (g l^{-1})
Starter fertiliser until the first truss	15-30-15 + Mg	1.0
First truss set to first picking	15-5-30 + Mg	1.5
First picking to end of season	15-6-20 + Mg	1.3

2.4 Irrigation Frequency

This section provides information about irrigation frequency in crop plants in general and application of this information in soil-less and greenhouse condition. Previous studies pertinent to the development of the knowledge of irrigation frequency of crop plant, in terms of bell pepper performance as well as its effect of the incidence of blossom end rot (BER) are reviewed and presented in this section.

2.4.1 Impact of fertigation frequency

Greenhouse grown peppers enjoy a longer growing season. They consume, therefore, a larger amount of water than open-field grown peppers during their respective growing season. Water stress affects bell pepper growth by reducing the number of leaves and the leaf area, resulting in less transpiration and photosynthesis (Silber, 2005). Root density is reduced by about 20 % under water stress conditions, compared to sufficiently irrigated plants (Silber, 2005). On the other hand, excessive irrigation especially in soil-grown plants will cause water-logging, root death due to anaerobic soil conditions, delayed flowering and fruit disorders (Silber, 2005).

Frequent application of water and nutrients ensures that the root surface and its vicinity are well supplied with fresh nutrient solution during the fertigation events and the subsequent distributions (Silber et al., 2005). These frequent replenishments prevent the formation of a depletion zone in the vicinity of the root surface by uptake of nutrients between successive fertigation events, decrease the concentration gradient between the medium solution and the root-medium interface, and diminish the role of diffusion in transporting nutrients towards the roots (Silber et al., 2003).

Previous studies demonstrated that increased fertigation frequency significantly increased plant yield, especially at low nutrient concentration (Silber et al., 2003) and that the yield improvement was primarily related to enhanced nutrient uptake, especially of P. It was suggested that the yield reduction at low fertigation frequency resulted from nutrient ion deficiency rather than water shortage, and that high fertigation frequency might overcome nutrient deficiency.

Silber et al., (2005) suggested that high fertigation frequency improved the uptake of nutrients through two main mechanisms: (i) continuous replenishment of nutrients in the depletion zone near the root/medium interface; (ii) enhanced transport of dissolved nutrients by mass flow, because of the higher time-averaged water content in the medium during daytime. Very frequent or continuous fertigation of drip irrigated vegetables has been recommended in the literature (Silber et al., 2005).

A study on irrigation scheduling was done by Sezen et al. (2006a). That study was carried out to determine the most suitable irrigation scheduling of fresh market tomato

grown on volcanic ash, peat and their mixture (1:1) under plastic house conditions. The quality and yield response on tomato to drip irrigation was also investigated. Four different irrigation levels: 75%, 100%, 125% and 150% (Class A Pan Evaporation) and two irrigation frequencies (once or twice daily application) were evaluated. Highest yield and fruit number were obtained from the ash+peat (1:1) with irrigation with once a day at 150% pan evaporation and ash+peat (1:1) with twice daily watering at 125% and 150% pan evaporation irrigation levels. Soluble solids of tomato fruit decrease with increasing available water.

Al-Jaloud and Ongkingo (1999) studied four drip irrigation frequencies namely: once, two times and three-times daily and two times every other day, were evaluated for their corresponding effects on growth and production of greenhouse cucumber. Plant height data for the summer trial, after 4-5 weeks from planting showed that treatments receiving fertiliser and irrigation (fertigation) daily either one, two or three cycles were significantly higher than that the treatment receiving fertigation every other day. On the other hand, during winter, the growth advantages by treatment with three fertigation daily. However, at eight weeks or fruiting stage growth components were not significantly influenced by fertigation frequencies.

For crop yield during summer, treatments which received one and three fertigations daily, significantly out yielded the treatment fertigated every other day by more than four tonnes per hectare. But during winter, the effect of various treatments on yield was non-significant. Likewise total production data analyses indicate no marked relationship among treatments with varying frequencies of fertiliser and water application; hence, fertigation every other day could be a feasible alternative. Results of the study imply that fertigation practices in greenhouse farming could be manipulated and labour attention to farm facilities can be reduced, thereby justifying any change in practice during the cropping season.

Proper irrigation management is essential for improving the productivity and quality of crops grown in the greenhouse. Exact time and amount of irrigation are two deterministic factors for efficient irrigation management. Inside greenhouse, crops require frequent irrigation in order to minimise water stress and achieve maximum production and high quality. Scheduling water application is very critical, as excessive

irrigation reduces yield, while inadequate irrigation causes water stress and reduces production (Locascio and Smajstrla, 1996).

In soil-less culture use of drip irrigation also facilitates frequent fertiliser application via injection in the irrigation system which allows growers to improve the synchronisation between nutrient application and crop nutrient uptake. Future demand on the world's limited water resources and the demand to adequately feed and clothe an expanding population require that irrigation efficiency and crop productivity from irrigated lands improve. Irrigation scheduling is an important element in improving water use efficiency (Howell, 1996).

According to Werner (1996), irrigation scheduling is critical in order for irrigators to achieve profitable results in their operation. In irrigated agriculture, irrigation scheduling is also essential to obtain effective water conservation and reduced water-carried pollutants. Irrigation scheduling is a collection of technical procedures developed to forecast the timing and amount of irrigation applications (Fereres, 1996). Irrigation scheduling is a decision-making process that managers follow to arrive at solutions concerning their irrigation practices.

Irrigation scheduling can reduce water use only by reducing runoff from either irrigation or rainfall, by decreasing percolation of water beneath the root zone in excess of any required leaching in salinity management, by reducing substrate water evaporation after irrigation (Howell, 1996). In some cases, irrigation scheduling may actually increase irrigation water use, while concurrently increase crop yield by avoiding critical water deficits that reduce crop yield or by supplying both water and nutrients needed by the crop at a more "optimum" time for the particular crop (Howell, 1996).

Frequency and timing of water application have a major impact on yields and operating costs (Segars, 2007). For the most efficient use of water it is desirable to frequently determine the substrate moisture conditions throughout the root zone of the crops being grown. Two proven practical field methods for measuring substrate moisture are tensiometers and electrical resistance meters (Segars, 2007).

2.4.2 Effects of irrigation frequency on plant growth and yield

According to Silber and Bar-Tal (Silber and Bar-Tal, 2008) irrigation frequency may have an effect on the root system through two main mechanisms: (i) the direct effect of wetting patterns and water distribution (ii) indirect effect on nutrient availability, especially of P, which significantly modify root system efficiencies. The effect of irrigation frequency on the shoot/root ratio has been reported to be smaller than that of P concentration (Xu et al., 2004) and to be very sensitive to plant age. The main impact of irrigation frequency actually arises from the increase of P availability and the consequently higher P uptake by the plant (Silber and Bar-Tal, 2008). Silber et al. (2005) has shown that yield gained under high irrigation frequency can be primarily related to increased availability of nutrients, especially P. Multiple stepwise regressions relating nutrient concentrations in the plant to the yield revealed a significant correlation between dry weight (DW) production and P concentration in leaves.

Other indirect effect of irrigation frequency on the concentrations of starch in the leaves and of sucrose and reducing sugars in the fruits have been reported (Silber et al., 2005). The beneficial effects of high frequency irrigation were recognised some decades ago, and it is considered a useful tool for optimising the root environment. Although the findings were based on studies on soil and soil-grown plants, their basic approach is valid for soil-less media as well (Raviv and Lieth, 2008).

2.4.3 Nutrient availability and uptake by plants affected by irrigation frequency

Adsorption on the solid phases and precipitation of insoluble compounds decrease the concentration of the nutrients in the root area (Raviv and Lieth, 2008). Thus, the nutrient concentrations in the vicinity of the roots may be high or even excessive immediately after irrigation, and may subsequently fall (Figure 2.4).

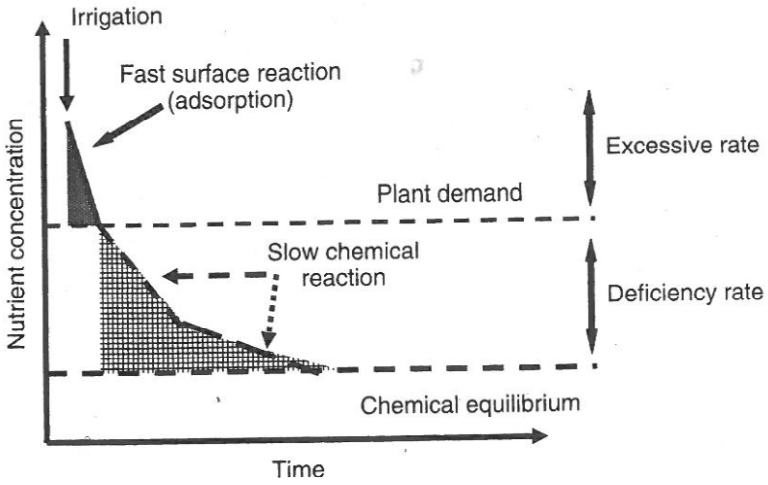


Figure 2.4 Schematic representation of the time variation of nutrient concentration under conventional conditions (Silber, 2005)

These processes are time dependent; therefore, reducing the time interval between successive irrigations to maintain constant, optimal water content in the root zone may also reduce the variation in nutrient concentrations (Figure 2.5), thereby increasing their availability to plants and reducing their leaching out of the root zone.

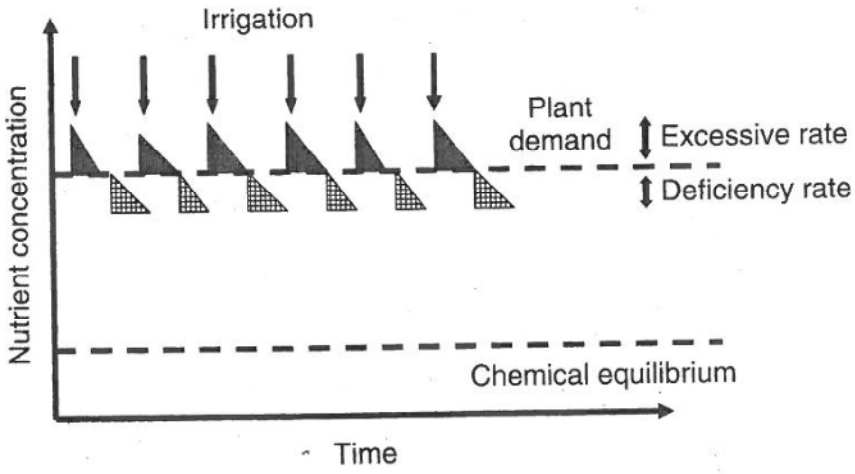


Figure 2.5 Schematic presentation of the time variation of nutrient concentration in the vicinity of the roots under frequent irrigation (Silber, 2005)

Water and nutrient acquisition by plants, and the formation of a depletion zone in the immediate vicinity of the roots, drive solute movement towards the root. Nutrient transport to the root surface takes place by two simultaneous processes: convection in the water flow (mass flow), and diffusion along the concentration gradient (Tinker and

Nye, 2000). Medium properties, crop characteristics and growing conditions affect the relative importance of each mechanism, but the general situation is that the mobile NO_3 ion supply is taken up mainly through mass flow, whereas for less mobile elements such as P and K, diffusion is the governing mechanism (Tinker and Nye, 2000).

Nitrate, the main N source for soil-less-grown plants (Sonneveld, 2002), is hardly ever involved in the adsorption or precipitation reactions; therefore, the concentration of NO_3^- in the irrigation water and its actual concentration in the vicinity of the roots are quite similar (Raviv and Lieth, 2008). In contrast, P availability to plant roots is time dependent, as a result of adsorption and precipitation (Raviv and Lieth, 2008). Potassium ions are hardly ever involved in precipitation reactions, but may be adsorbed on negatively charged surfaces. Therefore the difference between the K concentrations in the irrigation solution and the vicinity of the roots lies between those between the respective NO_3^- and P concentrations. Consequently, it can be expected that the impact of fertigation frequency on uptake of nutritional elements by plants will be related to both mobility and their availability (Silber et al., 2003).

The increases in the leaf N, P and K concentrations on high fertigation frequency were attributed to both direct and indirect effects of irrigation frequency on the P and K concentration at the root surface (Raviv and Lieth, 2008). The direct effect is the frequent elimination of the depletion zone at the root surface by the supply of fresh nutrient solution during and soon after the irrigation events (Silber, 2005). Moreover, a higher irrigation frequency maintains higher dissolved N, P and K concentrations in the substrate solution by shortening the period during which precipitation takes place (Raviv and Lieth, 2008). The indirect effect of irrigation frequency on nutrient availability is manifested through higher connective and diffusive fluxes of dissolved nutrients from the substrate solution to the root surface, which increase with increasing frequency (Silber, 2005).

The findings that increasing the fertiliser rate improved nutrient uptake and plant yield and that increased irrigation frequency resulted in systematic dwindling of nutrient uptake enhancement, may indicate that main effect of increased fertigation frequency was related to an improvement in nutritional status mainly with regard to P (Silber et al., 2003). Thus increasing the irrigation frequency may compensate for certain nutrient

deficiencies (Raviv and Lieth, 2008).

2.4.4 Effects of irrigation frequency on root growth and root/shoot ratio

Alterations of growth conditions generally lead to modifications of the root system, therefore irrigation frequency may have an effect on the root system through two main mechanisms: (i) the direct effect of wetting patterns and water distribution in the substrate volume, which modulate root distribution and growth (Coelho and Or, 1999); and (ii) indirect effect on nutrient especially that of P, which significantly modify root system efficiency (Lynch and Ho, 2005).

The effect of irrigation frequency on the root/shoot ratio has been reported to be smaller than that of P concentration (Xu et al., 2004). The reasons for the age-linked diminution of the effect of irrigation frequency on root/shoot ratio (Figure 2.6) could be the following: (i) during early growth, the roots were mainly located at the top of the pots and were more sensitive to the drying and rewetting processes than later on; (ii) adsorption of the added P by the sand substrate induced stronger deficiency conditions in the early growth period than later, and (iii) the young roots in the early stages were mostly active roots, whereas at later stages, part of the roots became inactive and probably masked the changes (Xu et al., 2004).

Similar to the findings with lettuce, observations in bell pepper plants showed high sensitivity of the root/shoot ratio to variations in irrigation frequency under low P application and a diminished response under high P application (Figure 2.7). Note that the root/shoot ratio under low P and high-frequency irrigation was very similar to that under high P and low-frequency irrigation, which may indicate that both treatments affect the same mechanism. Irrespective of the experimental causes for leaf-P variations (P level or irrigation frequency), the values of root/shoot ratio were significantly correlated with leaf-P concentration (Silber et al., 2005).

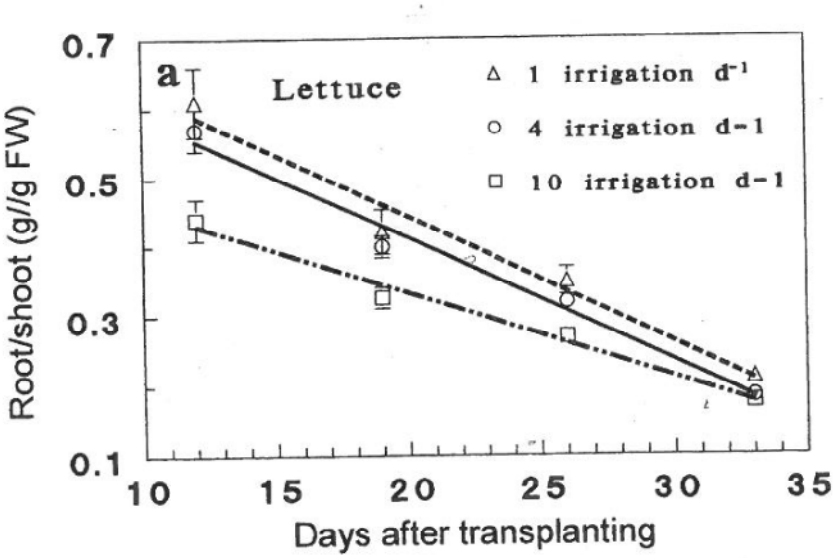


Figure 2.6 Root/Shoot ratio of lettuce plants under three irrigation frequencies: 1, 4 and 10 irrigations per day (Xu et al., 2004)

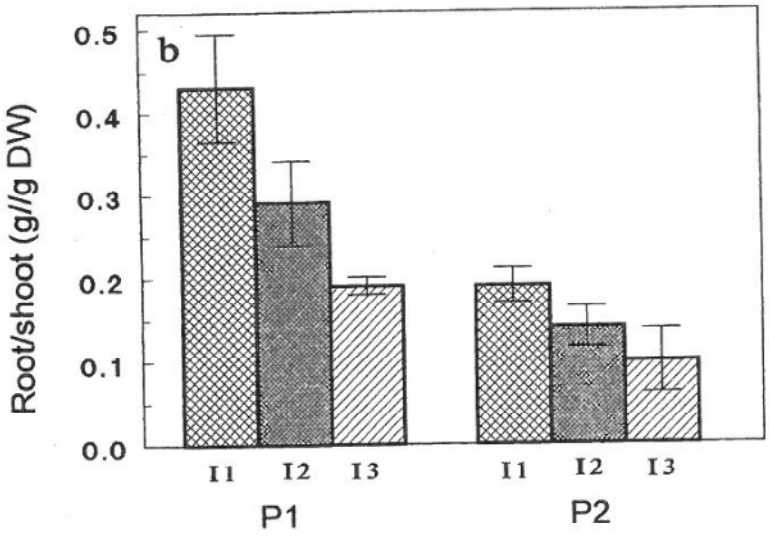


Figure 2.7 Root/Shoot ratio of bell pepper under two water P-levels: P1 and P2 (3 and 30 mg l^{-1}, respectively) and three irrigation frequencies: I1 (two irrigation events per day), I2 (four irrigation events per day) and I3 (1.5 min every 30 min throughout the day) (Silber et al., 2005)

2.4.5 Effects of irrigation frequency on yield and growth aspects

It has been shown that yield gained under high irrigation frequency can be primarily related to increased availability of nutrients especially P (Silber et al., 2005). The relationship between dry weight (DW) production of several crops and leaf-P

concentration induced by irrigation frequency has been studied in lettuce (Silber et al., 2003) and bell pepper. Multiple stepwise regressions relating nutrient concentrations in the plant to yield revealed a significant correlation between DW production and P concentration in leaves (Silber et al., 2005), indicating that the main effect of fertigation frequency was related to improvement in P mobilisation and uptake.

Irrigation frequency also directly and indirectly influenced other processes in plants. Indirect effects of irrigation frequency on the concentrations of starch in the leaves and of sucrose and reducing sugars in the fruits have been reported (Silber et al., 2005). Increased starch and reduced sucrose and hexose concentrations have previously been found in phosphorus-deficient plants (Paul and Stitt, 1993), therefore, the differences in the concentrations of starch in the leaves and of sucrose and reducing sugars in the fruits were attributed to variations in leaf P (Silber et al., 2005).

2.4.6 Effects of irrigation frequency on blossom end rot (BER) incidence

A considerable and important effect of irrigation frequency on blossom-end rot (BER) incidence has been reported recently (Silber et al., 2005). The cause(s) of high BER incidence under low-frequency fertigation is/are unclear, but it is generally accepted that BER incidence may be associated with water stress, for example substrate water deficit, high osmotic pressure or high salinity (Saure, 2001).

BER has also been related to Ca deficiency and, especially, to low Ca transport to the fruits, particularly to the distal fruit tissue (Ho and White, 2005). However, unlike BER incidence, the fruit Ca concentrations were almost unaffected by the fertigation frequency (Silber et al., 2005). The discrepancy between the Ca concentration in the fruits and BER incidence was consistent with the general remark of Saure (2001) that the role of calcium (Ca) in BER should be reassessed.

2.5 Conclusion

Unlike the cultivation in soil, in soil-less (i.e. substrate) culture there is a need to supply all of the essential elements, including micro-nutrients, continuously because of the limited buffer capacity of the medium and its limited supply of nutrients (Savvas, 2001). Since the development of all-purpose nutrients solution by Hoagland and Arnon (1938), many authors have published recommended amounts of solution composition for

different crops grown in soil-less culture (Raviv and Lieth, 2008). However, the exact composition of nutrient solution varies according to crop stage of development, environmental conditions and irrigation regimes (Raviv and Lieth, 2008).

Using fertigation to manage crop performance needs to be based on a good knowledge of when and to what extent each mineral nutrient is taken up by the crop's roots and how it affects crop growth, development, and yield. With open fertigation systems this knowledge is even more critical. There is a tendency to assume that all crops behave similarly, but this is not the case. It must be stated that there are still major knowledge gaps in this area for specific crops (Raviv and Lieth, 2008). Another gap in technology is the ability to measure crop nutrient status in 'real time', and to interpret that information correctly and use it to manage the fertigation system (Raviv and Lieth, 2008).

Several examples of recommended nutrient solution composition, adjusted for the stage of development and season are presented by various researchers (Silber and Bar-Tal, 2008). However extrapolation of known NPK uptake data to environmental conditions different from that specified should be done carefully, and treated only as a first approximation (Bar-Yosef, 1999). Not only can the total demand fluctuate, but the specific demand of the individual nutrients can vary independently of fluctuations in total demand (Silber and Bar-Tal, 2008). The total uptake of nutrients is more or less determined by the growth and transpiration rates, but the uptake of individual nutrients depends more on the stage of growth (Voogt, 2003b). There is a knowledge gap warranting research focus. Part of the thesis research addresses this issue and attempts to determine the interrelationships between bell pepper growth stages and varying N and K rates as well irrigation frequency of fertigated bell pepper in rockwool substrate.

The experiments presented in this thesis aim to contribute and enhance the understanding of improved use fertiliser of bell pepper in soil-less production systems and provide information on the fertiliser concentration (N and K rates) and irrigation frequency to meet the plant's requirement at different growth stages. Irrigation (water) and fertilisation (nutrients) are the most important management factors for plant development, yield and quality. The introduction of simultaneous application of fertiliser with irrigation water (fertigation) opened new possibilities for controlling

water and nutrient supplies to crops and maintaining the desired concentration (Bar-Yosef, 1999). The main advantages of fertigation over surface irrigation and broadcast/band fertilisation are manifested in improved crop yield and quality (Silber and Bar-Tal, 2008). The goal is to match nutrient supply with crop demand i.e. timing the fertiliser application in relation to crop demand based on development and growth stage of crops. Potentially higher yield, improved quality of produce and reduced fertiliser losses due to leaching can be achieved

Nutrients such as nitrogen (N) and potassium (K) were among the elements that affect the yield and quality of vegetables grown in soil-less cultivation (Silber et al., 2005). Nitrogen (N) is among the nutrients that have been manipulated by farmers due to the relations of N to reproduction development in bell peppers and especially fruit quality (Jones, 2005). While Potassium (K) is the important aspect to maintain N metabolism in plants and as an activator for a number of enzymes, mostly those involved in photosynthesis and respiration process (Jones, 2005). Increased N has been shown to increase the number and size and overall yield while increased K rate increases the number of fruits per plant and seed yield (Locascio, 2005). The proper use of N and K fertilisers in the soil-less culture and fertigation are important due to their relations to the stage of plant growth and environmental condition (Grattan and Grieve, 1999).

Fertilisation above plant requirements not only increases the production costs but is also detrimental to the environment such as through salt accumulation in soil and ground water contamination due to leaching (Raviv et al., 2008). It is therefore necessary to carry out studies on different N and K concentration and N:K ratios in the nutrient solution, under greenhouse conditions in order to improve understanding of optimal management of fertigation.

Numerous studies have been published in the past few decades on crop responses to fertigation. A summary of a literature search on these subjects is presented in Table 2.9 which shows that the responses to fertigation of the various vegetable crops in several locations. Most of the nutrients studies pertaining to fertigation focused on the effects of NPK as a whole as well as individual or combination effects of N, P, K have contributed to generating knowledge about bell pepper production, however there is no or little information on the effect of N K rates and fertigation frequency at different

growth stages on bell pepper plants growth in rockwool substrate. Although information on N and K effect on plant growth had been reported in sugarcane (Ingram and Hilton, 1986); tomato (Clough et al., 1990, Chormova, 2010); and bell pepper (Ahmad, 2009) these results may not be pertinent or directly applicable to bell pepper production in soil-less systems. The experiments presented in this thesis aimed to enhance our understanding of improved use of fertigation of bell peppers grown in rockwool substrate.

Table 2.9 Summary of literature search on crop responses to fertigation

Crop	Topic studied	Location	Reference
Potato	N drip fertigation	Cyprus	(Papadopoulos, 1988)
	P drip fertigation	Cyprus	(Papadopoulos, 1992)
	Economy of water and fertiliser	India	(Chawla and Narda, 2001)
Lettuce	N,P,K fertigation	Israel	(Bar-Yosef and Sagiv, 1982)
	N fertigation vs broadcasting	Netherlands	(Bakker et al., 1984)
Strawberry	Drip fertigation scheduling	USA	(Locascio et al., 1977)
	K drip fertigation	USA	(Hochmuth et al., 1996)
	Soil vs soil-less system	Spain	(Recamales et al., 2007)
	Electrical conductivity, Plant spacing	Australia	(Sarooshi and Cresswell, 1994)
Muskmelon	N drip fertigation	USA	(Bhella and Wilcox, 1985)
Sugarcane	N,K drip fertigation	USA	(Ingram and Hilton, 1986)
	Drip fertigation, N	Mauritius	(Kee Kwong et al., 1999)
Sweet corn	P surface, subsurface, drip fertigation	Israel	(Bar-Yosef et al., 1989)
Cucumber	EC-based irrigation, CO_2 enrichment on water use efficiency	Spain	(Sanchez-Guerrero et al., 2009)
	Fertigation frequencies	Saudi Arabia	(Al-Jaloud and Ongkingco, 1999)
	Nutrient sources in different substrates	Turkey	(Gul et al., 2007)
Zucchini squash	Growth, yield, fruit quality and nutrient uptake affected by irrigation systems and growing seasons	Italy	(Rouphael and Colla, 2005)
Eggplants	NaCl vs nutrient induced salinity	Greece	(Savvas and Lenz, 2000)
Broccoli	Fertigation frequency, subsurface irrigation	USA	(Thompson et al., 2003)

Table 2.9 ... continued

Crop	Topic studied	Location	Reference
Lettuce	Fertigation frequency	Israel	(Silber et al., 2003)
Tomato	N drip fertigation in calcareous soil	USA	(Kafkafi and Bar-Yosef, 1980)
	N drip fertigation	USA	(Miller et al., 1975)
	P drip fertigation vs banding	USA	(Rauschkolb et al., 1979)
	N, P subsurface drip fertigation	USA	(Phene et al., 1982)
	N, P drip fertigation in calcareous soil	USA	(Mikkelsen and Jarrel, 1987)
	N, K drip fertigation	USA	(Clough et al., 1990)
	Electrical conductivity and transpiration	Netherlands	(Ling Li et al., 2001)
	N,P,K drip fertigation	India	(Hebbar et al., 2004)
	Macronutrient accumulation	Brazil	(Marcussi et al., 2001)
Tomato (soil-less)	N drip fertigation	Cyprus	(Papadopoulos, 1987)
	Drip irrigation and fertigation relationship	Israel	(Bar-Yosef, 1988)
	P drip fertigation	Israel	(Bar-Yosef and Imas, 1995)
	N,P,K fertigation	Netherlands	(Sonneveld, 1995)
	Growth and photosynthesis affected by N deficiency	Greece	(Guidi et al., 1997)
	Fertigation strategy on water and nutrient efficiency with saline water	Italy	(Pardossi et al., 2008)
	Irrigation management and different soil-less culture	Turkey	(Sezen et al., 2006a)
	Fertigation management on growth and photosynthesis grown in peat, rockwool and NFT	Canada	(Xu et al., 1995)
	Osmotic potential in nutrient solution	UK	(Ehret and Ho, 1986)
	Uneven distribution of nutrients in root zone, BER	UK	(Tabatabaie et al., 2004)
	N and P supply on plant growth, yield and quality	UK	(Chormova, 2010)
Bell pepper	Drip fertigation	Florida	(Neary et al., 1995)
	N drip fertigation vs broadcasting	New Zealand	(Haynes, 1988)

Table 2.9 ... continued

Crop	Topic studied	Location	Reference
Bell pepper	N fertigation	Jordan	(Qawasmi et al., 1999)
	Drip and surface irrigation on yield and water use efficiency	India	(Antony and Singandhupe, 2004)
	Organic vs mineral fertilisation	Spain	(del Amor, 2007)
	Drip irrigation regimes	Turkey	(Sezen et al., 2006b)
	Frequency and nutrient use efficiency	Israel	(Silber, 2008)
	N fertigation	Jordan	(Qawasmi et al., 1999)
	Fertiliser levels and quality of irrigation water	Spain	(Contreras et al., 2006)
	Fertigation in Hungry	Hungry	(Oncsik and Nagy, 2006)
	Fertigation frequency and phosphorus level	Israel	(Silber et al., 2005)
	N rates	Brazil	(Oliveria et al., 1997)
	NaCl salinity during growth stages	Greece	(Chartzoulakis and Klapaki, 2000)
	N and K concentration under rain shelters in lowland	Malaysia	(Ahmad, 2009)
Bell pepper (soil-less)	N form and concentration during growing season	China	(Xu et al., 2001)
	Fertigation frequency and phosphorus level	Israel	(Silber et al., 2005)
	Salinity and irrigation frequency - interactions	Greece	(Savvas et al., 2007)
	Drip fertigation under tropical greenhouse	Malaysia	(Kamaruddin, 2006)
	Soil-less greenhouse	Florida	(Jovicich et al., 2001)
	Recirculating nutrient, Salinity	Greece	(Lycoskoufis et al., 2005)
	Salinity affected by K^+ and $Ca2^+$	Spain	(Rubio et al., 2010)
	Drip irrigation and fertigation	India	(Muralikrishnasamy et al., 2006)
	Fertigation, Soil-less culture	Spain	(Garcia Lozano et al., 2005)
	Solar radiation-based irrigation and container media	USA	(Jovicich et al., 2007)
	Water content in rockwool	Netherlands	(Abdel-Mawgoud et al., 2006)
	Effects of fertiliser formulations	UK	(ALsodany, 2011)

Chapter 3
General Materials and Methods

Three separate greenhouse experiments were conducted within the period 2009-2010 to look at different aspects of fertigation of bell pepper grown in rockwool (Table 3.1). The general description of materials used and experimental techniques employed for these experiments are described in this chapter. More specific details for each experiment are described in the subsequent chapters (Chapters 4 - 6).

Table 3.1 Experiments conducted in the process of this thesis

Expt. No	Name	Description	Chapter
1	Effect of varying nitrogen and potassium concentration	Greenhouse experiment to investigate the effect of different rates of N and K at three plant growth stages on growth and reproduction of bell pepper	4
2	Further evaluation of the effects of fertiliser concentration	Greenhouse experiment to investigate the effects of higher and lower fertiliser concentration (N and K rates) on bell pepper production	5
3	Effect of varying fertigation frequency	Greenhouse experiment to investigate the effect of varying fertigation frequency at different plants growth stages on growth and reproduction of bell pepper. A supplementary experiment was conducted concurrently to investigate the effect of fertigation frequency and defoliation.	6

3.1 Location of the Experimental Site

The experiment was conducted in two greenhouses, located at Cockle Park farm of Newcastle University (latitude 55^{o} 20'N, longitude 1^{o} 69'W, Ordinance Survey map grid reference: NZ20159115) in the north-east of England.

3.2 Climatic Condition

The data on the climatic parameters namely temperature (maximum and minimum) and estimated rate of evaporation for each experiment are presented in the respective chapters describing the individual experiments. Rate of evaporation estimated using an open pan inside the greenhouse. Temperatures and pan data provide an indication of the

daily fluctuations of growing conditions inside the greenhouse. Vapour pressure deficit would have provided a better indication of the ability of the atmosphere to draw water from the leaf. However, there was no attempt by the author to monitor humidity in the current study.

The greenhouses used supplemental heating (fan heater) during the cooler days to maintain minimum temperature above 15^{o}C. Control of maximum temperature was dependent on natural ventilation provided by roof vents that opened and closed passively in response to temperature (www.baylissautovents.co.uk).

3.3 Experimental Design and Layout

The general layout of the greenhouse experiments is shown in Figure 3.1. Detailed experimental layouts for each experiment are described in the subsequent chapters (Chapters 4–6). The experiment, laid out in a completely randomised design with three replicates, was used to compare different fertiliser concentrations. Each experimental unit consisted of one rockwool slab containing 3 plants spaced at 30cm. Spacing between slabs was also 30cm resulting in a density of 3 plants m^{-2}.

3.4 Varietal Description

In this study two different varieties were used namely *Capsicum annuum* var. California Wonder and *Capsicum annuum* var. Ferrari F1. The varietal descriptions of these bell peppers are described in this section.

California Wonder bell peppers are the traditional bell peppers that are seen in supermarkets. This variety is a mid-season, open-pollinated sweet bell pepper with crisp, thick-walled fruit that ripens from dark green to bright red. Its extra large, blocky, three-or four-lobed fruits are prolifically and consistently borne on upright, bushy plants resistant to tobacco mosaic virus. A long growing season, high quality fruit and sweet flavour have resulted in California Wonder becoming one of the most popular bell peppers (Parkseed, 2010).

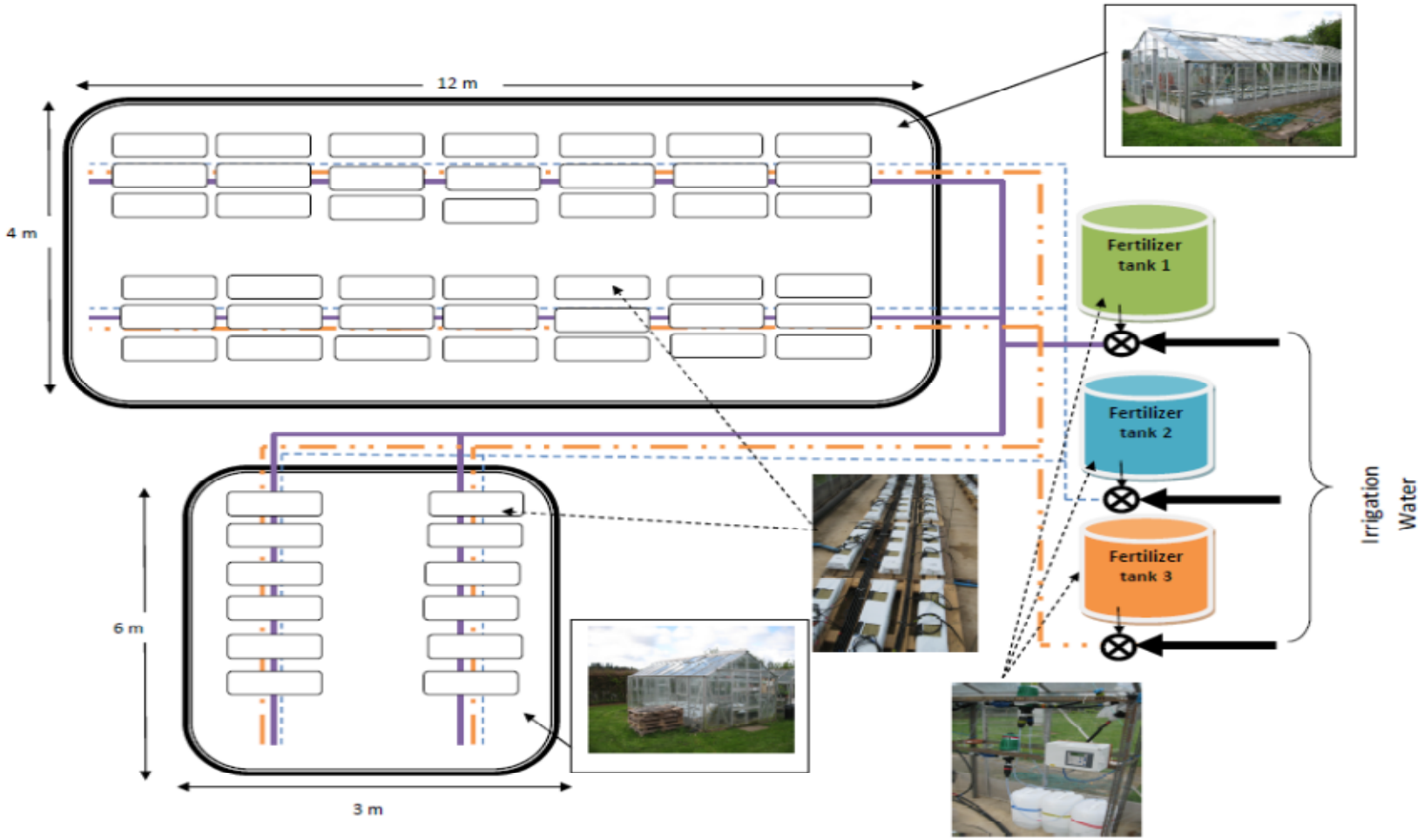


Figure 3.1 Schematic diagram to show the experimental layout

Ferrari F1 bell peppers are similar to California Wonder; it is a blocky and green to red variety. This very productive, thick-walled red blocky pepper combines high quality with excellent flavour. Its powerful and generative short plants produce a strong root system. Ferrari's high fruit weight and low susceptibility to blossom end rot, russetting and shoulder cracking also contribute to its fantastic performance (Vitalis, 2010).

3.5 Cultural Practices

The cultural practices were followed as per the recommended practices suggested by Calpas (2002) for bell pepper production and Grodan (2005) for soil-less production using rockwool. The cultural practices performed in this study are described in this section which includes the uses and forms of rockwool; nursery; transplanting to greenhouse; plant protection measures; plant pruning and training; and finally flower and fruit set.

3.5.1 Uses and forms of rockwool

The main use of rockwool in horticulture is as a propagation and growing substrate in its own right (Smith, 1987). For this purpose the material is almost exclusively formed into plugs, blocks or slabs. Plants of most crops are propagated in small plugs until transplanting stage when they are then transferred into blocks. These blocks are then placed into slabs. Diagrammatic representation of the cycle of a bell pepper crop grown in rockwool is shown in Figure 3.2.

3.5.2 Nursery

The starter plugs were soaked by dipping in nutrient solution at quarter strength. Pre-germinated bell pepper seeds were sown into the hole of the wet rockwool plugs (Figure 3.3). The starters were then placed in a tray with a clear humidity dome. The starters were misted with nutrient solution at the onset of drying while avoiding the starters getting soaking wet.

The ventilation of the dome was gradually adjusted when roots were visible. When the seedlings had four leaves, they were transferred to rockwool 10 x 10 cm blocks (Figure 3.4). The nutrient strength was increased ending at half strength before transplanting to the blocks.

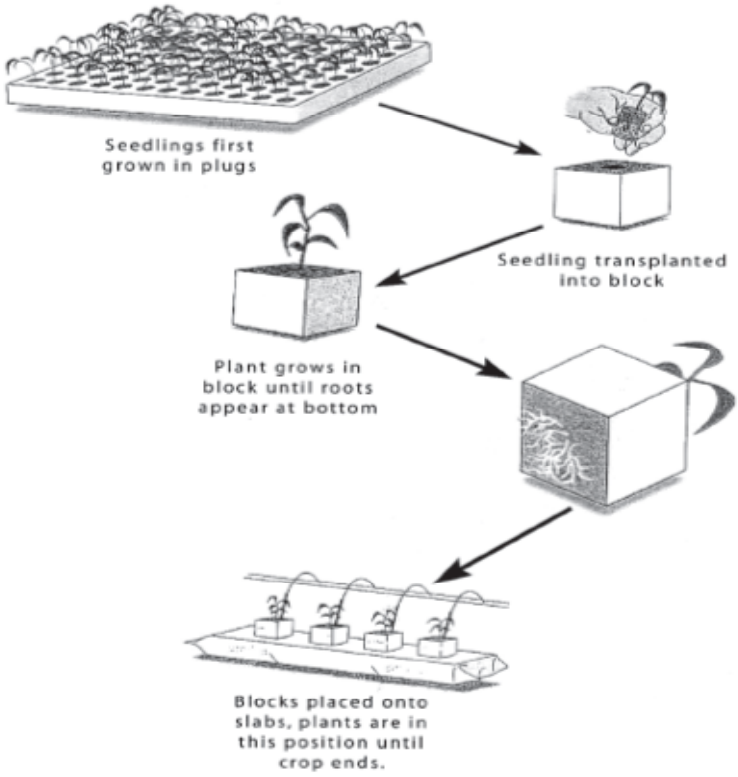


Figure 3.2 Diagrammatic representation of the cycle of a bell pepper crop grown in rockwool (Grodan, 2005)

Figure 3.3 Planting the pre-germinated seeds into the rockwool plugs

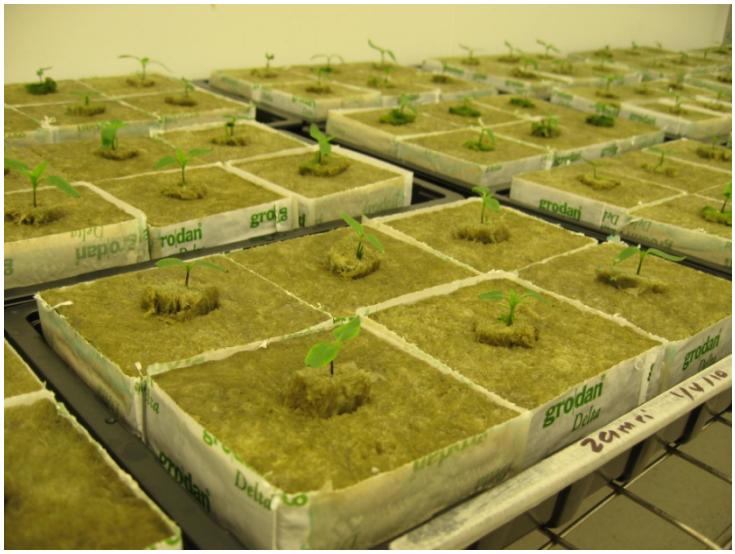


Figure 3.4 The seedlings were transferred to the rockwool block

When the plants were about 15 cm tall, a full strength nutrient solution was used and kept until roots appeared from the bottom of the blocks which signalled it was ready to be transplanted onto the rockwool slabs in the greenhouse.

3.5.3 Transplanting in the greenhouse

Holes in the plastic of the rockwool slab were cut to fit the 10cm x 10cm block (Figure 3.5). The slabs were filled completely with water, and then left for 30 minutes. Two drain holes on either side of the slab were made to flush out waste with nutrient mix. The drain holes were made as per manufacturer's recommendation. The blocks were then placed on the cut plant holes of the slab. Emitter stakes were placed for each plant directly on to the respective blocks (Figure 3.6).

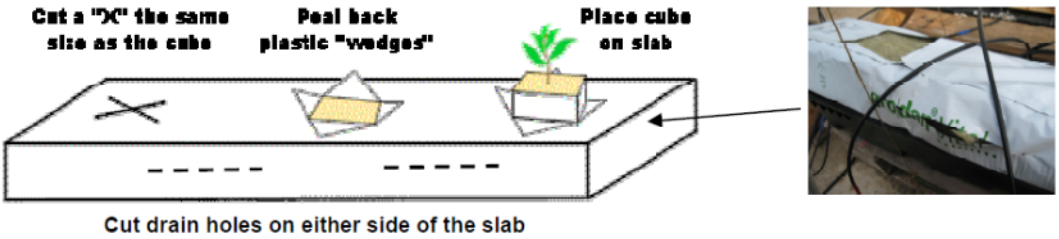


Figure 3.5 Preparation of the rockwool block hole and drain holes

Figure 3.6 Individual emitters were placed into the rockwool block

Each rockwool slab was placed inside a 1 metre tray where the leachate solutions were collected before being emptied manually once a day. The leachate solutions were collected from the tray, the volume recorded and pH and EC analysed for nutrient contents.

3.5.4 Plant protection measures

The greenhouses were fumigated with greenhouse sulphur candle about 2 weeks prior to transplanting the plants. Fumigation was done in order to kill pests and fungal spores in the greenhouses. Pre-mixed general insecticides and fungicides (Figure 3.7) were used to prevent and control pests and diseases such as aphids, mites, sucking pests, leaf spots and mildew.

3.5.5 Plant pruning and training

The plants were managed with two main stems per plant (Figure 3.8) resulting in a density of 6 stems m^{-2} from the planting density of 3 plants m^{-2}. Pruning improves air circulation around the plant which helps to reduce disease (Horbowicz and Stepowska, 1995). The plants were supported by twine attached 1.8 m above the plant row on a horizontal wire and trained to two stems ("V" system) per plant by pruning auxiliary shoots.

3.5.6 Flower and fruit set

In terms of flower and fruit set, flowers developing at the fork were removed and resulting fruit set targeted for the second node above the fork (Calpas, 2002). After this flower sets, the flower at the third node was removed and the fourth node was left to develop. The flowers that follow at the fifth node and upwards were allowed to set freely (Calpas, 2002). The general schematic diagram to show the flower and fruit set used in the experiments is shown in Figure 3.9.

a b

Figure 3.7 Plant protection measures against pests and diseases using (a) pre-mixed pesticides; (b) greenhouse sulphur candle

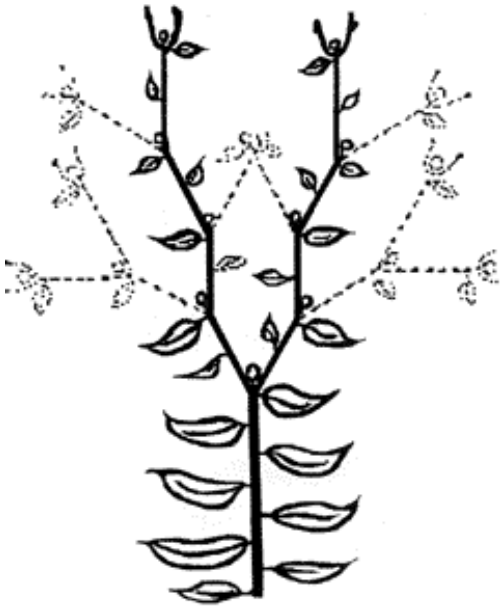


Figure 3.8 Pruning a plant with two stems (Nederhoff, 1998)

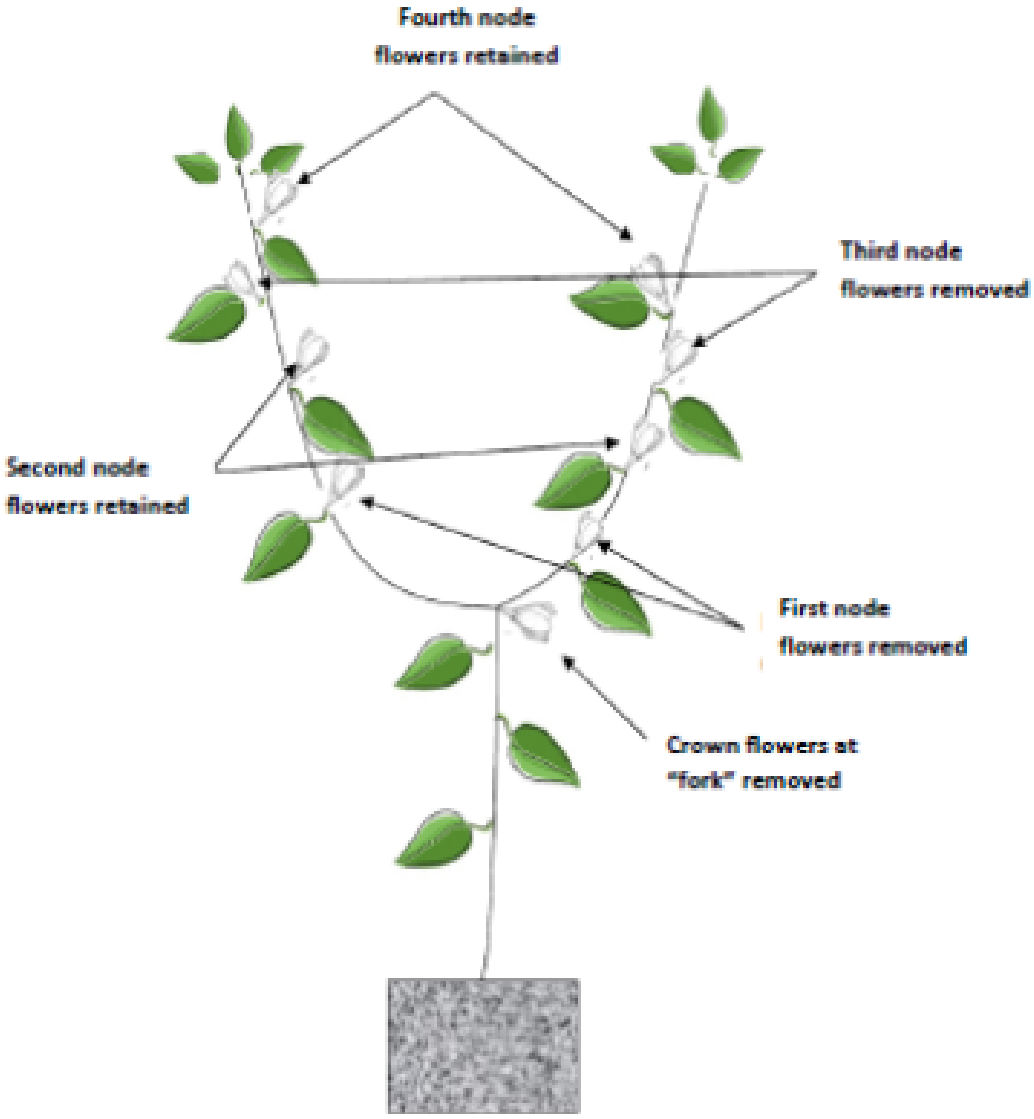


Figure 3.9 General scheme for targeting flower and fruit set

3.6 Fertigation System

Figure 3.10 shows a schematic diagram of the fertigation system used in the experiment which was an open (run to waste) fertigation system. The fertigation system consists of irrigation controller, fertiliser dispenser, fertiliser tanks, filter, tubes and emitters (Figure 3.11).

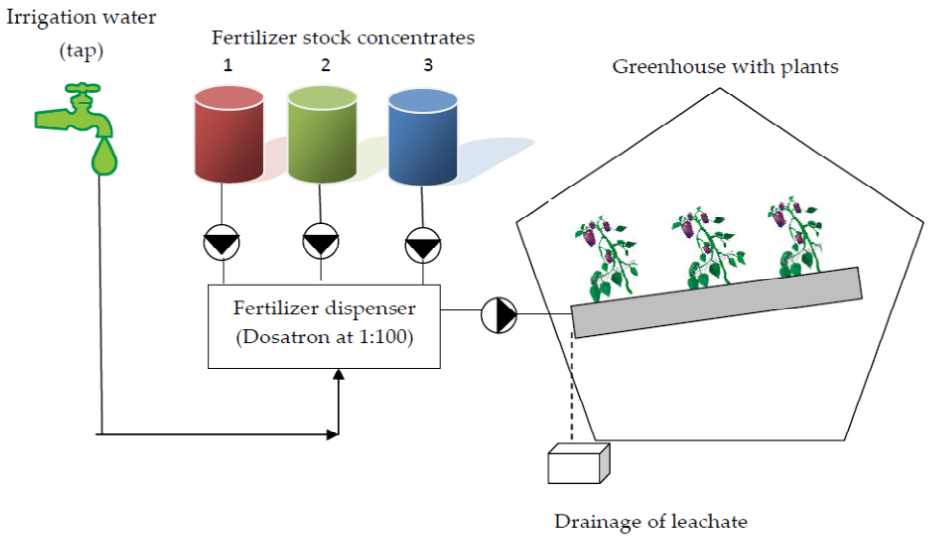


Figure 3.10 Schematic diagram to show the fertigation system used in the study which is an open fertigation system

Figure 3.11 Fertigation system consist of irrigation controller, fertiliser dispenser, fertiliser tanks, filter and tubes

3.6.1 Emitters

The emitters were placed at the end of the spaghetti tube which had a length of 75 cm (Figure 3.12). The emitters used had a discharge of 2 litres h^{-1}. Each plant had individual emitters spaced to 30cm between each emitter.

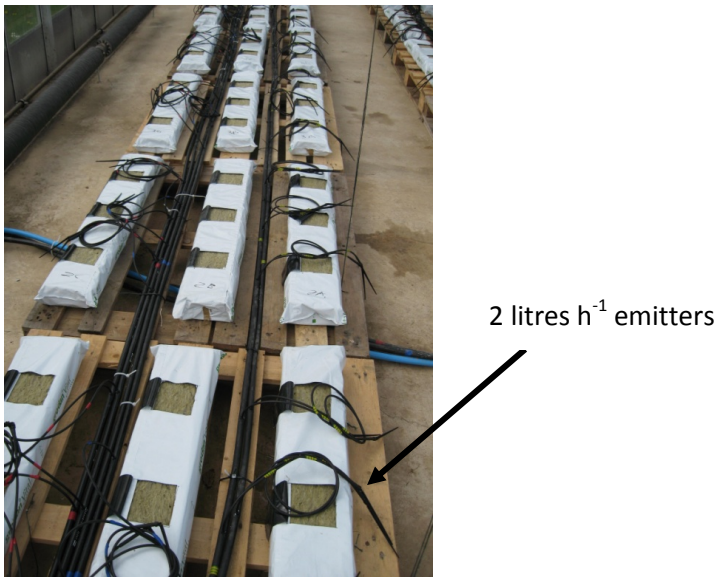


Figure 3.12 Emitters at the end of spaghetti tube were allocated one per plant

3.6.2 Calibration of emitters (uniformity)

The system was checked periodically to maintain a high degree of uniformity throughout the growing season. This was to obtain maximum benefits of approximately the same amount of water and fertiliser received by individual plants.

The emitters were calibrated before the start of any experiment to ensure the emitters were working properly with no significant differences between the emitters. This was done by collecting the emitter solution for a specific time period (5 minutes) in containers and the volume collected was measured (Figure 3.13). The discharge rate was computed by dividing the volume of water by the time period. Volumetric method was used for computing the uniformity coefficient (Uc) of the fertigation system (Eq. (1)) (Mahajan and Singh, 2006) where q is the mean emitter discharge and Δq, the mean deviation of the emitter discharge from mean value.

$$Uc = 1 - \left(\frac{\Delta q}{q}\right) \quad (1)$$

The dripper uniformity was then compared with acceptability range of statistical uniformity of drip irrigation provided by American Society of Association Executives (ASAE): Standards of Conduct (Table 3.2) (Lesikar et al., 2004).

Table 3.2 Statistical uniformity of drip irrigation (ASAE)

Dripper uniformity	Rating
90 – 100%	Excellent
80 – 90%	Good
70 – 80%	Fair
Less than 70%	Poor

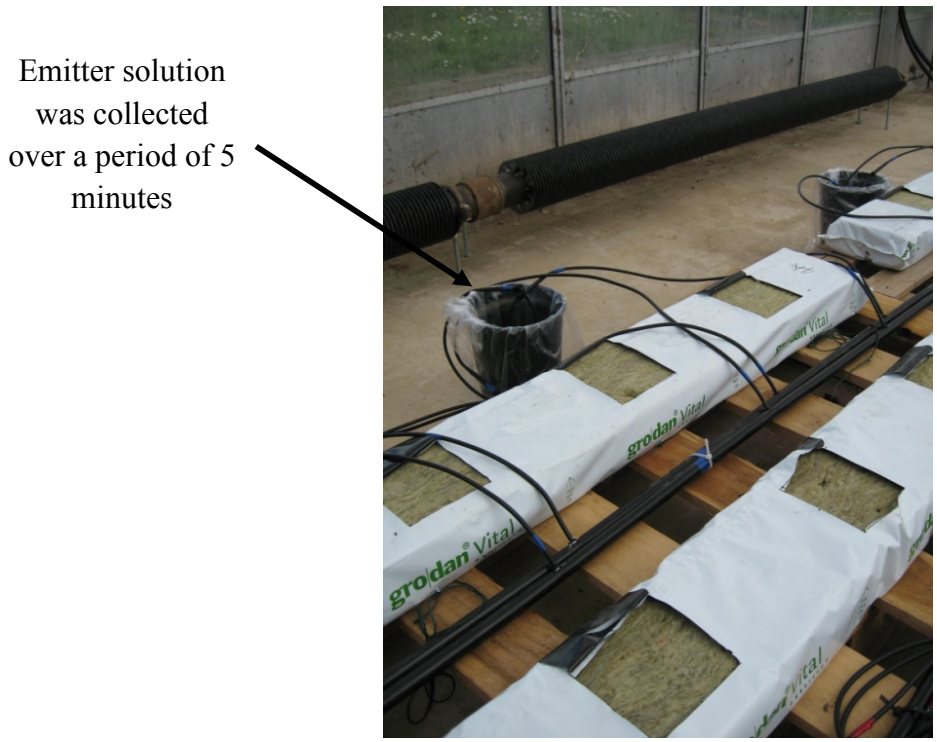


Figure 3.13 Fertigation calibration and uniformity

Flushing of the irrigation systems by opening the flush valves at the end of the main and lateral line was done at beginning and at the end of the growing season. This was done to discharge any accumulated precipitate from the tubes.

3.6.3 Irrigation controller

The irrigation scheduling was carried out by the controller (Heron, M*i*-4). Irrigation frequency (e.g. 5, 10 and 20 irrigation events per day) and duration (e.g. 5 min, 6 min, and 9 min per day) were manipulated using this controller.

3.6.4 Fertiliser dispenser

The fertiliser dispenser unit ensured that the concentrated fertilisers were diluted to a nutrient solution to be taken by the plants. Fertiliser solutions were proportioned using

fertiliser dispenser (Dosatron, DI.1500) with rate 1:100 or at 1% concentration.

3.7 Collection of Experimental Data

Biometric observations were recorded on selected plants from each treatment at different growth stages. For this particular purpose, parameters on growth; yield; leaf chlorophyll; and leaf gas exchange were recorded. Nutrient uptake; emitters and leachate solution monitoring; and analysis of plant samples were also measured and recorded. The next section describes the collection of experimental data used in this study.

3.7.1 Growth parameters

Plant growth analysis is an explanatory, holistic and integrative approach of interpreting plant form and function. It uses simple primary data, such as weight, areas, volumes and contents of plant comportments to investigate process within and involving the whole plant (Hunt et al., 2002). In this study, plant height; stem diameter; plant dry matter production and leaf area were the growth parameters analysed. This section described data collection for growth parameters.

3.7.1.1 Plant height

Plant height was measured from the top level of the rockwool block to the top most leaf (Figure 3.14). The mean plant height was expressed in centimetres (cm).

3.7.1.2. Stem diameter

Plant stem diameter was measured using vernier callipers at 10cm from the top of the rockwool block (Figure 3.15). The stem diameter was expressed in millimetres (mm).

3.7.1.3 Plant dry matter production

Representative plants from each treatment were cut just above the rockwool block level at different stages. Samples were separated into leaves, stem and fruits. They were dried in hot air oven at 80^{o}C for 24 hours, recorded and expressed as grams plant^{-1}.

Figure 3.14 Plant height was measured from the top of the rockwool block to the top most leaf

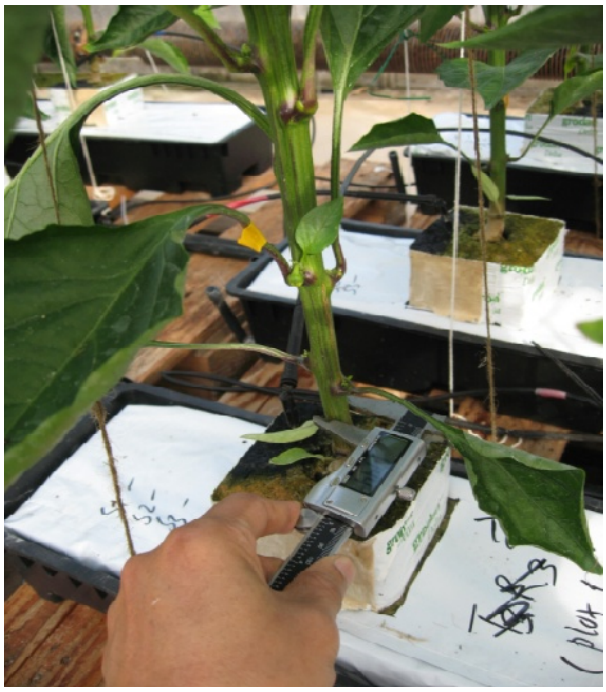


Figure 3.15 Stem diameter was measured using a vernier calliper

3.7.1.4 Leaves area

The leaves' green areas were calculated using the WinDIAS 3 image analysis system (Delta-T Devices, Cambridge, UK) (Figure 3.16), recorded and expressed as cm^2, per plant.

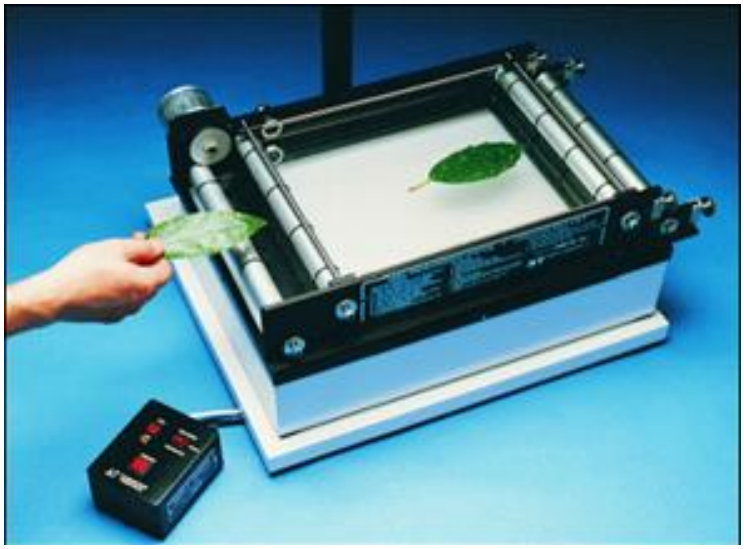


Figure 3.16 Measuring leaf area

3.7.1.5 Leaf weight ratio (LWR) and Specific leaf area (SLA)

Leaf weight ratio (LWR; g g^{-1}) is the ratio of leaf dry biomass to total plant dry biomass and thus a measure of the proportion of the plant dry biomass in the leaf material (Bhattarai, 2003). LWR was calculated as proportion of the total leaf dry weight to the total above-ground dry weight of the sample plants at harvest.

Specific leaf area (SLA; leaf area (cm^2)/ leaf dry biomass (g)) is the ratio of leaf area to leaf plant dry biomass and thus a measure of leaf thickness (Harrington et al., 1997). For SLA, leaf area was determined using a WinDIAS 3 image analysis system as described in the section 3.7.1.4. Specific leaf area (SLA) was expressed in cm^2 leaf area g^{-1} dry weight.

3.7.2 Yield parameters

Number of fruits; fruit weight; fruit length and width; fruits with BER and harvest index were the yield parameters used in the study. This section described data collection of these various parameters.

3.7.2.1 Number of fruits

The fruits obtained from the selected plants at destructive harvest at different growth stages were counted and expressed as number of fruits $plant^{-1}$.

3.7.2.2 Fruit weight

The fruits obtained from all the pickings from the selected plants were mixed and the weight was recorded and expressed as grams plant^{-1}.

3.7.2.3 Fruit length and width

The length was measured excluding the pedicel and the breadth was measured at the middle of the fruit.

3.7.2.4 Fruits with BER

The number of fruits affected with Blossom End Rot were recorded and expressed as number of fruits with BER plant^{-1}.

3.7.2.5 Harvest Index (HI)

Harvest index (HI) was calculated by dividing the oven dried mass of mature fruit by above-ground dry weight expressed as a percentage (Hay, 1995).

3.7.3 Leaf chlorophyll content

Chlorophyll content was measured with a SPAD-502 chlorophyll meter (Konica, Minolta), which measures chlorophyll content in arbitrary units. Measurements were taken from apical leaves as well as from marked leaves at the bottom of the plants (Figure 3.17).

3.7.4 Leaf gas exchange

Photosynthesis is one of the most important factors affecting biomass production (Evans, 1975) closely related with growth rate. Photosynthetic capacity (µmol m^{-2} s^{-1}); Transpiration rate (mmol m^{-2} s^{-1}), Sub-stomatal CO_2 (vpm), Stomatal Conductance (mol m^{-2} s^{-1}), Photosynthetically Active Radiation (PAR, µmol m^{-2} s^{-1}), Leaf chamber temperature (^{o}C) were measured on the apical leaflet using LC*i* infrared gas analyser (ADC BioScientific Ltd, Hertfordshire, UK) (Figure 3.18). This was done on fully expanded uppermost leaves. Measurements were taken in each stage on cloudless day.

Figure 3.17 Leaf chlorophyll was measured using the SPAD-502 chlorophyll meter

Figure 3.18 Photosynthetic parameters were made using the infrared gas analyser

3.7.5 Nutrient uptake

The uptake of macronutrients was calculated by multiplying the biomass (g/plant) of each plant organ (leaves, stems, and fruits) by its nutrient concentration (g/g of dry weight). All nutrient amount of plant organs were then summed to get the nutrient uptake of the whole plants (g/plant).

3.7.6 Emitters and leachate solution

Figure 3.19 shows the schematic representation of fertiliser feed monitoring. The pH and Electrical Conductivity (EC) of the leachate and emitters solution were recorded using pH meter (Hanna, HI-98107 Phep) and conductivity meter (Hanna, HI-98311 Dist5) (Figure 3.20) respectively. The amount of leachate was collected from each slab and the volume measured and analysed for nutrient content.

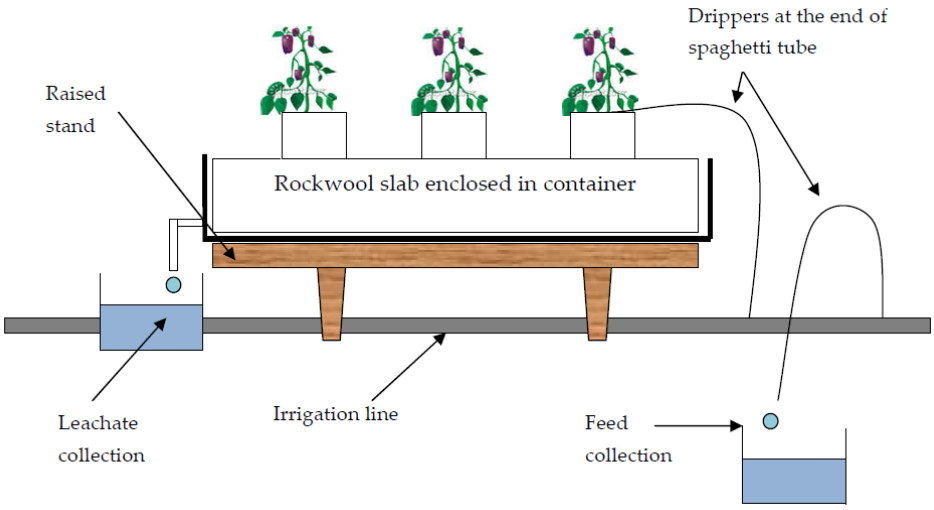


Figure 3.19 General schematic of a fertiliser feed monitoring

Figure 3.20 pH meter and conductivity meter used to measure pH and EC of nutrient solutions and leachate

3.7.7 Analysis of plant samples

The plants were divided into leaves, stems and fruits. Fresh biomass of leaves, stems, fruits and dry biomass after oven drying at 80^{o}C for up to 24 hours were determined and the nutrient content were determined by the following analyses. This section described the procedure in the analysis of the plant samples which include sample preparation;

nitrogen; phosphorus; potassium and other nutrients analysis.

3.7.7.1 Sample preparation

The dried plant samples were grounded by milling using a one millimetre sieve (Christy and Norris Ltd (UK), 8" labmill) (Figure 3.21) to reduce the samples to manageable size and to facilitate the preparation of homogenous sub-samples for chemical analysis. The prepared samples were stored briefly in plastic bags until analysis. The plant material was analysed for nitrogen, phosphorus, potassium as well other nutrients.

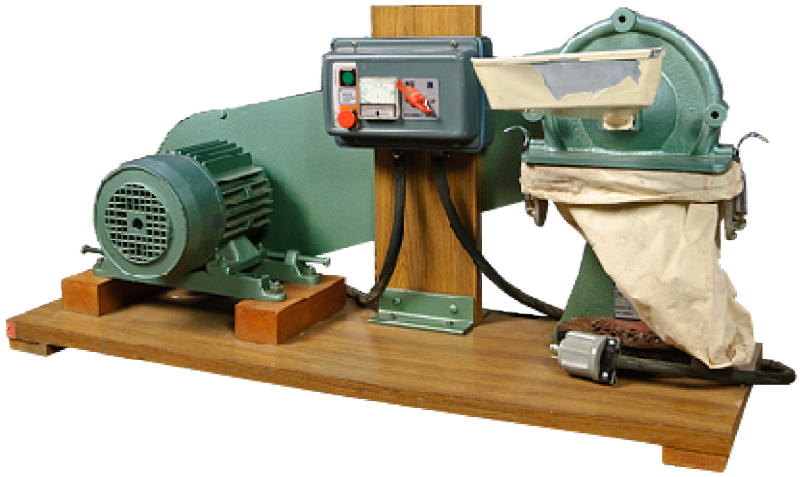


Figure 3.21 Milling machine used to grind the plant samples before being used for nutrient analysis

3.7.7.2 Nitrogen nutrient analysis

The LECO (LECO FP428, St Joseph, MI) (Figure 3.22a) and Elemantar (Elementar *Vario EL*, *Hanau*, *Germany)* (Figure 3.22b) were used to determine N contents from leaves dry samples.

The determination of N (NO_3) in liquid samples (emitters, leachates, irrigation water) was done using the Dionex BioLC (Dionex, California, USA) (Figure 3.22c).

3.7.7.3 Phosphorus nutrient analysis

Phosphorus (P): The plant samples were digested with nitric acid (HNO_3), sulphuric acid (H_2SO_4) and perchloric acid ($HClO_4$) mixture (9:4:1) as described by Winkleman et al., (1990). The absorbance was recorded on spectrophotometer (Libra 12, Biochrom) at 880 nm (Figure 3.22d).

3.7.7.4 Potassium nutrient analysis

Potassium (K): The plant samples were digested with nitric acid (HNO_3), sulphuric acid (H_2SO_4) and perchloric acid ($HClO_4$) mixture (9:4:1) as described by Winkleman et al., (1990). Potassium concentration in the digests was determined by flame photometer (Jenway PFP7) (Figure 3.22e).

3.7.7.5 Other nutrients analysis

Inductively coupled plasma emission spectroscopy (ICP-AES) (Figure 3.22f) was used to analyse other nutrients namely: Calcium (Ca), Magnesium (Mg), Sulfur (S), Iron (Fe), Manganese (Mn), Zinc (Zn), Copper (Cu), Boron (B) and Molybdenum (Mo).

3.8 Nutrient Treatment

The fertiliser used in the experiment was a pre-mixed Scotts Peters Professional water soluble fertiliser. The details of the nutrient constituents, including micro-nutrients as well as N, P, K of the fertilisers are given for each experiment. The technical analysis of each individual fertiliser formulations used in this study as provided by the manufacturer is presented in Appendix 5. The pre-mixed water soluble fertilisers were dissolved in water to achieve the desired treatment rates of Nitrogen, Phosphorus and Potassium in term of mg l^{-1} as required using the following formula in Eq. 2 (Boyle, 2009):

$$\text{Amount of fertilizer to make 1 volume of stock} = \frac{\text{Desired concentration in ppm} \times \text{Dilution factor}}{\text{\% of element in fertilizer} \times C} \quad (2)$$

C = Conversion constant (C=10 for conversion to gram $litre^{-1}$)
Dilution Factor = 100 (injector ratio of 1:100 was used in the study)

Different concentrations of nitrogen and potassium were applied in the experiments phosphorus level was maintained at 55mg l^{-1}, the recommended rate for bell pepper production (Calpas, 2002). The fertiliser calculation used to estimate the amount of N, P, and K for each fertiliser formulation can be found in Appendix 6.

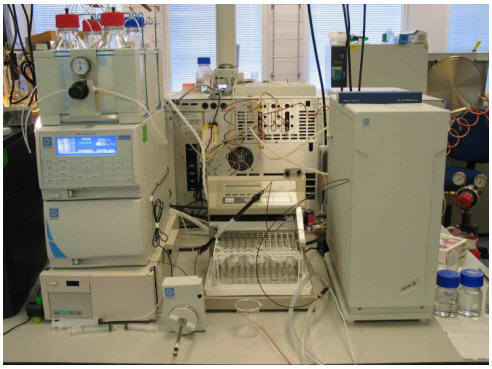
3.9 Statistical Analysis

Statistical analyses were carried out using MINITAB 15 statistical software. All data parameters were subjected to general linear model of analysis of variance (ANOVA) at the 95% ($p<0.05$) level of confidence by Tukey's test.

a

b

c



d

e

f

Figure 3.22 Instrument for mineral analysis: (a) Leco; (b) Elemantar; (c) Dionex; (d) Spectrophotometer; (e) Flame photometer; and (f) Inductively coupled plasma emission spectroscopy (ICP-AES)

Chapter 4

A greenhouse study of the effects of fertiliser concentration (N and K rates) at different growth stages on bell pepper production

4.1 Introduction

Bell pepper is one of the most popular and widely grown vegetable crops in the world. It responds well to fertiliser applications and is reported to have a high demand for NPK. Efficient use of fertilisers and water is highly critical to sustain agricultural production. However, because fertilisers applied by traditional methods (separate fertiliser and irrigation application) are generally not utilised efficiently by bell peppers (Hebbar et al., 2004), development of techniques and fertiliser regimes to improve efficiency is of paramount importance. Application of fertilisers with irrigation water (fertigation) has several advantages over traditional methods. By fertigation, the time and rate of fertiliser applied can be regulated precisely according to the plants' requirements. This will also ensure the application of the proper amount of N, P and K at the particular growth stage. This will improve the efficient use of fertiliser, decrease leaching and minimise environmental contamination (Singandhupe et al., 2003).

A plant differs in its nutrient requirements according to the type, the growth stage and the environmental condition under which it is grown (Ross, 1998). For fruiting fruit such as bell pepper, the plant goes through an initial vegetative stage, followed by flowering and fruit set phase and then a fruit development phase (Hoyos and Rodriguez-Delfin, 2007, HAIFA, 2011). Nutrient elements are taken up according to the plant demands at specific development stages (Andre et al., 1978), therefore phased applications of nutrients by fertigation may be particularly effective in greenhouse bell pepper. To supply adequate nutrition for optimum plant growth, the growth stage of development must be considered when adjustments to nutritional regimes are required. This requirement is attributed to the fact that nutrient concentrations in plant tissues and the demand for those nutrients fluctuate with the stage of plant development (Mills and Jones Jr, 1996).

Nutrients such as nitrogen (N) and potassium (K) were among the elements that affect the yield and quality of vegetables grown in soil-less cultivation (Johnson and

Decoteau, 1996). According to Miller (1975) and Leigh and Jones (1984), N is among the nutrients that has been manipulated by farmers due to the relations of N to reproduction development in peppers especially fruit quality. While K is the important aspect to maintain N metabolism in plants and as an activator for a number of enzymes, mostly those involved in photosynthesis and respiration process (Hopkins and Huner, 2004). Increased N has been shown to increase the number and size and overall yield (Johnson and Decoteau, 1996) while increased K rate increases the number of fruits per plant and seed yield (Osman et al., 1984). The proper use of N and K fertilisers in the soil-less culture and fertigation are important due to their relations to the stage of plant growth and environmental conditions (Grattan and Grieve, 1999). Fertilisation above plant requirements not only increases the costs but is also detrimental to the environment such as salt accumulation in soil and ground water contamination due to leaching (Villa-Castorena et al., 2003). While nutrients are in short supply, depression of growth and yield can occur (Mengel and Kirkby, 2001). For that reason, it is necessary to carry out studies on different N and K concentrations in the nutrient solution, using fertigation technique under greenhouse condition for higher production of bell pepper and to estimate the potential yield.

Growth pattern and fertiliser management of fertigated bell pepper inside a greenhouse are quite different compared to the open field and should be thoroughly investigated. More research is needed to study not only growth rate, nutrient uptake and yield response, but also to study the effect of fertilisation regimes on these changes over different growth stages. This will be required to develop a rational fertigation scheduling for bell pepper in greenhouse conditions. Relatively little is known about the effects of fertigation applied at different growth stages with varying N and K concentrations.

The hypothesis of this investigation was that increasing N from 126 to 256 and 385mg l^{-1} and increasing K from 106 to 214 and 321mg $^{-1}$ would increase growth and yield of bell pepper. The key component investigated was that different growth stages of bell pepper (vegetative, flowering and fruiting stages) would have unique nutritional needs and consequently different fertilisation regimes. Matching the nutrient supply to the plant's nutritional needs would increase growth and yield whilst eliminating application of excess fertiliser.

4.2 Materials and Methods

A detailed description on the methodology and materials employed in this experiment can be found in Chapter 3.

4.2.1 Experimental condition

The experiment was conducted in the summer to autumn season of 2009 in a 48m^2 greenhouse situated at Cockle Park farm of Newcastle University (Latitude: 55.2137, Longitude: 1.6841). Greenhouse thermometer and evaporating pan inside the greenhouse monitored the daily maximum and minimum temperature and evaporation rate respectively. Daily minimum and maximum air temperatures ranged from 8^oC to 16^oC and 18^oC to 49^oC respectively and evaporation rate ranged from 0.1 to 5mm throughout the experiment as presented in Figure 4.1. Evaporimeter data was also collected to provide an indication of the daily fluctuations of growing conditions inside the greenhouse. There was no attempt to monitor water demand in order to adjust supply.

4.2.2 Crop details

Seeds of "California Wonder" hybrid were germinated in rockwool plugs (Grodan) on May 8, 2009. At four true-leaf stage (23 days after seedling) bell pepper plants were transplanted to rockwool 10x10cm blocks (Grodan). The plants in the 10x10cm blocks were finally transferred to 1m rockwool slabs (Grodan) on July 11, 2009 in the greenhouse at a plant density of 3 plants m^{-2}. Plants were grown under natural light conditions; ventilation was provided automatically.

4.2.3 Experimental design and treatments

Three different pre-mixed fertiliser formulations (Scotts Peters Professional water soluble fertiliser) were used: 20N-20P_2O_5-20K_2O; 20N-10P_2O_5-20K_2O; and 21N-07P_2O_5-21K_2O to provide NPK concentrations of (F1) 126-55-106; (F2) 256-55-214; and (F3) 385-55-321mg l^{-1} respectively. P concentration (55mg l^{-1}) and the ratio of N:K concentrations (1.2:1.0) were kept constant whilst N and K concentration trebled from F1 to F3. Fertigation regimes were applied according to plant growth stages: (S1) 1 to 44-DAT, (S2) 45 to 69-DAT, and (S3) 70 to 122-DAT stage. P concentration was set at 55mg l^{-1} as it is the recommended rate for bell pepper production (Calpas, 2002). The experiment comprised of seven treatments replicated three times in a completely

randomised design. Each experimental unit consist of one rockwool slab containing 3 plants (Figure 4.2).

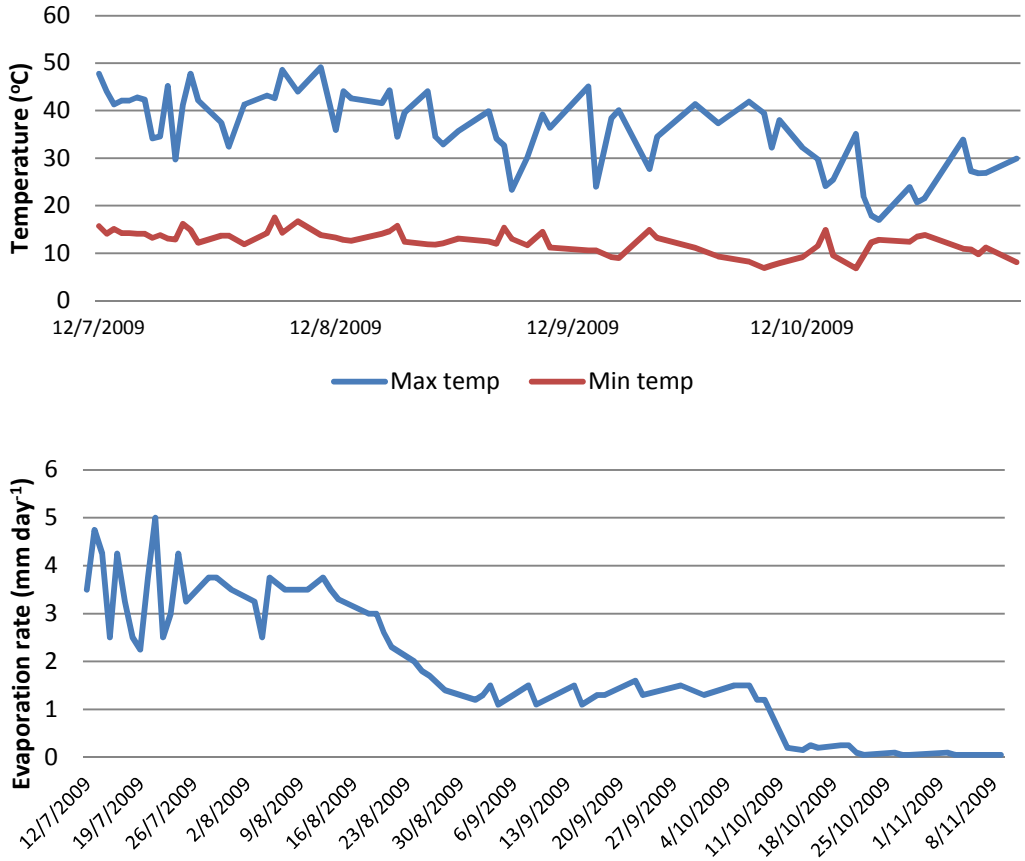


Figure 4.1 Temperature and evaporation inside the greenhouse during the experiment

In six treatments, the N and K concentrations changed from one growth stage to another to provide different planes of nutrition during growth and development. The combinations were (1) F1/S1, F2/S2, F3/S3; (2) F1/S1, F3/S2, F2/S3; (3) F2/S1, F1/S2, F3/S3; (4) F2/S1, F3/S2, F1/S3; (5) F3/S1, F1/S2, F2/S3; (6) F3/S1, F2/S2, F1/S3. Different planes of N and K nutrition were applied at different stages because the plant nutrient demand is expected to be different at each stage. Treatment 7 was the control whereby the plants received constant inputs of N and K throughout the season. Diagrammatic representation of fertigation treatments to indicate how the type and level of nutrients applications changed over the three growth stages is shown in Figure 4.3.

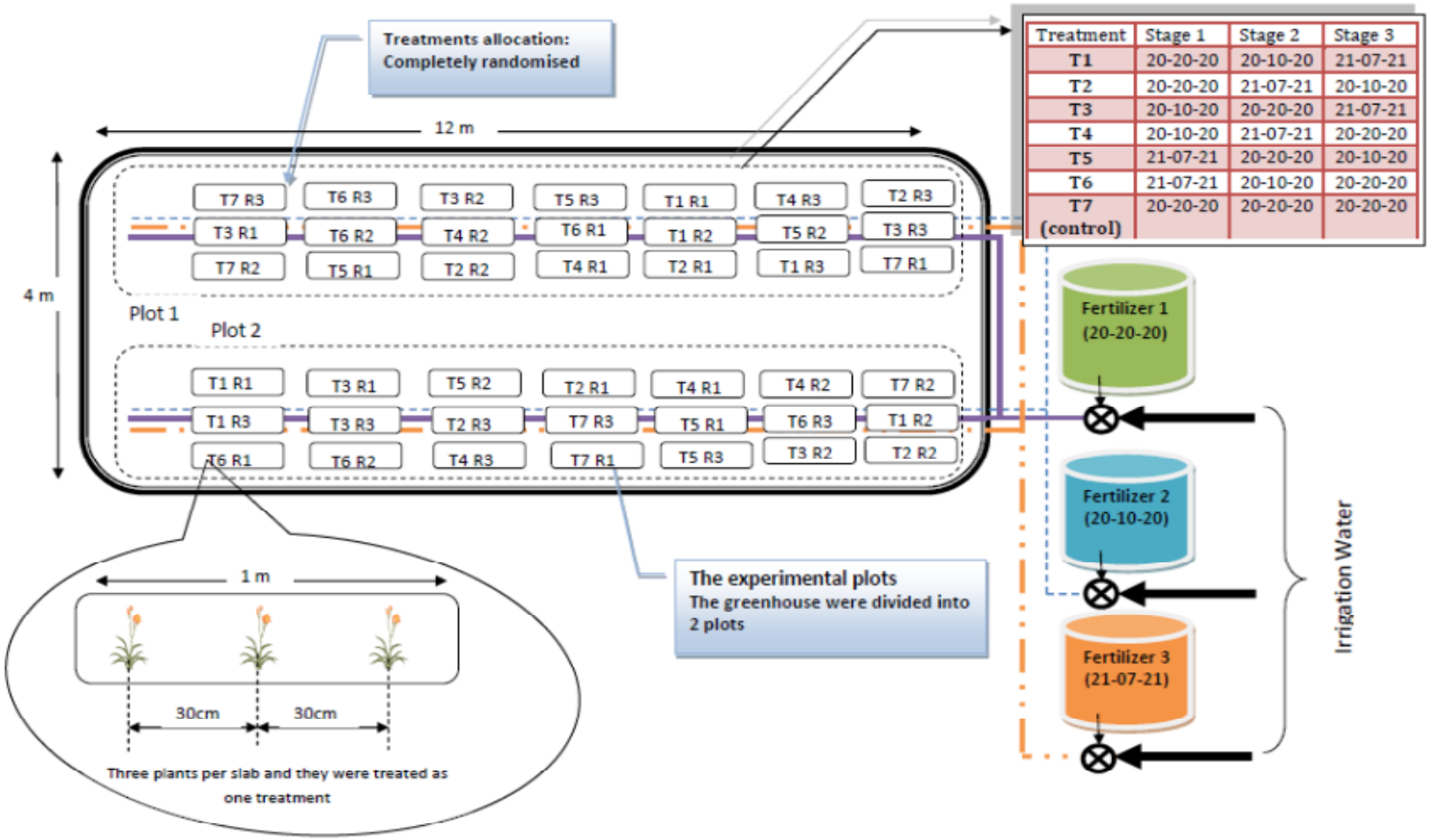


Figure 4.2 Layout of the experiment

The plants were supported by twine attached to a horizontal wire 1.8 m above the plant row and trained to two stems ("V" system) per plant by pruning auxiliary shoots. A drip irrigation system equipped with an individual emitter per plant was used to supply nutrient solution automatically at a rate of 0.8, 1.0 and 1.5 L (for 5, 6 and 9 minutes respectively) to the plants per irrigation event at S1, S2 and S3 respectively. The drip emitters were placed 30cm apart. The drips had a discharge of 2 litres h^{-1}. The fertigation frequency was 5 irrigation events per day applied at 08:00; 10:00; 12:00; 14:00; and 16:00h. The fertiliser dosage was 100:1 or 1% which was achieved by using a fertiliser proportional injector (model: DI.1500, Dosatron International Inc.).

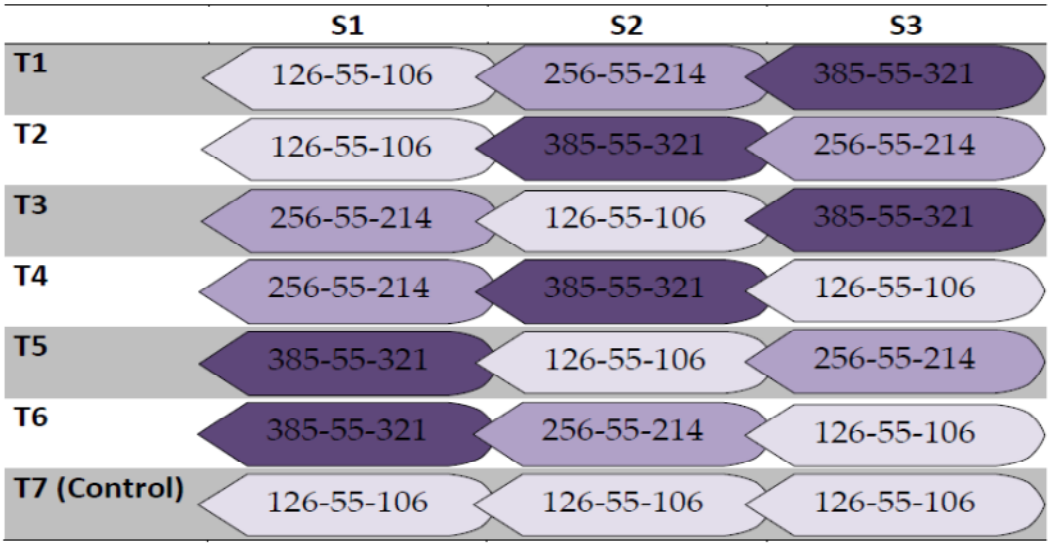


Figure 4.3 Diagrammatic representation of fertigation treatments. The colour scheme represents the concentration of the fertiliser at different stage, the concentration increases from light (low) to darker (high) colour.

4.2.4 Nutrient treatments

The fertiliser used in the experiment was a pre-mixed Scotts Peters Professional water soluble fertiliser. Three different fertilisers (N-P_2O_5-K_2O: 20-20-20; 20-10-20 and 21-07-21) were prepared at known concentration in separate stock tanks to achieve the desired (set) treatment rates of nitrogen (N), phosphorus (P) and potassium (K) in term of mg l^{-1} as shown in Table 4.1 using the suggested formula in Eq.(2) (Boyle, 2009). The calculation used to estimate the amount of nitrogen, phosphorus and potassium in each fertiliser formulation is in Appendix 6. Nutrient concentration of the irrigation water was included in determination of the final nutrient concentration.

$$Amount\ of\ fertilizer\ to\ make\ 1\ volume\ of\ stock\ = \frac{Desired\ concentration\ in\ ppm\ \times Dilution\ factor}{\%\ of\ element\ in\ fertilizer\ \times C} \quad (2)$$

C = Conversion constant (C=10 for conversion to gram litre^{-1})
Dilution Factor = 100 (injector ratio of 1:100 was used in the study)

Tap water was used to mix the fertiliser and for irrigation supply water having nutrients presented in Table 4.1 This is within range of the desirable concentration of nutrients in water for greenhouse production (Calpas, 2002). Samples of nutrient solution were collected from the drippers at different growth stages (S1, S2, and S3) and analysed for nutrient content.

Table 4.1 Nutrient content of irrigation water

Irrigation water	$N(NO_3)$	P	K	Ca	Mg	S	Fe	Mn	Zn	Mo
	mg l^{-1}									
	1.22	18.00	3.80	33.16	5.76	1.50	0.01	0.01	0.02	0.002

4.2.5 General methodology

The fertigation system was checked at the beginning of the experiment (April 23, 2009) to maintain a high degree of uniformity. This was to ensure that approximately the same amount of water and fertiliser was applied to all parts of the system to obtain maximum benefits. Volumetric method was used for computing the uniformity coefficient (Uc) of the fertigation system (Eq. (1)) (Mahajan and Singh, 2006) where q is the mean emitter discharge and Δq, the mean deviation of the emitter discharge from mean value.

$$Uc = 1 - \left(\frac{\Delta q}{q}\right) \quad (1)$$

The dripper uniformity was then compared with acceptability range of statistical uniformity of drip irrigation provided by American Society of Association Executives (ASAE): Standards of Conduct (Table 3.2) (Lesikar et al., 2004)

Samples of the leachate solutions were collected to monitor their pH, electrical conductivity (EC) and volume throughout the different stages of the study. The leachate solution was also collected to be analysed for its nutrient content. Plant height and stem

diameter were measured at 37-DAT (S1); 67-DAT (S2); and 102-DAT (S3). Leaf area of the destructively harvested plants was measured at the end of each growth stage (43-DAT, 72-DAT; and 126-DAT for S1, S2 and S3 respectively) using WinDIAS 3 image analysis system (Delta-T Devices, Cambridge, UK).

One plant (above ground parts, minus the roots) per experimental unit was taken at the end of each of the three plants' growth stages (S1: vegetative; S2: flowering; and S3: fruiting) at 43-DAT, 72-DAT; and 126-DAT respectively. The plants were separated into stem, leaf, and fruits and their weight determined. The harvested fruits were weighed, counted, and measured for length and diameter. Fruits with blossom end rot (BER) were also recorded. The plant's parts were dried at 80^{o}C in a ventilated oven for 24 hours before their dry weights were determined. Harvest index (HI) was also determined by dividing the oven dried mass of mature fruit by above ground dry weight.

The leaf chlorophyll concentration (SPAD units) was made in stage 1 (at 9, 16, 23, 30, and 37-DAT); stage 2 (at 51, 60, and 67-DAT) and stage 3 (at 74, 82, 88, 95, 102, and 115-DAT) on (i) apical leaves and (ii) bottom leaves using a Minolta chlorophyll metre SPAD-502. The selected bottom leaves were marked and all subsequent observations were made on the same leaves. Leaf gas exchange was measured on attached fully developed apical leaves at 31-DAT (S1); 58-DAT (S2); and 110-DAT (S3), one leaf per plant with an infrared gas analyser (IRGA) model LC*i* (ADC BioScientific Ltd, UK). Leaf, stem and fruit samples of bell pepper were collected at the end of different growth stages (43-DAT, 72-DAT; and 126-DAT for S1, S2 and S3 respectively).

4.3 Results and Discussions

4.3.1 Fertigation uniformity

The uniformity coefficient (Uc) of fertigation system used in the study was found to be 93.2% (Table 4.2) which is an excellent rating for drip irrigation uniformity when compared to statistical uniformity of drip irrigation provided by ASAE (Table 3.2). The high values of uniformity coefficient indicated excellent performance of the fertigation system in this study in supplying nutrient solution throughout the emitters during the experiment.

Table 4.2 Uniformity coefficient of the fertigation system (%)

Volume (5 minutes)		Mean discharge rate (q)		Mean deviation (Δq)	Uniformity coefficient (%)
Mean	SEM	Mean	SEM		
148.2	1.08	29.6	0.22	1.80	93.2

4.3.2 Nutrient solution mineral concentration

The actual concentration of nitrogen (N (NO_3)), phosphorus (P), potassium (K) and other micro-nutrients of the fertigation solutions are presented in Table 4.4, which also includes their electrical conductivity (EC) and pH details for each of the fertiliser formulations.

The actual nitrogen concentration was 2.9 to 6.3 % lower than the set value, while the actual phosphorus was 7.3 to 9.1 % lower than the set value. On the other hand, the potassium concentration was 2.1 to 5.4% higher than the set value. The lower concentration of nitrogen may have been due to the fact that the Dionnex measurement in this study was for nitrate (NO_3) concentration only. Further analysis for NH_4 (ammonium) may have resulted in a higher value for the N concentration but NH_4 was not assessed in this study. The technical analysis of the fertiliser as provided by the manufacturer showed that the concentration of N in each fertiliser formulation consisted of N-NO_3, N-NH_4 and N-Urea (details in Appendix 5). The lower N concentration may also have been due to the loss of nitrogen by volatization as gaseous ammonia or through denitrification (Prasad and Kumar, 2001). The possible explanation for less phosphorus might be the formation and precipitation as calcium phosphate (Dhakal et al., 2005). The possible reason for higher potassium is that it is not sufficiently soluble and readily taken by plants (Tiwari, 2003).

Table 4.3 Details of target amount of N, P and K in the fertigation solution

Fertiliser	Amount (g) in stock solution		Nutrients (mg l^{-1})		
	1 litre	20 litres	Nitrogen	Phosphorus	Potassium
20N-20P_2O_5-20K_2O (F1)	63.2	1264	126	55	106
20N-10 P_2O_5-20K_2O (F2)	127.9	2558	256	55	214
21N-07 P_2O_5-21K_2O (F3)	183.3	3666	385	55	321

Table 4.4 Actual amount of N, P and K and micronutrients in the fertigation solution, electrical conductivity (*EC*) and pH

Fertiliser	EC	pH	N (NO_3)	P	K	Ca	Mg	S	Fe	Mn	Zn	Cu	B	Mo
	dS m^{-1}		mg l^{-1}											
20N-20P_2O_5-20K_2O (F1)	0.923	6.5	118	51	112	33.82	8.07	1.01	1.61	0.45	0.11	0.15	0.29	0.03
20N-10 P_2O_5-20K_2O (F2)	1.126	6.4	241	50	223	36.08	6.41	0.88	1.38	0.44	0.10	0.14	0.33	0.02
21N-07 P_2O_5-21K_2O (F3)	1.385	6.3	374	51	328	33.25	29.31	3.21	2.40	0.83	0.19	0.25	0.44	0.04

Table 4.5 NPK concentration in leaf, stem and fruit at final harvest (S3)

Treatment	Nitrogen			Phosphorus			Potassium		
	Leaves	Stem	Fruit	Leaves	Stem	Fruit	Leaves	Stem	Fruit
	mg g^{-1} dry matter								
T1	66.5	53.4	58.3	1.5	1.1	1.4	60.2	64.0	68.1
T2	65.3	53.1	55.7	1.6	1.0	1.3	59.1	62.3	65.6
T3	63.2	50.2	54.4	1.4	1.1	1.4	57.4	60.5	62.5
T4	60.3	48.0	52.2	1.6	1.1	1.2	56.8	59.2	60.4
T5	61.6	46.3	52.0	1.6	1.0	1.3	55.1	58.0	61.6
T6	59.4	44.9	53.1	1.4	1.0	1.4	55.5	59.8	59.8
T7 (control)	57.6	43.0	51.2	1.6	1.0	1.2	53.5	55.6	58.3

Values of means in each column. Results were not significantly different between treatments.

4.3.3 Nutrient analysis

Table 4.5 shows the nitrogen (N), phosphorus (P) and potassium (K) concentration respectively in leaf, stem, and fruit of bell pepper at final harvest (S3). The stem contained the lowest proportion of nitrogen and phosphorus, while leaf contained the lowest proportion of potassium. Similar pattern was observed in first and second stage (details in Appendix 1). A similar observation was also noted by other researchers (Hegde, 1987).

4.3.3.1 Nitrogen

There were no significant differences in the nitrogen concentration in the leaves in the first and second stage (details in appendix). In the third stage, Treatment 1 (66.5mg g^{-1}) registered the highest value among the treatments and higher than the control (Treatment 7; 57.6mg g^{-1}) by 13%. This was followed by Treatment 2 (65.3mg g^{-1}) which was higher than the control (Treatment 7) by 12%. However the differences were not significant (Table 4.5).

Nitrogen concentration in leaves was expressed as means over three harvests with respect to different fertiliser formulations (F1, F2 and F3), the concentration of N in leaves declined in leaves (Figure 4.4). The N in leaves at first stage (S1) for fertiliser 1 (126-55-106 mg l^{-1}) was 65.9 mg g^{-1} decreasing to 60.7 mg g^{-1} at second stage (S2) and to 57.8 mg g^{-1} at third stage (S3). Similar patterns were observed in fertiliser 2 (256-55-214 mg l^{-1}) and fertiliser 3 (385-55-321 mg l^{-1}).

Nitrogen concentration in the leaves increased as the fertiliser level increased. At first stage (S1), N concentration in the leaves increased from 65.9 mg g^{-1} to 68.9 mg g^{-1} and to 70.4 mg g^{-1} as the fertiliser level increased from fertiliser 1 (F1) to fertiliser 2 (F2) and finally fertiliser 3 (F3) (Figure 4.4). Similar patterns were observed in second (S2) and third (S3) growth stages.

No significant differences in the nitrogen concentration in the leaves with respect to different fertiliser formulations within the three growth stages were detected (Figure 4.4). However over the three sampling periods, the concentration of N was significantly ($p \leq 0.05$) higher in the first stage than in the third stage for all fertiliser formulations.

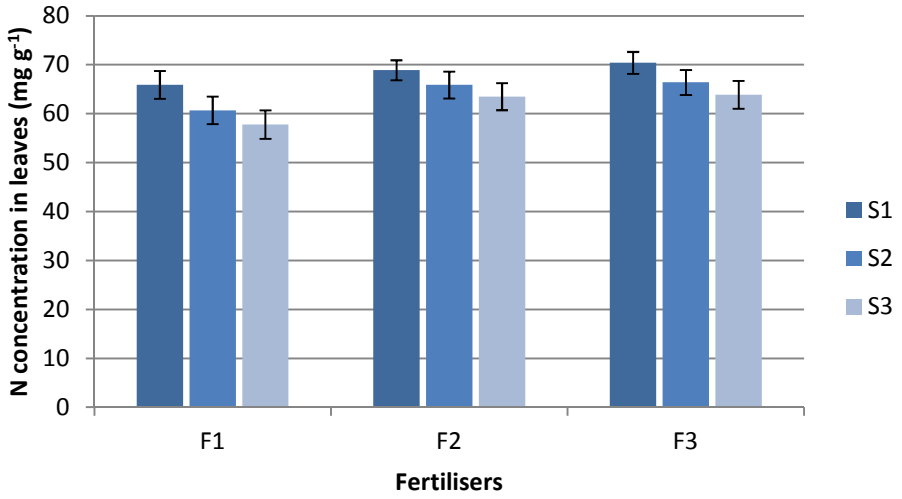


Figure 4.4 Nitrogen concentrations in leaves (mg g^{-1}) as a function of different fertiliser formulations and plant development stage

The mean concentration of N in the leachate at all three stages of development increased with increasing fertiliser concentration (Table 4.6). Nitrogen concentration in leachates expressed as means over three harvests with respect to different fertiliser formulations (F1, F2 and F3), is shown in Figure 4.5. The N concentrations in the leachate for fertiliser 1 (F1) was highest at first stage (S1), 61.0mg l^{-1} and third stage (S3), 67.3mg l^{-1} than at second stage (S2), 53.3mg l^{-1}. Similar patterns were observed in fertiliser 2 (F2) and fertiliser 3 (F3). Nitrogen concentration in the leachate was highest in treatments subjected to fertiliser 3 (F3) followed by fertiliser 2 (F2), and the lowest was those treatments subjected to fertiliser 1 (F1). All the differences were significantly ($p \leq 0.01$) different (Figure 4.5).

Table 4.6 Nitrogen concentration of the leachate as a function of different treatments and plant development stage

Treatment	S1	S2	S3
	Leachate N concentration (mg l^{-1})		
T1	63.1c	105.8b	181.2a
T2	60.4c	179.3a	140.8b
T3	125.3b	52.1c	185.0a
T4	136.0b	180.5a	70.4c
T5	185.4a	55.1c	135.8b
T6	189.2a	102.4b	69.5c
T7 (control)	59.6c	52.7c	62.1c

Means in each column, followed by different letters are significantly different at $p \leq 0.01$ by Tukey's test

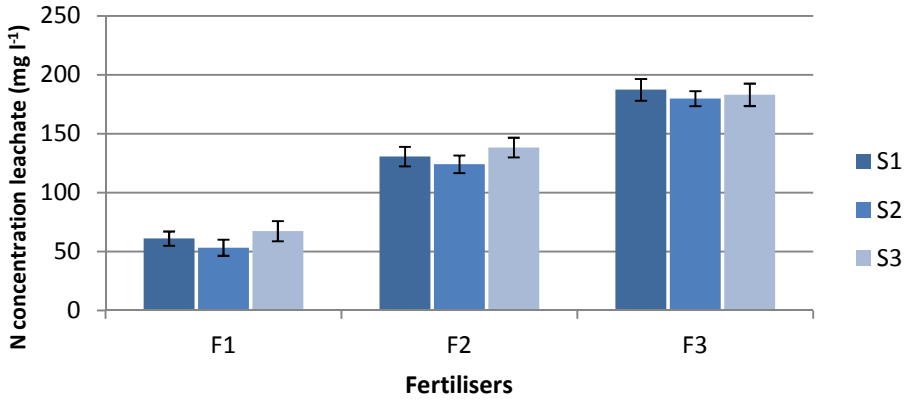


Figure 4.5 Nitrogen concentrations of the leachate as a function of different fertilisers and plant development stage

4.3.3.2 Phosphorus

Over all three growth stages, the mean concentration of phosphorus (P) in tissues decreased as plant development progressed (Figure 4.6). The P in leaves at first stage (S1) for treatment 1 (T1) was 2.0mg g^{-1} decreasing to 1.8mg g^{-1} at second stage (S2) and to 1.5mg g^{-1} at third stage (S3). Similar patterns were observed in other treatments (T2, T3, T4, T5, T6, and T7). Phosphorus concentration in tissues at each growth stage did not differ significantly between treatments which can be attributed to the fact that P concentrations were kept the same (55mg l^{-1}). However over the three sampling periods, the concentration of P was significantly ($p \leq 0.05$) higher in the first stage than in the third stage for all treatments (Figure 4.6).

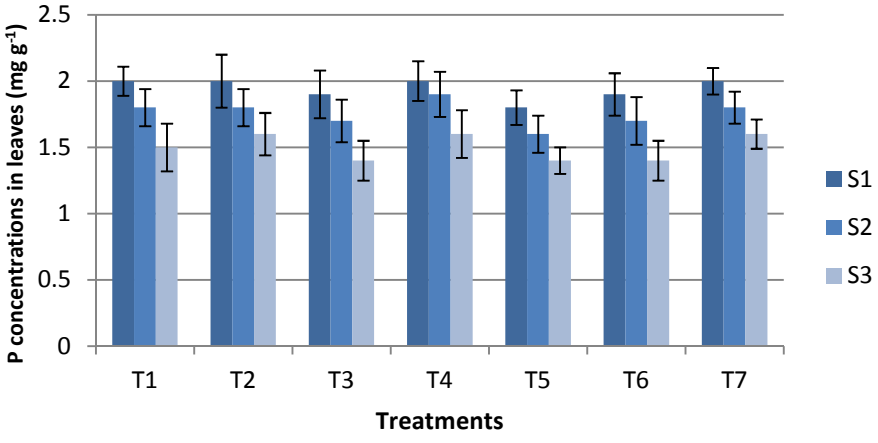


Figure 4.6 Phosphorus concentrations in leaves (mg g^{-1}) as a function of different treatments and plant development stage

The mean concentration of P in the leachate at all three stages of development decreased as plant development progressed (Table 4.7 and Figure 4.7). The P concentrations in the

leachate for treatment 1 (T1) at first stage (S1) was 20.5mg l^{-1} decreasing to 19.5mgl^{-1} at second stage (S2) and to 17.5mg l^{-1} at third stage (S3). Similar patterns were observed in other treatments (T2, T3, T4, T5, T6, and T7). No significant differences were observed in the amount of phosphorus in the leachate among the treatments (Table 4.7).

Table 4.7 Phosphorus concentration of the leachate as a function of different treatments and plant development stage

Treatment	S1	S2	S3
	Leachate P concentration (mg l^{-1})		
T1	20.5	19.5	17.5
T2	20.6	20.1	18.1
T3	20.7	19.3	17.7
T4	20.9	19.9	17.4
T5	20.6	19.2	17.9
T6	20.7	19.4	18.3
T7 (control)	20.8	19.2	17.6

Values are the mean in each column. Results were not significantly different between treatments

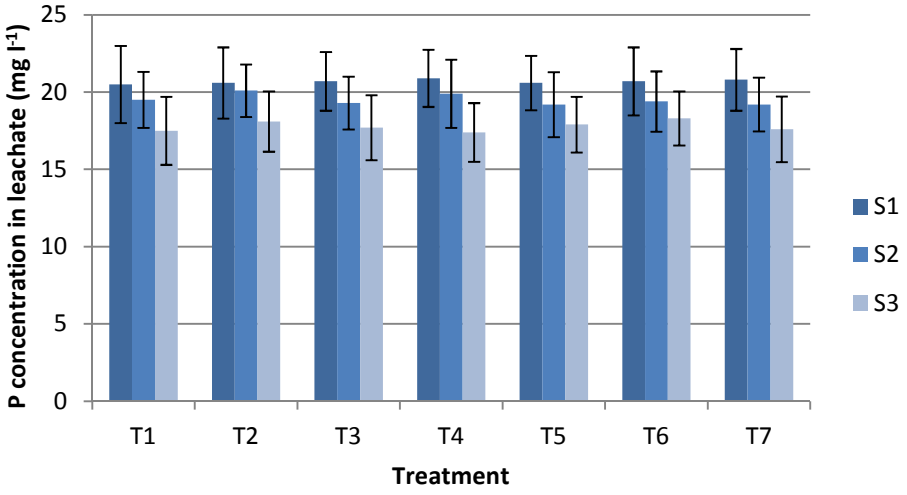


Figure 4.7 Phosphorus concentrations of the leachate as a function of different treatments and plant development stage

4.3.3.3 Potassium

There were no significant differences in the potassium concentration in the leaves in the first and second stage (details in appendix). In the third stage, Treatment 1 (60.2mg g^{-1}) registered the highest value among the treatments and higher than the control (Treatment 7, 53.5mg g^{-1}) by 11%. This was followed by Treatment 2 (59.1mg g^{-1}) which was higher than the control (Treatment 7) by 9%. However the differences were not significant (Table 4.5).

Potassium (K) concentration in leaves expressed as means over three harvests with respect to different fertiliser formulations (F1, F2, and F3), the concentration of K in the leaf tissues was greatest during the vegetative growth stage (S1) and flowering initiation stage (S2) and declined as plant maturity progressed (Figure 4.8). The concentration of K in leaf peaked at S2 and was lowest at S3. The K in leaves at first stage (S1) for fertiliser 1 (126-55-106 mg l^{-1}) was 68.3mg g^{-1} and peaked at second stage (S2) at 69.8mg g^{-1} and then decreased to 52.3mg g^{-1} at third stage (S3). Similar patterns were observed in fertiliser 2 (256-55-214mg l^{-1}) and fertiliser 3 (385-55-321mg l^{-1}).

Potassium concentration in the tissues increased with increasing levels of fertiliser concentration. At first stage (S1), K concentration in the leaves increased from 68.3mg g^{-1} to 68.5mg g^{-1} and to 70.9mg g^{-1} as the fertiliser level increased from fertiliser 1 (F1) to fertiliser 2 (F2) and finally fertiliser 3 (F3). Similar patterns were observed in second (S2) and third (S3) growth stages. No significant differences in the potassium concentration in the leaves with respect to different fertiliser formulations within the three growth stages were detected (Figure 4.4). However over the three sampling periods, the concentration of K was significantly ($p \leq 0.05$) higher in the first and second stage than in the third stage for all fertiliser formulations.

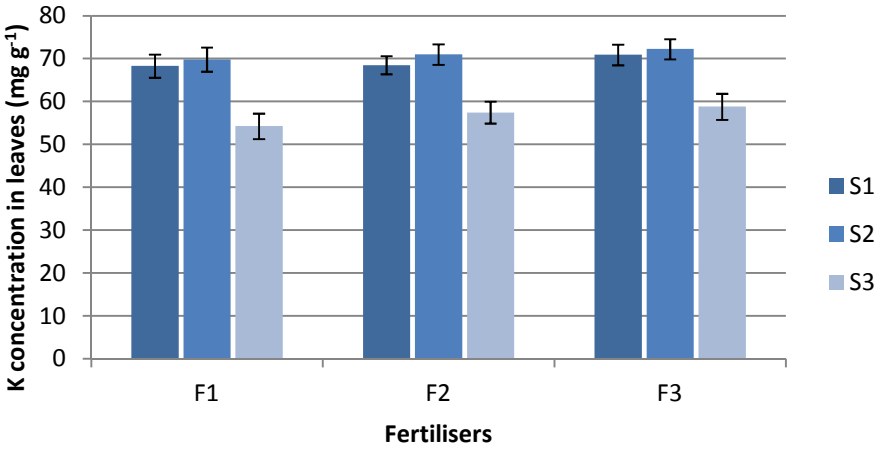


Figure 4.8 Potassium concentrations of the leaves (mg g^{-1}) as a function of different fertilisers and plant development stage

The mean concentration of K in the leachate at all three stages of development increased with increasing fertiliser concentration (Table 4.8). Potassium concentration in the leachate was highest in treatments fertiliser 3 (F3) followed by fertiliser 2 (F2), and lowest in treatments fertiliser 1 (F1). All the differences were significant ($p \leq 0.01$)

(Figure 4.9). Potassium concentration in leachates expressed as means over three harvests with respect to different fertiliser formulations (F1, F2 and F3), decreased as time progressed (Figure 4.9). The K concentrations in the leachate for fertiliser 1 (F1) were higher at first stage (S1) with 52.5mg l^{-1} than at second stage (S2) with 49.2mg l^{-1} or third stage (S3) with 45.5mg l^{-1} (Figure 4.9). Similar patterns were observed in fertiliser 2 (F2) and fertiliser 3 (F3). All the differences were significantly ($p \leq 0.01$) different (Figure 4.9).

Table 4.8 Potassium concentration of the leachate as a function of different treatments and plant development stage

Treatment	S1	S2	S3
	Leachate K concentration (mg l^{-1})		
T1	51.8c	97.7b	129.2a
T2	52.6c	133.6a	93.8b
T3	98.7b	45.5c	115.6a
T4	97.3b	134.0a	41.5c
T5	149.8a	51.8c	90.2b
T6	153.1a	93.1b	49.7c
T7 (control)	53.0c	50.3c	45.3c

Means in each column, followed by different letters are significantly different at $p \leq 0.01$ by Tukey's test

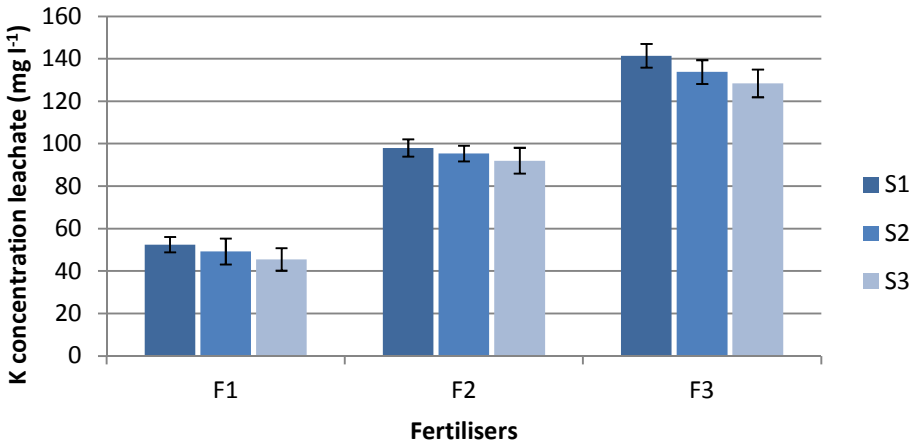


Figure 4.9 Potassium concentrations of the leachates as a function of different fertilisers and plant development stage

4.3.3.4 Other nutrients

The concentration of micro-nutrients in the fertiliser treatments varied considerably (Table 4.4). Therefore, it was expected that plant growth might be affected by the various level of micro-nutrients as well as NPK. However there were no indications that the plants exhibited micronutrient deficiency or toxicity through: (i) visual inspection of

the plants in the greenhouse, and (ii) nutrient analysis of leaves (Table 4.9). The leaf nutrient analysis showed that plants in each treatment were within the micronutrient ranges considered necessary for bell pepper (Hochmuth, 2003a) (details in Appendix 7).

Table 4.9 Mineral concentrations in leaves at final harvest in bell pepper as influenced by varying N and K rates

Treatment	Micronutrient concentration (mg g^{-1})							
	Ca	Mg	Fe	Mn	Zn	Cu	B	Mo
T1	0.198	0.069	0.030	0.033	0.029	0.006	0.025	0.0001
T2	0.201	0.062	0.032	0.034	0.027	0.006	0.023	0.0001
T3	0.203	0.075	0.032	0.035	0.028	0.006	0.024	0.0001
T4	0.213	0.079	0.030	0.031	0.030	0.005	0.022	0.0001
T5	0.183	0.073	0.033	0.033	0.031	0.005	0.023	0.0001
T6	0.178	0.066	0.032	0.034	0.032	0.006	0.022	0.0001
T7 (control)	0.235	0.056	0.033	0.031	0.031	0.005	0.021	0.0001

4.3.4 Plant growth characteristics

Plant growth parameters (plant height, stem diameter and leaf area) shown in Figures 4.10, 4.11 and 4.12 respectively. Bell pepper plant height and stem diameter were recorded at 37-DAT (S1); 67-DAT (S2); and 102-DAT (S3), while leaf area was recorded at the end of each growth stage (44-DAT (S1), 69-DAT (S2), and 122-DAT (S3)). No marked variations in plant height, stem diameter and leaf area were exhibited by all treatments in the first and second stage (details in Appendix 1). However, the third stage data showed significant differences ($P \leq 0.05$) generally in favour Treatment 1 (126-55-106; 256-55-214; 385-55-321mg l^{-1} NPK) and Treatment 2 (126-55-106; 385-55-321; 256-55-214mg l^{-1} NPK) outgrowing the T7 (control, receiving same fertiliser concentration, 126-55-106mg l^{-1} NPK, throughout the season).

4.3.4.1 Plant height

Figure 4.10 shows that Treatment 1 (43.3cm) registered significantly ($p \leq 0.05$) higher plants over Treatment 7 (control, 35.2cm) by 19% (8.1cm). Plant height did not show any significant difference among Treatment 2 (126-55-106; 385-55P-321; 256N-55-214mg l^{-1} NPK); Treatment 3 (256-55-214; 126-55-106; 385-55-321mg l^{-1} NPK); Treatment 4 (256-55; 385-55-321; 126-55-106mg l^{-1} NPK); Treatment 5 (385-55-321; 126-55-106; 256-55-214mg l^{-1} NPK) and Treatment 6 (385-55-321-; 256-55-215; 126-55-106mg l^{-1} NPK).

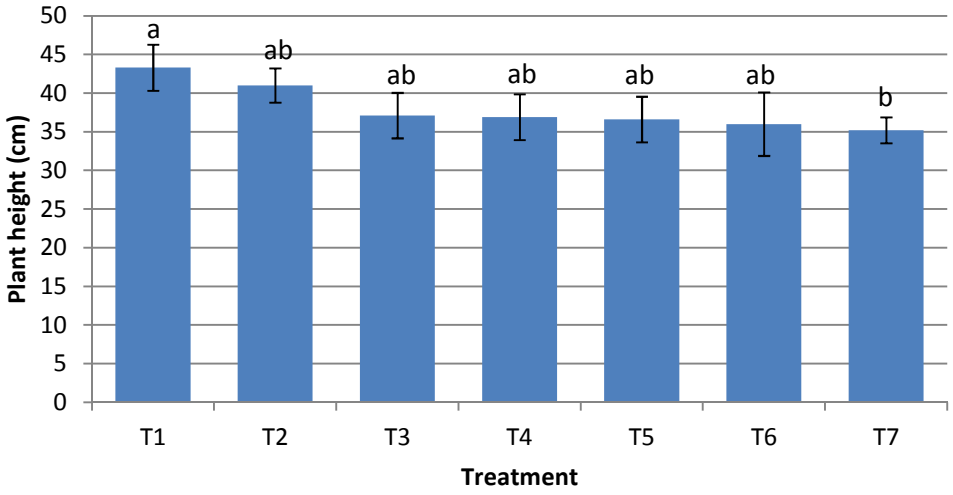


Figure 4.10 Mean plant height as affected by different treatments at final harvest. Significant difference ($p \leq 0.05$) by Tukey's test between treatments are indicated by different letters

4.3.4.2 *Stem diameter*

Figure 4.11 gives mean bell pepper plant height records at final harvest. No significant differences were recorded between treatments. However, Treatment 1 (16.7mm) exhibited thicker stems followed by Treatment 2 (15.5mm) compared with other treatments and outgrowing Treatment 7 (control, 14.6mm) by 2.1 millimetres (13%) and 0.9 millimetres (6%).

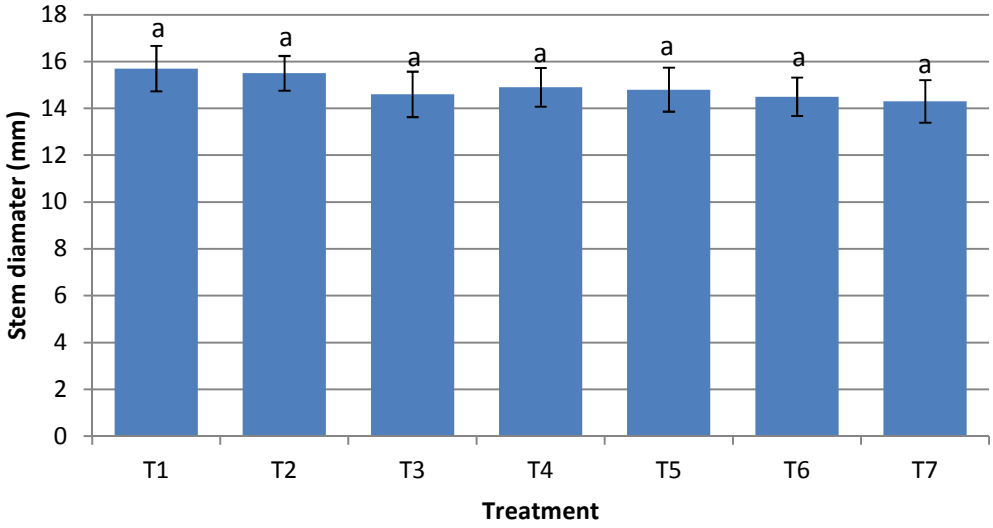


Figure 4.11 Mean plant stem diameter as affected by different treatments at final harvest. No significant differences were observed between the treatments.

4.3.4.3 Leaf area

Treatment 1 (4251cm^2) exhibited greater (P≤0.05) leaf surface area over Treatment 7 (control, 3086cm^2) by 1166 cm^2 (27%) at final harvest (Figure 4.12). This was followed by Treatment 2 (4038cm^2) having significantly greater (p≤0.05) leaf area over the control (Treatment 7) by about 23%. There were no significant differences among other treatments (T3-T6).

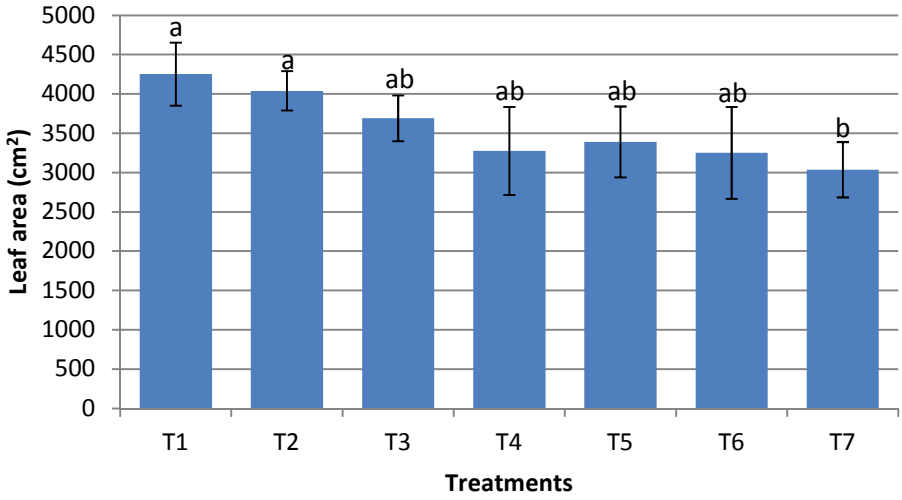


Figure 4.12 Mean leaf area as affected by different treatments at final harvest. Significant difference (p≤0.05) by Tukey's test between treatments are indicated by different letters

4.3.5 Yield parameters

4.3.5.1 *Yield*

Fertigation with gradual increase in fertiliser concentration (T1-356.9g; 126-55-106; 256-55-214; and finally 385-55-321 mg l^{-1} NPK) significantly increased (P≤0.05) fruit yield per plant over the other treatments including control (T7-297.8g) (Table 4.10) by 17%. This was followed by Treatment 2 (345.3g; 126-55-106; 385-55-321 and finally 256-55-214 mg l^{-1} NPK) which also registered significantly (P≤0.05) higher yield over the control (Treatment 7) by 14% (Table 4.10).

This increase can be attributed to more fruits per plant in Treatment 1 and Treatment 2 over the control (Treatment 7). Treatment 1 (8.9 fruits plant^{-1}) and Treatment 2 (8.4 fruits plant^{-1}) had 12% and 7% more fruits per plants respectively than the control (T7, 7.8 fruits plant^{-1}). However, there were no significant differences among other

treatments in number of fruits per plant. This can be attributed to the removal of some fruit buds by pruning to control the number of fruits set per plant to ensure that they achieved marketable size. In terms of quality, fruits from Treatment 1 were bigger than in the control (T7) in length (38.2mm) and width (54.8mm), by 22% and 14% respectively (Table 4.8). This is followed by Treatment 2 which was bigger in fruit length (34.7mm) and diameter (52.5mm) by 14% and 10% respectively over the control. However no significant differences were observed among the other treatments.

There were no significant differences in the number of fruits affected by blossom-end rot (BER) between the treatments (Table 4.10). Fruits with BER ranged between 21 and 28% of total fruit yield which corresponds with general estimates of the economic loss of bell pepper due to BER in the range of 20-40% (Silber, 2008). This result would indicate that levels of N and K did not influence the occurrence of BER in bell peppers. Previous studies have associated the incidence of BER in bell peppers with various stress conditions such as high salinity, high air temperatures and low air humidity, water stress, high ammonium/nitrate and high K/Ca ratios (Silber et al., 2005).

4.3.5.2 *Dry matter partitioning*

Yield is a complex phenomenon and partitioning of dry matter is an important process that causes variations in yield (Antony and Singandhupe, 2004). Figure 4.13 shows the percentage of dry matter production of bell pepper for Treatment 1 at various growth stages. Similar trends were found in other treatments (T2-T7).

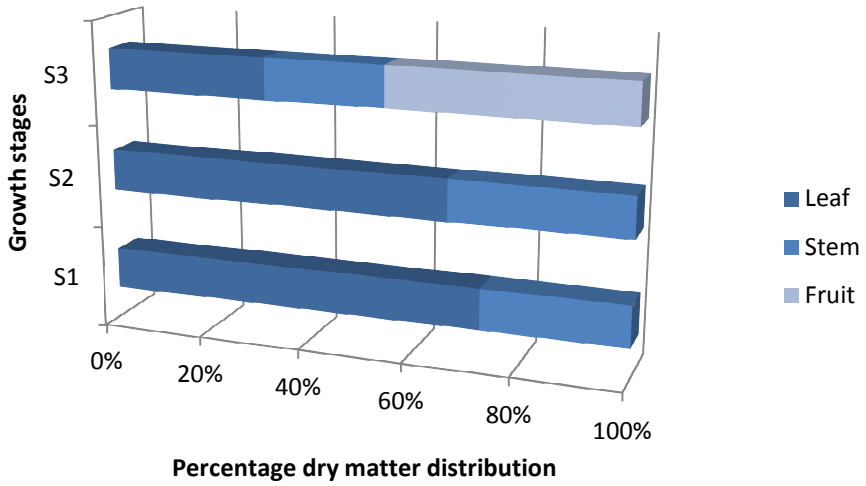


Figure 4.13 Percentage of dry matter distribution in bell pepper (Treatment 1)

Table 4.10 Yield parameters in bell pepper as influenced by varying N and K rates at final harvest

Treatment	Total Fresh Yield (kg)	Fruits (g plant^{-1})	Fruit number plant^{-1}	Fruit with BER plant^{-1}	% of fruits with BER plant^{-1}	Fruit quality	
						Fruit width (mm)	Fruit length (mm)
T1	1.07a	356.9a	8.9	1.8	23.4	54.8	38.2
T2	1.04a	345.3a	8.4	2.1	25.0	52.5	34.7
T3	0.98ab	327.4ab	8.2	1.9	24.7	50.7	33.5
T4	0.95ab	315.7ab	8.2	2.4	27.6	45.7	28.9
T5	0.93b	309.5ab	8.2	1.7	20.7	49.3	31.2
T6	0.90b	301.3ab	8.3	2.3	26.4	50.4	30.7
T7 (control)	0.89b	297.8b	7.8	1.8	23.1	47.0	29.8

Means in each column, followed by different letters are significantly different at p≤0.05 by Tukey's test

Table 4.11 Effects of varying N and K rates on biomass production, partitioning and harvest index (HI) of bell pepper.

Treatment	Dry weight (g plant^{-1})										HI
	S1			S2			S3				
	Leaves	Stem	TDM	Leaves	Stem	TDM	Leaves	Stem	Fruits	TDM	
T1	15.5	5.8	21.3	19.3	9.7	29.0	23.5a	17.1	33.6a	74.2a	45.2a
T2	15.3	6.1	21.3	17.8	9.8	27.6	23.2a	16.8	31.5a	71.5a	44.1a
T3	16.2	6.7	22.9	16.2	9.2	25.4	22.1ab	16.5	26.9ab	65.5ab	41.1b
T4	15.3	6.1	21.4	16.0	8.9	24.8	22.8ab	16.9	26.7ab	66.4ab	40.2b
T5	16.2	6.3	22.4	16.3	8.2	24.5	23.3ab	15.7	26.8ab	65.8ab	40.7b
T6	15.8	6.9	22.7	16.3	8.3	24.6	22.7ab	16.3	26.2ab	65.2ab	40.2b
T7 (control)	15.3	6.0	21.3	15.8	7.8	23.6	21.2b	15.2	24.6b	61.0b	40.3b

Means in each column, followed by different letters are significantly different at p≤0.05 by Tukey's test

Accumulation of dry matter by bell pepper was slow in the first two stages and then increased markedly as the fruiting stage began (Figure 4.13) as also observed by other researchers (Marcussi et al., 2001). In the early stages (S1 and S2) dry matter is accumulated mostly in the leaves followed by the stem. Dry matter accumulated in the leaves decreased in stage 3 which can be attributed to allocation of dry matter in fruit. The leaf dry matter decreased as a proportion of total dry matter as growth progressed from 70-73% (S1) to 64-68% (S2); and finally 30-36% (S3). The stem dry matter increased in stages 1 and 2 which contributed 27 to 30% and 28 to 38% respectively; but decreased in stage 3, to 22 to 26% of the total dry weight of bell pepper (Table 4.11). The decrease in dry matter accumulation in the leaves and stem at stage 3 can be attributed to a switch of dry matter allocation to fruit formation which contributed 40 to 48% of the total dry matter production.

The total dry matter production (Table 4.11) was significantly higher ($P \leq 0.05$) in Treatment 1 (which provided gradual increase of N and K through the three growth stages) in the third stage. This was followed by Treatment 2 (126-55-106; 385-55-321 and finally 256-55-214mg l^{-1} NPK). There were no significant differences in the first and second stages. In the third stage Treatment 1 at 74.2g $plant^{-1}$ outyielded Treatment 7 (control) at 61.0g $plant^{-1}$ which was an increase of 18%. This was followed by Treatment 2 (71.5 g $plant^{-1}$) which was significantly higher ($P \leq 0.05$) than the control (Treatment 7) by about 15% at stage 3. However the total dry weight did not differ significantly among Treatment 3 (126-55-106; 385-55-321; 256-55-214mg l^{-1}), Treatment 4 (256-55-214; 385-55-321; 126-55-106mg l^{-1}), Treatment 5 (385-55-321; 126-55-106; 256-55-214mg l^{-1}) and Treatment 6 (385-55-321; 126-55-106; 126-55-106mg l^{-1}). The difference in the dry matter production due to different treatments can be ascribed to the leaf area production (Figure 4.12). Significantly ($P \leq 0.05$) higher leaf area was recorded in the third stage in Treatment 1 and Treatment 2 over control (Treatment 7) in the third stage. Higher leaf area contributed to more solar radiation interception, carbohydrate synthesis (Silber et al., 2003) and resulted in higher yield (Table 4.10).

4.3.5.3 *Harvest Index (HI)*

Treatment 1 (45.2) registered the highest harvest index (HI) and was significantly

different (P≤0.05) from the control (Treatment 7: 40.3) with an increase of about 11%. This was followed by Treatment 2 (44.1) which was also significantly different (P≤0.05) from Treatment 7 (control) by about 9% respectively (Table 4.11). This higher HI in Treatment 1 and 2 can be attributed to significantly higher (*P*≤0.05) fruit dry matter production in these treatments (Table 4.11). There were no significant differences among other treatments.

4.3.5.4 *Specific leaf area (SLA) and leaf weight ratio (LWR)*

Table 4.12 showed the specific leaf area (SLA) and leaf weight ratio (LWR) of different treatments at various growth stages. At every growth stage SLA increased while LWR decreased at every growth stage.

There were no significant differences in the SLA between the different treatments in the first and second stage (Table 4.12). In the third stage, specific leaf area (SLA) was significantly (p≤0.05) higher in Treatment 1 (180.9cm^2 g^{-1}) and Treatment 2 (174.1cm^2 g^{-1}) over the control (Treatment 7, 145.6cm^2 g^{-1}) and other treatments (T3, T4, T5 and T6) (Table 4.12). This would indicate that leaf of plants in Treatment 1 and 2 were significantly thicker than the leaf of plants from other treatments.

Leaf weight ratio (LWR) was not affected by different treatments (Table 4.12) at any growth stage. This would indicate that leaf thickness and proportion of plant dry biomass in the leaf material was similar to all treatments.

Table 4.12 Specific leaf area (SLA) and leaf weight ratio (LWR) of bell pepper plants as affected by different treatments

Treatment	S1		S2		S3	
	SLA	LWR	SLA	LWR	SLA	LWR
	cm^2 g^{-1}	g g^{-1}	cm^2 g^{-1}	g g^{-1}	cm^2 g^{-1}	g g^{-1}
T1	93.05	0.73	130.65	0.67	180.91a	0.32
T2	90.67	0.72	156.32	0.65	174.06a	0.32
T3	97.27	0.71	126.16	0.64	166.94b	0.34
T4	96.69	0.71	163.41	0.64	143.64b	0.34
T5	90.04	0.72	152.83	0.67	145.47b	0.35
T6	96.97	0.70	155.45	0.66	143.16b	0.35
T7 (control)	90.39	0.72	134.82	0.67	145.56b	0.35

Values of means in each column. Results were not significantly different between treatments

4.3.6 Leaf Chlorophyll

No significant differences of the leaf chlorophyll content (SPAD values) among the treatments were observed in any stage of plant growth in both top (Figure 4.14) and bottom leaves (Figure 4.15). However there seems to be some trends indicating the leaf chlorophyll (SPAD values) decreased at later growth stage. The decline in chlorophyll content in leaves can be attributed to decline in N concentration as plant ages (Figure 4.5)

4.3.7 Leaf gas exchange

Figure 4.16 – 4.19 showed no significant differences between treatments at each growth stage of bell pepper plant's growth among treatments on the leaf gas exchange parameters: photosynthetic capacity (µmol m^{-2} s^{-1}); transpiration rate (mmol m^{-2} s^{-1}); sub-stomatal CO_2 (vpm); and stomatal conductance (mmol m^{-2} s^{-1}). This can be attributed to relatively large variability in data. However, there appear to be some trends: photosynthetic capacity; transpiration rate and sub-stomatal conductance tended to decrease at every growth stage and were significantly ($p \leq 0.05$) higher in first stage (S1) than the third stage (S3) in all treatments. Most probably this was due to the reduced light and temperature towards the end of the experiment.

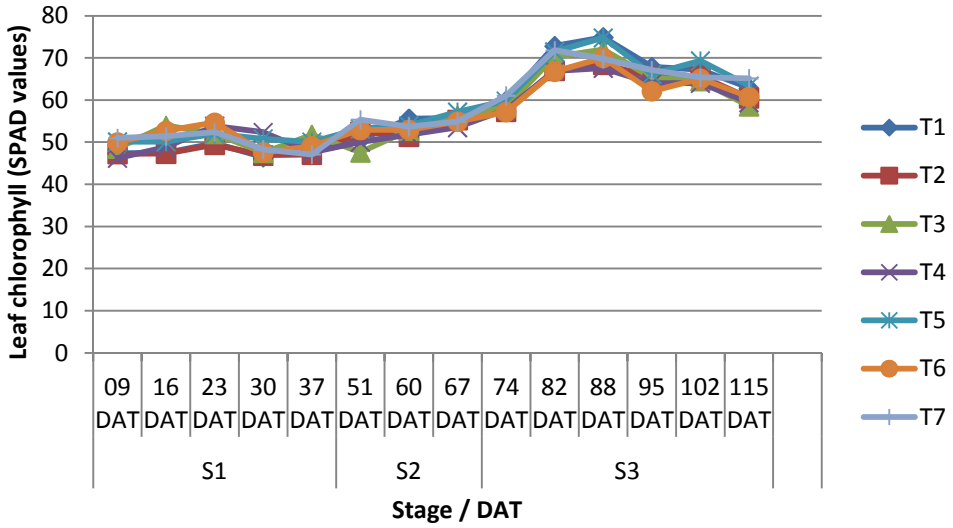


Figure 4.14 Leaf chlorophyll content (SPAD values) of top leaves at various stages as affected by different treatments. No significant differences were observed between the treatments.

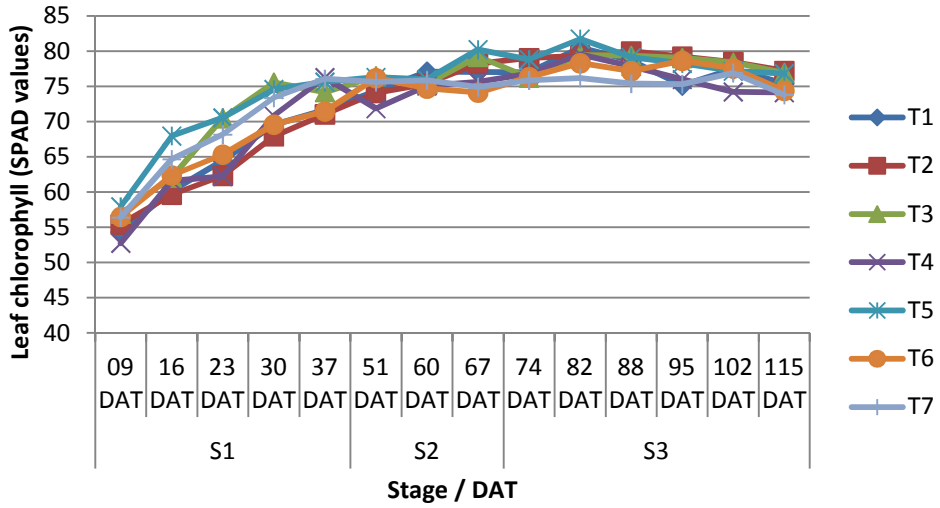


Figure 4.15 Leaf chlorophyll content (SPAD values) of bottom leaves at various stages as affected by different treatments. No significant differences were observed between the treatments.

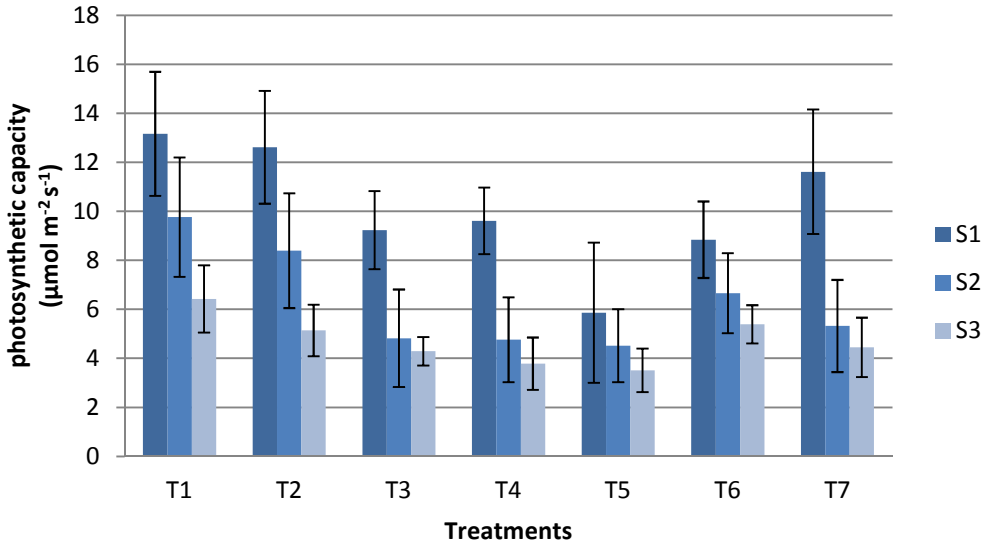


Figure 4.16 photosynthetic rate of bell pepper as affected by different treatments at various growth stages (S1-vegetative, S2-flowering, S3-fruiting)

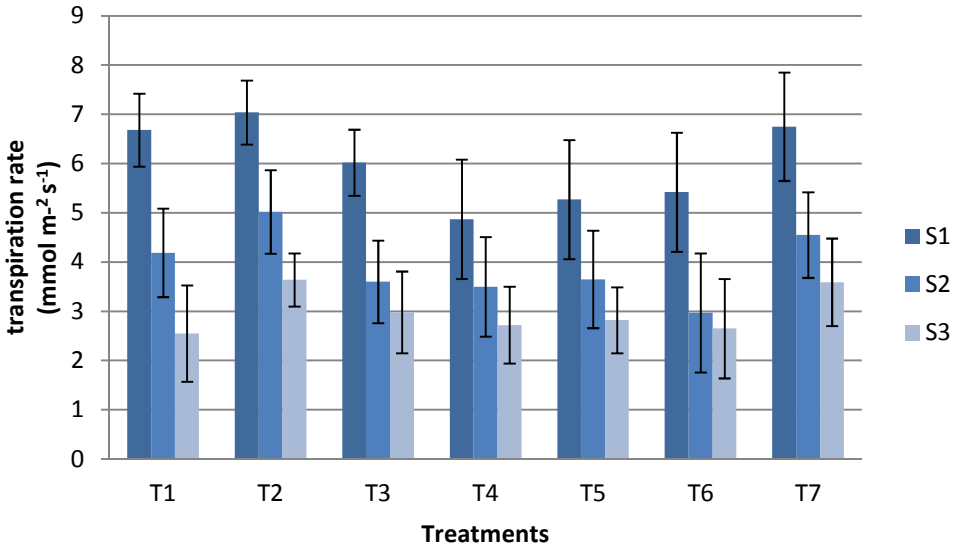


Figure 4.17 Transpiration rate of bell pepper as affected by different treatments at various growth stages (S1-vegetative, S2-flowering, S3-fruiting)

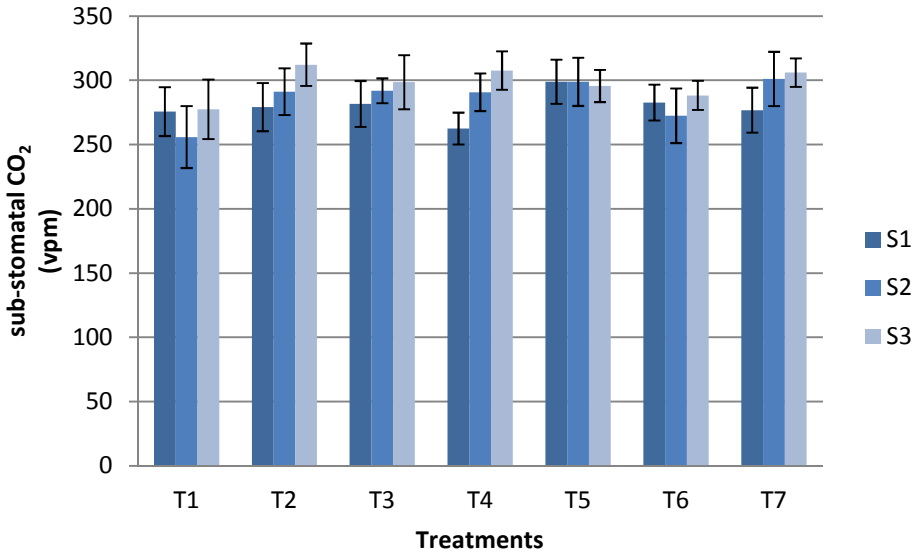


Figure 4.18 Sub-stomatal CO_2 of bell pepper as affected by different treatments at various growth stages (S1-vegetative, S2-flowering, S3-fruiting)

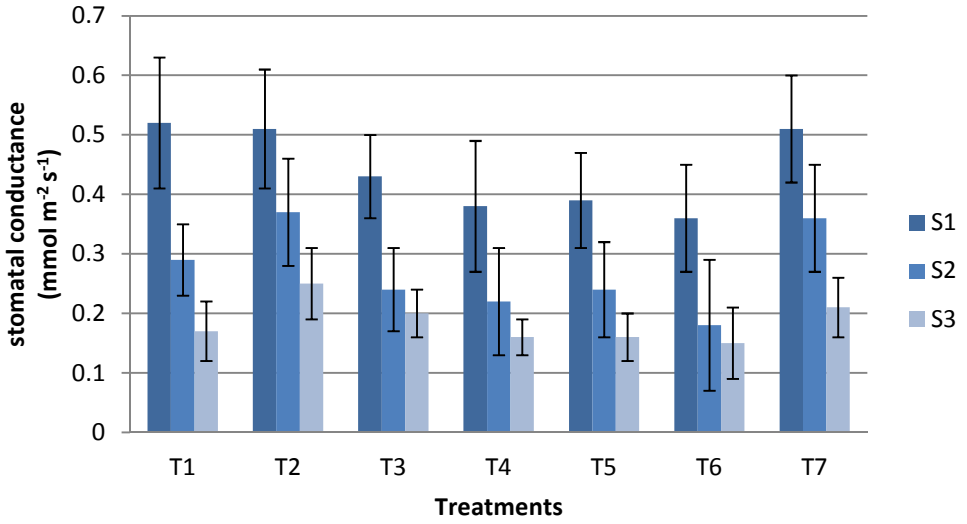


Figure 4.19 Sub-stomatal conductance of bell pepper as affected by different treatments at various growth stages (S1-vegetative, S2-flowering, S3-fruiting)

4.3.8 Uptake of NPK

There were no significant differences observed in NPK uptake by bell pepper plants in the first (S1) and second (S2) stages (details in Appendix 1). However there were significant differences being observed in the third (S3) stage (Table 4.13, 4.14 and 4.15).

In the third stage (S3), the total nitrogen uptake of Treatment 1 (4482 mg plant^{-1}) was significantly different ($P \leq 0.05$) from Treatment 7 (control, 2976 mg plant^{-1}) and also for total potassium uptake from 4797 mg plant^{-1} (T1) compared with 3413 mg plant^{-1} (T7) an increase 34% and 29% respectively. This was followed by Treatment 2 which also registered significance difference ($P \leq 0.05$) over Treatment 7 (control) on total nitrogen by 28% (4162 mg plant^{-1}) and potassium by 30% (4484 mg plant^{-1}) uptake. Other treatments (T3-T6) did not show significance differences. Total phosphorus uptake in Treatment 1 (101 mg plant-1) and Treatment 2 (95 mg plant^{-1}) were significantly ($p \leq 0.05$) higher than the control (Treatment 7, 79 mg plant^{-1}) by 22% and 17% respectively.

The higher N, P and K uptake in the third (S3) stage was a result of significantly higher dry matter production (Table 4.11) and secondly due to higher nitrogen and potassium concentration in different plant parts (Table 4.5).

Table 4.13 Nitrogen uptake in bell pepper at final harvest as affected by different treatments

Treatment	Nitrogen mg plant^{-1}			
	Leaf	Stem	Fruit	Total
T1	1609.8	913.1	1958.9	4481.8a
T2	1515.0	892.1	1754.6	4161.7a
T3	1396.7	828.3	1377.3	3602.3ab
T4	1374.8	811.2	1393.7	3579.7ab
T5	1435.3	726.9	1393.6	3555.8ab
T6	1348.4	666.7	1417.4	3432.5ab
T7 (control)	1136.3	501.6	1338.2	2976.1b

Means in each column, followed by different letters are significantly different at $p \leq 0.05$ by Tukey's test

Table 4.14 Phosphorus uptake in bell pepper at final harvest as affected by different treatments

Treatment	Phosphorus mg plant^{-1}			
	Leaf	Stem	Fruit	Total
T1	35.3	18.8	47.0	101.1a
T2	37.1	16.8	41.0	94.9a
T3	30.9	16.5	37.7	85.1ab
T4	36.5	18.6	32.0	87.1ab
T5	37.3	15.7	34.8	87.8ab
T6	31.8	16.3	36.7	84.8ab
T7 (control)	33.9	15.2	29.5	78.6b

Means in each column, followed by different letters significantly are different at $p \leq 0.05$ by Tukey's test

Table 4.15 Potassium uptake in bell pepper at final harvest as affected by different treatments

Treatment	Potassium mg plant^{-1}			
	Leaf	Stem	Fruit	Total
T1	1414.7	1094.4	2288.2	4797.3a
T2	1371.1	1046.6	2066.4	4484.1a
T3	1268.5	998.3	1681.3	3948.1ab
T4	1295.0	1000.5	1612.7	3908.2ab
T5	1283.8	910.6	1650.9	3845.3ab
T6	1259.9	974.7	1566.8	3801.4ab
T7 (control)	1134.2	845.1	1434.2	3413.5b

Means in each column, followed by different letters are significantly different at $p \leq 0.05$ by Tukey's test

4.4 Discussion

4.4.1 Nutrient concentration

Nitrogen

Over the three sampling periods (S1, S2, and S3), the concentration of N declined in leaves. This decline may be attributed to the relative increase in proportion of lignin, cell walls, and starch in the dry matter of tissues (Bryson and Barker, 2002). As plants age, the N that is absorbed and stored is diluted on a concentration basis by carbonaceous dry matter as plant development progress (Marschner, 1995). This decline is also attributed to the shift of sink-source relationship as the plant grows. In young leaves, most or all assimilates produced during photosynthesis (photosynthates) are required for growth and energy supply, therefore in their early growth stages green leaves act as a major sink (Marschner, 1995). The major sources of assimilates are from fully expanded leaves, which act as source. (Marschner, 1995). As plants age, N is remobilised from older leaves (source) to younger tissues (sink) Nitrogen concentration in the leaves increased with increasing levels of fertiliser concentration, indicating that the higher levels of fertilisation were beneficial to the N nutrition of the bell pepper plants.

The concentration of N in the leachate at all three stages of development increased as the level of fertiliser increased. The N concentrations in the leachate were highest in the first stage (S1) and third stage (S3). The demand for N within the plant appeared greatest in the second stage (S2), resulting in the lowest N concentration in the leachate among the three harvest dates, suggesting that an increase in N fertilisation at this stage could have been beneficial.

Phosphorus

Over the three growth stages, the concentration of P in tissues decreased as plant development progressed. This decline may be attributed to the shift of sink-source relationship as the plant grows. Phosphorus concentration in leaves was highest in the first stage (S1) compared to concentrations in the second (S2) and third (S3) stage. Plants have a high demand for P at an early stage of development (Mills and Jones Jr, 1996).

The P concentration in the leachate deceased as plant development progressed

indicating that the plants were continuing to absorb P and exhausting P from the medium. The concentration of P in the leachate was lowest in the third stage (S3) due to the demand by the large shoot biomass.

Potassium

The K concentration in the leaf tissues was greatest during the first (S1) and second stage (S2) and declined as plant maturity progressed at third stage (S3). The concentration of K in plant tissues peaked in the second stage (S2) and lowest in the third stage (S3). This trend has been reported by other researchers (Bryson and Barker, 2002, Marschner, 1995).

The concentration of K in the leachate decreased as plant growth progressed. Potassium in the leachate was lowest in the second (S2) and third (S3) stage indicating that the K supply was depleted and probably not enough K was supplied in the lower fertiliser concentration (126-55-106mg l^{-1}) treatment at the advanced stages.

4.4.2 Bell pepper performance

The effect of fertiliser concentration during the early growth stage was small (and not significant), owing to the relatively small nutrient requirements. However at later growing stages, as nutrients demands increased, fertiliser concentration significantly affected plant growth. No marked variations in growth and yield parameters were exhibited by all treatments in the first (1 to 44-DAT) and second stage (45-69-DAT). However, the third stage (70 to 122-DAT) data showed significant difference generally favouring the treatment receiving 126-55-106; 256-55-214; 385-55-321mg l^{-1} of NPK at S1, S2, and S3 respectively (Treatment 1) outperforming Treatment 7 (which was the control). This was followed by Treatment 2, plants receiving 126-55-106; 385-55-321; and finally 256-55-214 to mg l^{-1} of NPK at S1, S2, and S3 respectively.

Total dry matter production is an important determinant of the economic yield (Hebbar et al., 2004). The total dry matter production (Table 4.11) was significantly higher in Treatment 1, which provided gradual increase in N and K through the growth stages by 18% over the control (Treatment 7) in the third stage. This was followed by Treatment 2 which also registered significantly higher total dry matter over the control by 15%. The difference in the dry matter production in Treatment 1 and Treatment 2 can be ascribed

to greater leaf area production (Figure 4.12). Significantly higher leaf area was recorded in Treatment 1 and Treatment 2 over the control. Higher leaf area contributed to more carbohydrate synthesis and higher yield (Silber et al., 2003). The difference can also ascribed to other growth parameters in Treatment 1 and Treatment 2 where plants were taller with thicker stems compared with the control (Figure 4.10 and 4.11).

Treatment 1 also gave a significantly higher yield, 17% above the control. This was followed by Treatment 2 which also gave a significantly higher yield, 14% over the control. This yield increase can be attributed to more fruits per plant and better fruit quality in Treatment 1 and Treatment 2. The better performance of Treatment 1 and Treatment 2 was attributed to maintenance of favourable nutrient status in the root zone at different plant growth stages, which in turn helped the plants to utilize nutrients more efficiently from limited wetted area (Phene and Beale, 1976).

Treatment 1 and Treatment 2 had higher N, P and K uptake over the control (Treatment 7) and other treatments (Table 4.13, 4.14, and 4.15). This higher NPK uptake in Treatment 1 was associated with the higher N, P, and K concentrations in the plant parts (Table 4.5) and higher dry matter production (Table 4.11).

This study suggests that increasing the nitrogen and potassium concentration from vegetative to generative (flowering and fruiting) stage is important in bell pepper production. The reason is that nitrogen promotes vegetative growth while potassium promotes mature growth and generative growth (Calpas, 2002). Increasing potassium supply in the second and third stage will direct the plant to be generative. In this study it was done by increasing the feed concentration in Treatment 1 and Treatment 2.

4.4.3 Climatic condition

Environmental conditions inside the greenhouse may affect the growth of bell pepper (Calpas, 2002). Control of temperature is an important tool in control of crop growth (De Koning, 1996) and the optimum 24-hour mean temperature for vegetable crops grown in greenhouse ranges between 21 and 23^{o}C (Calpas, 2002). In this study, minimum and maximum temperature ranged from 8 to 16^{o}C and 18 to 49^{o}C respectively, with 24-hour mean temperature ranged between 13^{o}C to 32^{o}C. This may be not ideal for the growth of the plants.

Light limits the photosynthetic productivity and is an important variable affecting productivity in the greenhouse (Wilson et al., 1992). In the current study, the bell pepper plants were grown under natural light condition which may be insufficient especially during the short days of autumn. The evaporation rate of a greenhouse crop is the function of three variables: ambient temperature, light and humidity (Papadopoulos and Parraajasingham, 1997) and the evaporation rate during the current study was from 0.1 to 5mm which indicated a downward trend in these variables during the period of the current study.

These observations have the implication that the growth and yield of bell pepper plants from the current study are not directly comparable to results of experiments performed in ideal conditions.

4.4.4 Fertilisers

Whilst using pre-mixed fertilisers is satisfactory, mixing the individual nutrients in response to the plant requirement is more efficient (Calpas, 2002). In the current study, water soluble pre-mixed fertiliser was used (Table 4.4) which offered less flexibility in changing the nutrient supply to meet the plant demand and resulted in quite substantial amount of nutrients being leached out (Table 4.6, 4.7, and 4.8). This can be overcome by recycling of the leachate solution. Recycling can reduce nutrient leaching to the environment, give significant saving of water and fertiliser, better control of nutrient supply and reduced risk of ground water contamination (Magen, 1999). One of the main difficulties using recycling irrigation water is the perceived high risk of rapidly spreading plant disease from few isolated plants to the entire nursery as reported by several authors (Pettitt, 2003, Berkelmann et al., 1995, McDonald et al., 1994).

Another problem posed by the use of pre-mixed fertiliser is the variability of micro-nutrients content from one fertiliser to another (Table 4.4). Potentially, this could affect plant growth. However in the current study there were no indications that the plants exhibited micronutrient deficiency or toxicity (Table 4.6). Nutrient analysis of the leaves at the final harvest showed that plants in each treatment to be within the adequate sufficiency micronutrient ranges necessary for bell pepper as suggested by Hochmuth (2003).

4.5 Conclusion

It is well known that plant nutritional status affects growth and yield of plants. Hence it is essential to have a good knowledge of the plant's mineral requirements to ensure a good yield and to avoid nutrient wastage, which will decrease production costs and reduce the risk of water pollution. In order to support optimum growth, development and yield of the crop, the fertiliser feed has to continually meet the nutritional requirements of the plants (Calpas, 2002). The management of feed solution and its delivery to the crop has to be relatively flexible to meet its changing needs. It is best to start with moderate amounts of nutrients early in the season and increase concentrations as the plant grows (Hochmuth and Cordasco, 2009) and to change according to the growth stage of the crop with fertigation program being adjusted during the growing season to suit the plant development (Imas, 1999).

This study showed that fertigation with gradual increasing amounts of N and K from 126-106mg l^{-1} to 265-214mg l^{-1} and finally 385-321mg l^{-1} (Treatment 1) and by applying N and K from 126-106mg l^{-1} to 385-321mg l^{-1} and finally 265-214mg l^{-1} (Treatment 2) gave significantly higher yield than the control (126-106mg l^{-1} throughout the season). The author suspected that plants treated with 256-214mg l^{-1} or 365-321mg l^{-1} throughout the season would most likely have had similar effects to the result of Treatment 1 and Treatment 2. However they were not tested in the study. But again, the point of fertigation is to reduce fertiliser application whilst still produce high yield. This is an advantage of using fertigation; the level of nutrient concentration can be manipulated to match the plant's requirement.

Better synchronisation of nutrient supply with nutrient demand would result in better efficient use of fertiliser with greater yield as exhibited by plants from Treatment 1 and Treatment 2. Balanced fertilisation is the key to improve fertiliser use while excessive and unbalanced fertilisation are causes for low fertiliser use efficiency (Krauss, 2004).

This study was taken further (in the next chapter) in order to further investigate the effect of higher and lower of N and K concentrations beyond that tested in this first study. This was considered necessary in view of the potential effect of much higher and lower fertiliser concentrations on bell pepper production.

Chapter 5

Further evaluation of the effects of fertiliser concentration – Effects of higher and lower fertiliser concentration (N and K rates) on bell pepper production

5.1 Introduction

In Chapter 4, the study of different nitrogen (N) and potassium (K) rates in greenhouse bell pepper production grown in rockwool is presented. However, the nitrogen and potassium range used was considered to be narrow. Thus, a wider range needs to be investigated in order to further evaluate the effects of fertiliser concentration (N and K rates) of much higher and lower concentration than that used in the first experiment (Chapter 4).

The maintenance of nutrients and water at optimum levels within the vicinity of the roots of plants is a primary factor for achieving higher yields, and increased fertiliser and water use efficiencies. Therefore, the application of water soluble fertilisers through the irrigation water (fertigation) mainly with drip irrigation became a common practice in modern irrigated agriculture especially under greenhouse conditions (Bresler, 1977). Sustainable high yield depends entirely on the sustainable use of the limited sources of water and expensive fertiliser. This can only be attained with efficient use of water and fertilisers.

Fertigation is the precise application of irrigation water and plant nutrients through the irrigation system in order to match the current demand of the crop being nourished and irrigated (Papadopoulos, 1990). Since the application of fertilisers is becoming easier due to its higher solubility, the farmers are often applying much higher doses than the crop nutrient requirements which may eventually increase production cost. Furthermore this also leads to significant increase in leaching losses of applied nutrients, thus decreasing the use of fertiliser substantially and increasing tremendously the environmental pollution hazards. Hence, irrigation as well as fertiliser application should be based on crop requirements. Therefore, research on fertigation with the ultimate goal of improving the efficient use of fertiliser becomes more important.

An efficient use of fertigation technique requires good knowledge of the plant nutrient

uptake under optimum yield conditions (Bar-Yosef, 1986), lower concentration may reduce plant production and higher concentration may produce some nutrient imbalances due to nutrient interactions (Grattan and Grieve, 1999) and thus inhibit yield. More research is needed to study not only the growth rate, nutrient uptake, and yield responses, but also to study the effect of fertigation regimes over different growth stages.

The present study investigated further the effects of fertiliser concentration (nitrogen and potassium rates) much higher and lower than the rates set in the first experiment (Chapter 4) on growth, yield, leaf chlorophyll, photosynthesis and nutrient uptake of bell peppers. The hypotheses of this investigation were:

1. that decreasing the N and P concentrations from 126 and 106 mg l^{-1} to 44 and 71 mg l^{-1} respectively, while maintaining P concentration at 55 mg l^{-1}, will decrease growth and yield of bell pepper.
2. that increasing the N and P concentrations from 126 and 106 mg l^{-1} to 500 and 625 mg l^{-1} respectively, while maintaining P concentration at 55 mg l^{-1}, will not change growth and yield of bell pepper.

5.2 Materials and Methods

A detailed description on the methodology and materials employed in this experiment can be found in Chapter 3.

5.2.1 Experimental condition

The experiment was carried out during the summer-autumn (August to October) period of 2010. During the experiment the temperature ranged between 11.4 and 45.9 ^{o}C and the evaporation rate between 0.3 and 2.7mm per day (Figure 5.1).

5.2.2 Crop details

About eight weeks old bell pepper seedlings (*Capsicum annuum* L. var. Ferrari) raised in rockwool blocks by a commercial nursery were transplanted into the greenhouse on July 30, 2010.

Figure 5.1 Temperature and evaporation inside the greenhouse during the experiment

5.2.3 Experimental design and treatments

The experiment had eight treatments (Table 5.1) comprised of combinations of three levels of nitrogen (N) and potassium (K) concentrations (N-P-K: 126-55-106; 500-55-625; and 42-55-71 mg l^{-1}) and three levels of plant stages (S1- 1 to 33DAT; S2- 34 to 61 DAT; and S3- 62 to 95 DAT). P concentration (55 mg l^{-1}) was kept constant as it is the recommended phosphorus rate for bell pepper production (Calpas, 2002), whilst N and K ratios and concentration varied at different stages (Table 5.1).

The eight treatments were allocated in completely randomised design each replicated three times. Treatment 1 was the control whereby the plants received 126-55-106 mg l^{-1} of NPK throughout the season (as in Chapter 4). Each replication (experimental unit) included three plants in one 1m rockwool slab. The layout of the experimental design consisted of two separate plots (Plot 1 and Plot 2) in two different greenhouses (Figure 5.2). Each plot consisted of every experimental unit with replicates which were allocated randomly. Due to the potential implications of this arrangement of

experimental units on the robustness of the statistical analysis, only data from plot 1 were analysed.

Diagrammatic representation of fertigation treatments to indicate how the type and level of nutrients applications changed over the growth stages is shown in Figure 5.3. All treatments received the same amount of nutrients in the first stage (S1) but this varied between treatments in the second (S2) and third (S3) stages.

Table 5.1 Treatment details of the experiment

Treatments	S1 (1-33DAT)	S2 (34-61DAT)	S3 (62-95DAT)
	N-P-K (mg l^{-1}) with N:K ratio		
T1 (control)	126-55-106 (1.2:1.0)	126-55-106 (1.2:1.0)	126-55-106 (1.2:1.0)
T2	126-55-106 (1.2:1.0)	126-55-106 (1.2:1.0)	500-55-625 (1.0:1.25)
T3	126-55-106 (1.2:1.0)	500-55-625 (1.0:1.25)	126-55-106 (1.2:1.0)
T4	126-55-106 (1.2:1.0)	500-55-625 (1.0:1.25)	500-55-625 (1.0:1.25)
T5	126-55-106 (1.2:1.0)	500-55-625 (1.0:1.25)	42-55-71 (1.0:1.7)
T6	126-55-106 (1.2:1.0)	42-55-71 (1.0:1.7)	42-55-71 (1.0:1.7)
T7	126-55-106 (1.2:1.0)	42-55-71 (1.0:1.7)	500-55-625 (1.0:1.25)
T8	126-55-106 (1.2:1.0)	42-55-71 (1.0:1.7)	126-55-106 (1.2:1.0)

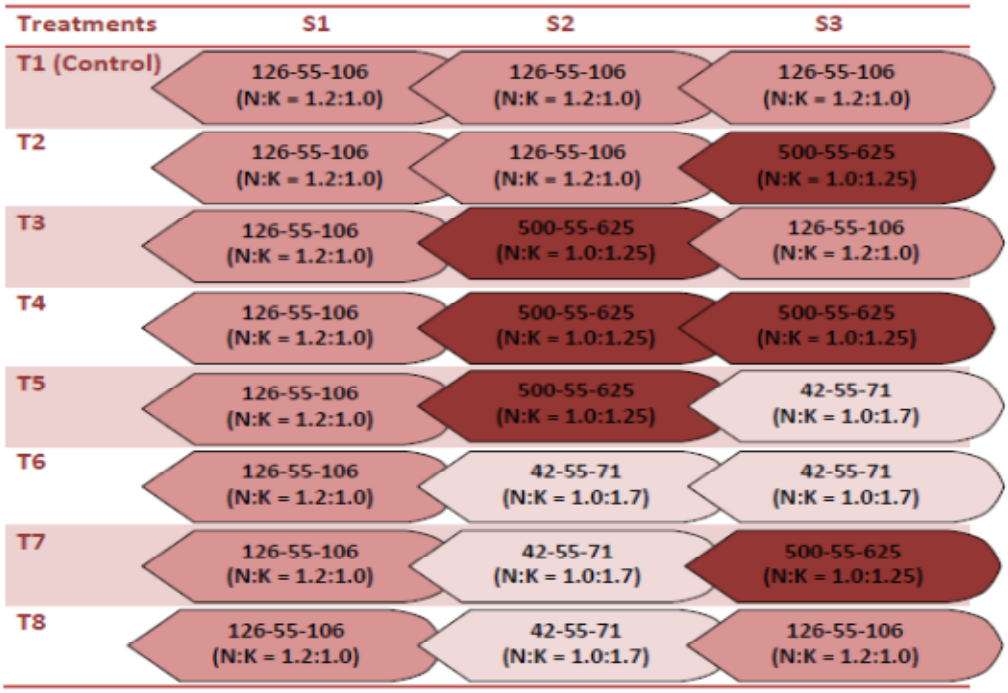


Figure 5.3 Diagrammatic representations of fertigation treatments. The colour scheme represents the N:K ratio concentration of the fertiliser at different stage, the concentration increases from light (low) to darker (high) colour.

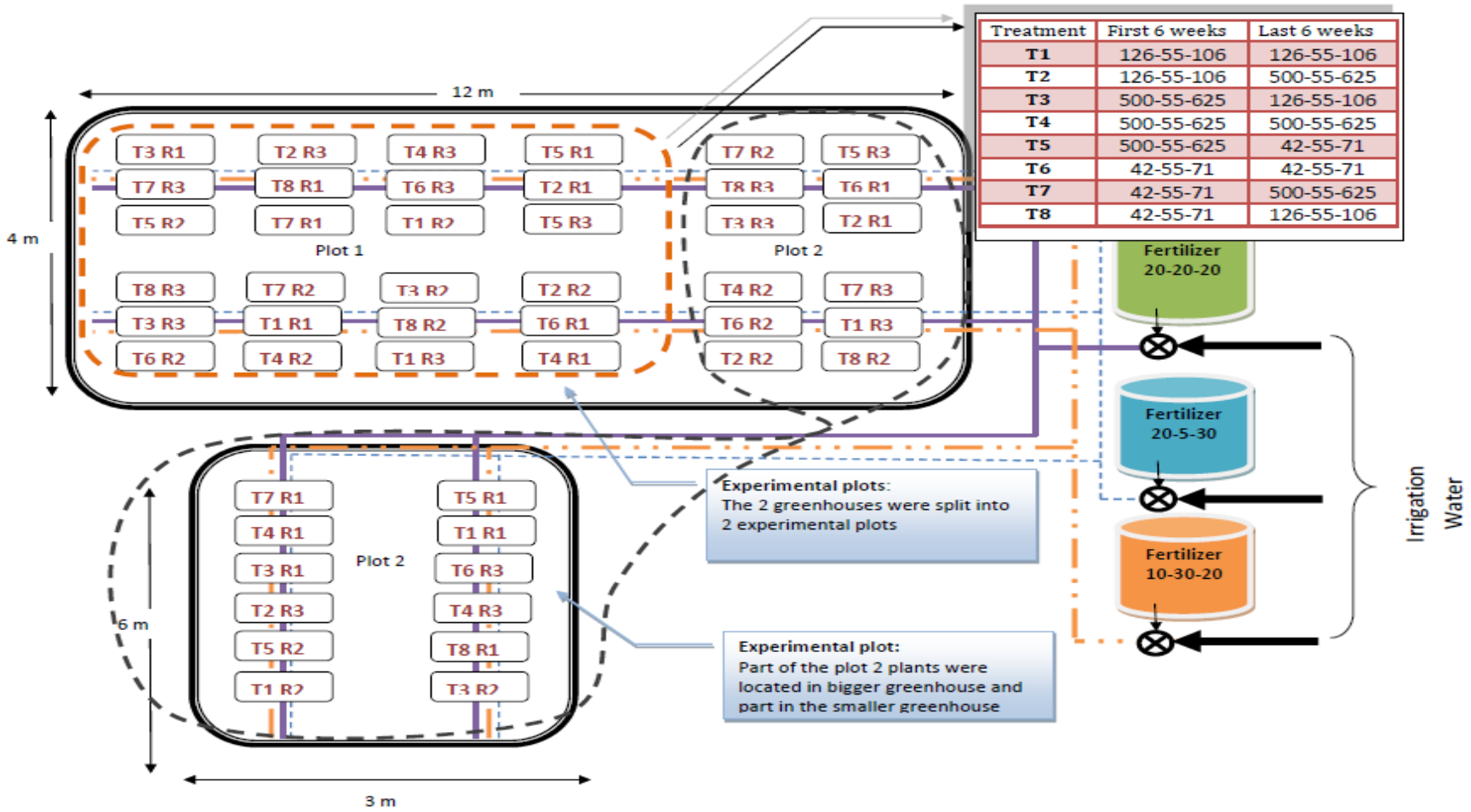


Figure 5.2 The layout of the experimental design and treatment allocation

5.2.4 *Nutrient treatment*

The nutrient solutions were prepared at known desired (target) concentration in separate stock tanks from three commercial water soluble fertilisers (20N-20P_2O_5-20K_2O (F1); 20N-05P_2O_5-30K_2O (F2); and 10N-30P_2O_5-20K_2O (F3); Scotts Inc.) having diverse percentages of nitrogen (N) and potassium (K) as well as N:K ratio (Table 5.2) using the suggested formula in Eq. (1) (Boyle, 2009). The calculation used to estimate the amount of nitrogen, phosphorus and potassium in each fertiliser formulation is in Appendix 6. Nutrient concentration of the irrigation water was included in determination of the final nutrient concentration.

Samples of the fertigation solutions from the drippers were collected (July 30, 2010) and the actual nutrients contents of the fertiliser solution received by the plants were analysed (Table 5.3).

Table 5.2 Details of the target amount of nitrogen, phosphorus and potassium in different fertiliser formulations

Fertilisers	N	P	K	N:K	To prepare 1 litre stock
N-P_2O_5-K_2O		mg l^{-1}		ratio	solution (g)
20-20-20 (F1)	126	55	106	1.2:1.0	63.2
20-05-30 (F2)	500	55	625	1.0:1.25	250
10-30-20 (F3)	42	55	71	1.0:1.7	42.3

The actual concentration (Table 5.3) of nitrogen and phosphorus fertiliser formulations was lower than the target value; however potassium was higher than the target value (Table 5.2). The differences were relatively small. The apparently lower concentration of nitrogen may have been because only nitrate (NO_3) concentration was assessed. Had further analysis for NH_4 (ammonium) been done the nitrogen concentration would have been higher. The lower concentration of nitrogen may also have been due to the loss of nitrogen by volatilisation as gaseous ammonia or through denitrification (Prasad and Kumar, 2001). The possible explanation for less phosphorus might be the formation of precipitation of calcium phosphate (Dhakal et al., 2005). The possible reason for higher potassium is that it is not sufficiently soluble and readily taken up by plants (Tiwari, 2003).

Table 5.3 Actual amount of N, P and K in the fertigation solution

Fertiliser	N (NO_3)	P	K
N-P_2O_5-K_2O		mg l^{-1}	
20-20-20 (F1)	118	51	112
20-05-30 (F2)	456	52	653
10-30-20 (F3)	39	51	74

The concentration of micronutrients supplied with the fertilisers were also analysed and are presented in Table 5.4, which also includes their electrical conductivity (EC) and pH details for each of the fertiliser formulations.

Table 5.4 Micronutrient content of the different fertiliser formulations

	EC	pH	Ca	Mg	S	Fe	Mn	Zn	Cu	B	Mo
	dS m^{-1}		mg l^{-1}								
F1	0.93	6.5	13.1	8.0	1.0	1.6	0.45	0.11	0.15	0.27	0.03
F2	2.64	6.3	16.2	20.4	0.6	5.7	1.02	0.22	0.30	0.51	0.06
F3	0.86	6.8	12.2	3.4	0.1	1.0	0.13	0.04	0.05	0.20	0.01

5.2.5 General methodology

The fertigation system was checked at the beginning of the experiment (July 25, 2010) to maintain a high degree of uniformity. This was to ensure approximately the same amount of water and fertiliser was applied to all parts of the system to obtain maximum benefits. Samples of the fertigation solutions from the drippers and leachates from the containers were collected to monitor their pH, electrical conductivity (*EC*) and volume throughout the period of the study. The fertigation and leachate solutions were also collected to be analysed for its nutrient content.

In the first stage (S1, where all treatments received similar amount of nutrients), one plant from each experimental unit was sampled at the end of the first stage (33-DAT) to ensure that plant development and dry weight were not different among treatments. Plant height (cm) and stem diameter (mm) were recorded at 32-DAT (S1); 61-DAT (S2) and 90-DAT (S3). Leaf area of the destructively harvested plants was measured at the end of the growth stage (33-DAT; 64-DAT; and 95-DAT for S1, S2 and S3 respectively).

One plant (above ground parts, minus the roots) per experimental unit was taken at the

end of Stage 1, Stage 2 and Stage 3 at 33-DAT; 64-DAT; and 95-DAT respectively. The plants were separated into stem, leaf, and fruits and their weight determined. The harvested fruit were weighed, counted, and measured for length and diameter. Fruits with blossom end rot (BER) were also recorded. The plant's parts were dried at 80^{o}C in a ventilated oven for 24 hours before their dry weights were determined. Harvest index (HI) was also determined by dividing the oven dried mass of mature fruit by above-ground dry weight.

The leaf chlorophyll concentration (SPAD units) was monitored on attached leaves using a Minolta chlorophyll metre SPAD-502 were made at 33-DAT (S1), 54-DAT (S2), and 81-DAT on (i) apical leaves and (ii) bottom leaves. Leaf gas exchange (photosynthetic capacity, transpiration rate, sub-stomatal CO_2 and stomatal conductance) was measured at 33-DAT (S1); 47-DAT (S2) and 88-DAT (S2), one leaf per plant with an infrared gas analyser (IRGA) model LC*i* (ADC BioScientific Ltd, UK).

Leaf, stem and fruit samples of bell pepper were collected at the end of stages (33-DAT, 64-DAT, and 95-DAT for S1, S2 and S3 respectively) and pooled for each treatment for nutrients analysis. The plant samples were dried in a ventilated oven at 80 ^{o}C for 24h and then ground to a fine powder using a one millimetre mesh sieve (Christy and Norris, UK) and stored in sealed plastic bags ready for nutrient analysis. Details of nutrient analysis can be found in Chapter 3.

5.3 Results and Discussions

5.3.1 Fertigation uniformity

The uniformity coefficient (Uc) of fertigation system used in the study was found to be 95% (Table 5.5) which is an excellent rating for drip irrigation uniformity when compared to statistical uniformity of drip irrigation provided by ASAE (Table 3.2). The high values of uniformity coefficient indicated excellent performance of fertigation system in this study in supplying nutrient solution throughout the emitters during the experiment.

Table 5.5 Uniformity coefficient of the fertigation system

Volume (ml in 5 minutes)		Discharge rate (q) (ml min^{-1})		Mean deviation (Δq)	Uniformity coefficient (%)
Mean	SEM	Mean	SEM		
149.9	0.70	30.0	0.14	1.47	95.1

5.3.2 Fertigation and leachate solution

Fertigation and leachate solution electrical conductivity (EC) generally increased with increasing fertiliser concentration. Similar increases have been reported previously (Cox, 2001). There were also changes in leachate EC over time, but these changes depended on fertiliser concentration (Figure 5.4a and 5.4b). There were some variations of the fertigation solution EC over time and this can be attributed to pressure difference of irrigation water from mains supply (Magen, 1999) as well as variations in fertiliser dosage. There were marked differences of the EC during the changeover of nutrient from one stage to another which was attributed to the differences in the nutrient treatment EC. The EC of fertigation ranged from 0.84 to 2.76 dS m^{-1}, while the EC of the leachate ranged from 0.90 to 2.97 dS m^{-1}. The higher EC values of the leachate solution compared to the fertigation solution were due to water uptake by plants (Magen, 1999).

Generally, fertigation and leachate solution pH decreased with increasing fertiliser concentration, although pH differences were small (Figure 5.4c and 5.4d). The pH of the fertigation solution ranged from 6.1 to 6.6 while pH of the leachate solution ranged from 6.0 to 6.5. The possible reason for low pH in the leachate solution compared to the fertigation solution is the formation of organic acid (Magen, 1999).

Figure 5.5 shows the variations of the leachate volume solution collected at different growth stages. There were marked differences in the volume of the leachate solution during the change over stage which can be attributed to the increase in amount of nutrient supply from 800 ml to 1000ml and finally to 1500ml in S1, S2 and S3 respectively. The leachate ranged from 28.0% and 39.3% of the total fertigation solution. The percentage of the leachate could be up to 40% of the fertigation solution (Magen, 1999).

The variation of nutrient concentration in the leachate solution was also observed (Table 5.6). There were no marked differences in nutrient concentration in the leachate solution in the first stage. This can be attributed to all treatments receiving similar nutrient treatment. The nitrogen (N) and potassium (K) concentration in the leachate solution of Treatments 2, 3, 5, 7 and 8 changes at S3 from S2 which can be attributed to the change over of fertiliser treatments. Treatments 1 (control), 4 and 6 received the same fertiliser throughout the growing season and did not show many differences in the amount of nitrogen and potassium in both stages. The phosphorus (P) concentration in the leachate solution in all treatments did not show much difference at all stages. This can be attributed to a similar amount of phosphorus in the nutrient treatments which were maintained at 55 mg l^{-1} for all treatments.

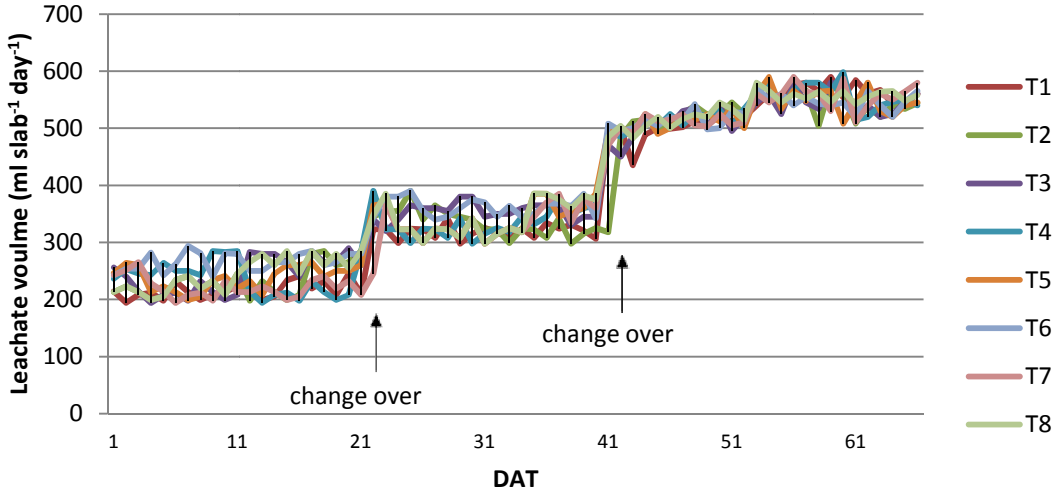


Figure 5.5 Amount of leachate solution at different days after transplanting (DAT)

Table 5.6 Evolution of (a) nitrogen; (b) phosphorus; and (c) potassium in the leachate

Treatments	Nitrogen			Phosphorus			Potassium		
	mg l^{-1}								
	S1	S2	S3	S1	S2	S3	S1	S2	S3
T1 (control)	64.8	61.4b	63.2b	16.8	16.7	16.4	48.1	45.4b	42.8b
T2	63.6	60.1b	205.2a	17.1	16.8	16.5	47.5	44.0b	165.4a
T3	61.4	199.4a	61.5b	17.2	17.0	16.9	47.4	170.6a	41.3b
T4	63.5	201.8a	214.3a	16.8	16.7	16.5	48.1	195.1a	168.4a
T5	63.7	199.7a	54.6c	17.0	16.9	16.6	46.5	186.8a	21.8c
T6	62.6	43.2c	56.3c	16.7	16.5	16.4	47.6	24.5c	19.2c
T7	61.8	46.8c	209.6a	17.1	16.7	16.6	47.0	26.3c	163.1a
T8	63.2	42.6c	64.5b	17.2	16.8	16.7	46.2	25.7c	43.2b

Means in each column, followed by different letters are significantly different by Tukey's test

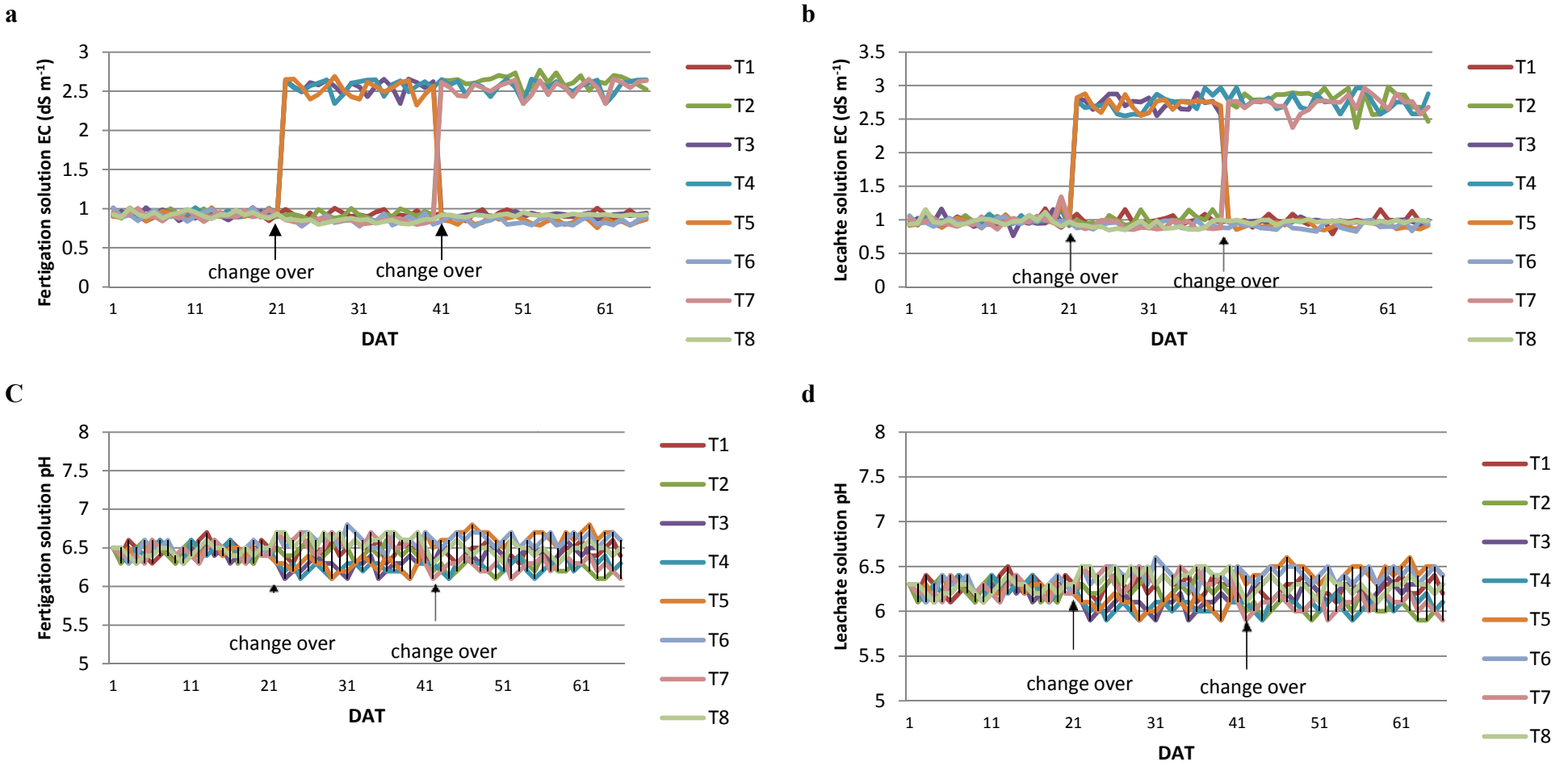


Figure 5.4 Fertigation and leachate solution details at different days after transplanting (DAT) (a) EC fertigation solution, (b) EC leachate solution, (c) pH fertigation solution, and (d) pH leachate

5.3.3 Growth parameters

5.3.3.1 Plant height

Table 5.7 gives bell pepper plant height records at 32-DAT (S1); 61-DAT (S2) and 90-DAT (S3). There were no marked differences in plant height in the first stage because all plants received similar nutrient treatments at this stage i.e. 126-55-106 mg l^{-1} of nitrogen, phosphorus and potassium respectively. However, in the second stage data showed significant differences ($P \leq 0.05$) generally in favour of the treatments receiving 126-55-106 and 500-55-625mg l^{-1} of NPK: Treatment 1 (control), Treatment 2, Treatment 3, Treatment 4 and Treatment 5 over plants subjected to low NPK rates (42-55-71 mg l^{-1}): Treatment 6, Treatment 7 and Treatment 8. The data of the second stage tend to suggest that increasing the nutrient solution from 44-55-71mg l^{-1} to 126-55-106mg l^{-1} of NPK significantly increases plant height but a further increase to 500-55-625mg l^{-1} of NPK did not significantly increase plant height any further.

Treatment 6 (64.6cm), Treatment 7 (64.1cm) and Treatment 8 (63.3cm) were significantly ($P \leq 0.05$) shorter than the control (Treatment 1, 70.1cm) by 5.5cm (8%), 6.0cm (9%) and 6.8cm (10%) respectively and significantly shorter than plants from other treatments (T2-T5). Treatment 2 (68.5cm), Treatment 3 (69.8cm), Treatment 4 (67.5cm) and Treatment 5 (69.6cm) did not show significant differences over the control (Treatment1). In the third stage (Table 5.7) data showed significant difference ($P \leq 0.05$) shorter plant height observed in Treatment 6 (67.4cm) over Treatment 1 (control, 72.4cm), Treatment 2 (71.7cm), Treatment 3 (73.2cm); and Treatment 4 (72.1cm) by 7% (5.3cm), 6% (4.3cm), 8% (5.8cm), and 7% (4.7cm) respectively. There were no significant differences among other treatments (T5, T7 and T8).

5.3.3.2 Stem diameter

Stem diameter (Table 5.7) did no differ in the first stage (32-DAT), however there were significant differences in the second (61-DAT) and third (90-DAT) stages. In the second stage, Treatments receiving low NPK rates (42-55-71mg l^{-1}) i.e. Treatment 6 (11.4mm), Treatment 7 (11.3mm) and Treatment 8 (11.4mm) exhibited significantly ($P \leq 0.05$) thinner stems over the control (Treatment 1, 12.5mm) by 1.1mm (9%), 1.2mm (10%), and 1.1mm (9%) respectively and over Treatment 2 (12.2mm), Treatment 3 (12.4mm), Treatment 4 (12.3mm) and Treatment 5 (12.2mm). No significant differences were

observed between Treatment 2, Treatment 3, Treatment 4 and Treatment 5 over the control (Treatment 1).

In the third stage, Treatment 6 (11.3mm) exhibited significantly (P≤0.05) thinner stems over the control (Treatment 1, 12.5mm), Treatment 2 (12.4cm), Treatment 3 (12.6cm), and Treatment 4 (12.2mm) by 1.2mm (10%), 1.1mm (9%), 1.3mm (10%), and 0.9mm (7%) respectively. There were no significant differences among other treatments (T5, T7 and T8).

Table 5.7 Plant height and stem diameter in bell pepper as influenced by varying nitrogen (N) and potassium (K) rates at different growth stages (plot 1 data only)

Treatment	31-DAT (S1)		61-DAT (S2)		90-DAT (S3)	
	Plant height (cm)	Stem diameter (mm)	Plant height (cm)	Stem diameter (mm)	Plant height (cm)	Stem diameter (mm)
T1 (control)	59.1	11.5	70.1a	12.5a	72.4a	12.5a
T2	58.5	11.2	68.5a	12.2a	71.7a	12.4a
T3	57.6	11.3	69.8a	12.4a	73.2a	12.6a
T4	55.1	11.5	67.5a	12.3a	72.1a	12.2a
T5	56.4	11.3	69.6a	12.2a	70.5ab	12.0ab
T6	56.6	11.3	64.6b	11.4b	67.4b	11.3b
T7	57.0	11.5	64.1b	11.3b	68.1ab	11.7ab
T8	56.1	11.4	63.3b	11.4b	67.6ab	11.8ab

Means in each column, followed by different letters are significantly different at p≤0.05 by Tukey's test

5.3.3.3 Leaf area

There were no significant differences in leaf area (Table 5.8) among the treatments in the first stage however significant differences were recorded in the second and third stages. Increasing nutrient NPK concentration from 40-55-71mg l^{-1} to 126-55-106mg l^{-1} significantly (P≤0.01) increased leaf area but a further increase in nutrient NPK concentration to 500-55-625mg l^{-1} had no significant effect on leaf area in the second and third stage.

Treatment 1 (control, 3315cm^2), Treatment 2 (3207cm^2), Treatment 3 (3762cm^2), Treatment 4 (3446cm^2) and Treatment 5 (3706cm^2) exhibited significantly greater (P≤0.01) leaf area over Treatment 6 (1863cm^2), Treatment 7 (2065cm^2) and Treatment 8 (2173cm^2) in the second stage. Treatment 6, Treatment 7 and Treatment 8 registered significantly (P≤0.01) lower leaf area over Treatment 1 (control, 3315cm^2) by 43%,

38% and 34% respectively. Treatment 2, Treatment 3, Treatment 4 and Treatment 5 did not show significant differences over the control (Treatment 1).

In the third stage (S3), Treatment 1, Treatment 2, Treatment 3, Treatment 4 and Treatment 5 exhibited significantly greater ($P \leq 0.01$) leaf area over Treatment 6, Treatment 7 and Treatment 8. Treatment 6, Treatment 7, and Treatment 8 registered significantly ($P \leq 0.01$) lower leaf area over the control (Treatment 1) by about 26%, 21% and 23% respectively. Treatment 2, Treatment 3, Treatment 4 and Treatment 5 did not show significant differences over the control (Treatment 1).

Table 5.8 Leaf area per plant in bell pepper as influenced by varying nitrogen and potassium rates at different growth stages (plot 1 data only)

Treatment	Leaf area (cm^2 $plant^{-1}$)		
	33-DAT (S1)	64-DAT (S2)	95-DAT (S3)
T1 (control)	2874	3315a	3874a
T2	2809	3207a	3907a
T3	2656	3762a	4484a
T4	2486	3446a	4175a
T5	2552	3706a	4213a
T6	2370	1863b	2877b
T7	2513	2065b	3044b
T8	2802	2173b	2986b

Means in each column, followed by different letters are significantly different at $p \leq 0.05$ by Tukey's test

5.3.4 Yield parameters

5.3.4.1 Yield

There were no differences between treatments in number of flowers and fruits per plant (Table 5.9). This was because some flowers were pruned off in order to control the number of fruits set per plant to ensure they achieved marketable size. Fertigation with the 126-55-106mg l^{-1} of NPK throughout the season (Treatment 1 - control, 636.7g) recorded highest fruit yield (fresh weight) per plant and registered significantly ($P \leq 0.05$) higher fruit yield over Treatment 6 (470.0g), Treatment 7 (493.3g) and Treatment 8 (503.3g) (Table 5.9) by 26%, 23% and 21% respectively. This increase can be attributed to bigger fruits in Treatment 1 over the Treatment 6, Treatment 7 and Treatment 8. Fruit width and length of Treatment 6 (61.6mm and 43.0mm), Treatment 7 (62.7mm and

45.1mm) and Treatment 8 (63.8mm and 44.3mm) were significantly (P≤0.05) lower than fruits from Treatment 1 (control, 75.1mm and 59.3mm) (Table 5.9).

No significant differences were recorded for the total fruit yield (fresh weight) per plant of Treatment 2, Treatment 3, Treatment 4 and Treatment 5 over the control (Treatment 1), however fruits from plants in Treatment 1 gave higher fruit fresh weight. Lower fruit fresh weight in T2, T3, T4 and T5 than the control (T1) can be attributed to high solution electrical conductivity as reported by other researchers (Ehret and Ho, 1986). Plants of T2, T3, T4 and T5 were subjected to nutrient solution of 500-55-625 (EC=2.64) in either stage 2 or stage 3 or both stages.

5.3.4.2 BER incidence

Fertigation with 500-55-625 mg l^{-1} of NPK throughout stage 2 and 3 (Treatment 4, 2.1 $plant^{-1}$), registered significantly more fruits with blossom end rot (BER) over the control (Treatment 1, 1.3 $plant^{-1}$) and other treatments (T2, T3, T5, T6, T7, T8) (Table 5.9). In Treatment 4 about 40% of total fruits per plant had BER. In other treatments (T1, T2, T3, T5, T6, T7 and T8) 23 to 27 per cent of total fruits were affected with BER. The general estimates of the economic loss of bell pepper due to BER is in the range of 20-40% (Silber, 2008).

5.3.4.3 Dry matter partitioning

There were no significant treatment differences in total dry matter (TDM) production in the first stage (Table 5.10). In the second stage, Treatment 1 (control, 53.6g $plant^{-1}$), Treatment 2 (53.1g $plant^{-1}$), Treatment 3 (56.7g $plant^{-1}$), Treatment 4 (55.5g $plant^{-1}$), and Treatment 6 (56.5g $plant^{-1}$) registered significantly (P≤0.05) higher TDM over Treatment 6 (43.1g $plant^{-1}$), Treatment 7 (43.8g $plant^{-1}$), and Treatment 8 (43.9g $plant^{-1}$). The difference in the dry matter production in the second stage can be ascribed to the differences in leaf production (Table 5.8). Significantly (P≤0.01) higher leaf area was recorded in Treatment 1, Treatment 2, Treatment 3, Treatment 4 and Treatment 5 over Treatment 6, Treatment 7, and Treatment 8. Higher leaf area may be associated with higher N supply.

Table 5.9 Yield parameters in bell peppers as influenced by varying nitrogen and potassium at final harvest (plot 1 data only)

Treatment	No of flowers plant^{-1} (59DAT)	Total fresh yield (kg)	Fruit fresh weight (g plant^{-1})	Fruit number plant^{-1}	Fruit with BER plant^{-1}	Fruit quality	
						Fruit width (mm)	Fruit length (mm)
T1 (control)	6.5	1.91a	636.7a	5.3	1.3b	75.1a	59.3a
T2	6.2	1.85a	616.7a	5.1	1.2b	70.4a	55.6a
T3	6.2	1.68a	556.0a	5.2	1.2b	72.8a	55.0a
T4	6.1	1.65a	550.7a	5.2	2.1a	65.6a	52.8a
T5	6.0	1.72a	573.3a	5.3	1.4b	67.3a	53.5a
T6	5.9	1.41b	470.0b	5.0	1.2b	61.6b	43.0b
T7	5.8	1.48b	493.3b	5.2	1.3b	62.7b	45.1b
T8	6.1	1.51b	503.3b	5.1	1.4b	63.8b	44.3b

Means in each column, followed by different letters are significantly different at p≤0.05 by Tukey's test

Table 5.10 Effects of varying nitrogen and potassium on biomass production, partitioning and harvest index (HI) of bell pepper (plot 1 data only)

Treatment	Dry weight (g plant^{-1})											HI
	S1			S2				S3				
	Leaves	Stem	TDM	Leaves	Stem	Young fruits	TDM	Leaves	Stem	Fruit	TDM	
T1 (control)	20.1	14.7	34.8	19.1	18.5	15.6	53.6a	20.1	19.6	50.4	90.1a	55.9
T2	19.6	14.3	33.9	18.4	17.8	16.9	53.1a	19.8	19.9	48.6	88.3a	55.0
T3	20.3	15.1	35.4	22.5	19.5	14.7	56.7a	22.2	18.8	45.8	86.8a	52.8
T4	20.6	15.5	36.1	23.2	18.8	13.5	55.5a	24.1	18.3	44.1	86.5a	51.0
T5	21.1	16.1	37.2	23.7	18.1	14.7	56.5a	25.4	19.4	41.0	85.8a	47.8
T6	22.5	15.7	38.2	13.8	15.1	14.2	43.1b	14.8	16.9	32.6	64.3b	50.7
T7	19.3	14.5	33.8	14.1	15.9	13.8	43.8b	15.6	17.4	38.2	71.2b	53.7
T8	19.8	14.8	34.6	14.5	16.0	13.4	43.9b	16.1	17.1	36.4	69.9b	52.1

Means in each column, followed by different letters are significantly different at p≤0.05 by Tukey's test

In the third stage, Treatment 1 (control, 90.1g plant^{-1}), Treatment 2 (88.3g plant^{-1}), Treatment 3 (86.8g plant^{-1}), Treatment 4 (86.5g plant^{-1}) and Treatment 5 (85.8g plant^{-1}) registered significantly ($P \leq 0.01$) higher TDM over Treatment 6 (64.3g plant^{-1}), Treatment 7 (71.2g plant^{-1}) and Treatment 8 (69.6g plant^{-1}). The differences in the dry matter production due to the different treatments in the third stage can be ascribed to the leaf (Table 5.8) and fruit (Table 5.9) production. Significantly higher leaf area and fruit yield was recorded in Treatment 1 (control), Treatment 2, Treatment 3, Treatment 4 and Treatment 5. Higher leaf area contributed to more radiation interception, carbohydrate synthesis (Silber et al., 2003) and resulted in higher yield (Table 5.9).

5.3.4.4 Harvest index (HI)

Treatment 1 - control (55.9) registered the highest HI over other treatments (T2, T3, T4, T5, T6, T7 and T8). However no significant differences were observed. The higher HI in Treatment 1 can be attributed to higher fruit dry matter production in Treatment 1 (Table 5.10).

5.3.4.5 Specific leaf area (SLA) and leaf weight ratio (LWR)

There were no significant differences on the SLA among the treatments in the first stage (Table 5.11). In the second stage, Treatment 6 (135.00 cm^2 g^{-1}), Treatment 7 (146.45 cm^2 g^{-1}), and Treatment 8 (149.86 cm^2 g^{-1}) were significantly ($p \leq 0.05$) lower than the control (Treatment 1; 173.56 cm^2 g^{-1}), and over other treatments (T2, T3, T4, and T6). This would indicate leaf of plants from Treatment 6, 7, and 8 were significantly thinner compared with other treatments including the control. In the third stage, Treatment 4 (201.98 cm^2 g^{-1}) was significantly higher than Treatment 6 (165.87 cm^2 g^{-1}). No other significant differences were observed among the other treatments.

In term of LWR, no significant differences were observed among the treatments in the first stage (Table 5.11). However in the second stage, Treatment 3 (0.40 g g^{-1}), Treatment 4 (0.42 g g^{-1}) and Treatment 5 (0.42 g g^{-1}) registered significantly ($p \leq 0.05$) over Treatment 6 (0.32 g g^{-1}), Treatment 7 (0.32 g g^{-1}), and Treatment 8 (0.33 g g^{-1}). No other significant differences were observed among other treatments. Similar patterns were seen in the third stage (Table 5.11). This would indicate that the proportion of the plant dry matter biomass in the leaf material was significantly higher in Treatment 3, 4,

and 5 were higher than those plants from Treatment 6, 7, and 8.

Table 5.11 Specific leaf area (SLA) and leaf weight ratio (LWR) of bell pepper plants as affected by different treatments

Treatment	S1		S2		S3	
	SLA	LWR	SLA	LWR	SLA	LWR
	$cm^2\ g^{-1}$	$g\ g^{-1}$	$cm^2\ g^{-1}$	$g\ g^{-1}$	$cm^2\ g^{-1}$	$g\ g^{-1}$
T1 (control)	142.98	0.58	173.56a	0.36ab	192.74ab	0.23ab
T2	143.32	0.58	174.29a	0.35ab	197.32ab	0.22ab
T3	130.84	0.57	167.20a	0.40a	173.24ab	0.26a
T4	120.68	0.57	158.53a	0.42a	201.98a	0.28a
T5	120.95	0.57	156.37a	0.42a	194.39ab	0.30a
T6	105.33	0.59	135.00b	0.32b	165.87b	0.20b
T7	130.21	0.57	146.45b	0.32b	195.13ab	0.21b
T8	141.52	0.57	149.86b	0.33b	185.47ab	0.21b

Means in each column, followed by different letters are significantly different at $p \leq 0.05$ by Tukey's test

5.3.5 Leaf chlorophyll content

Chlorophyll content (SPAD values) did not show significant differences in any of the treatments in the first stage (Table 5.12). This can be attributed to all plants receiving similar nutrient treatments of 126-55-106 mg l^{-1} of N, P and K respectively at this stage. However, significant differences were observed in the second and third stage. In the second stage and third stage (Figure 5.11), Treatment 1 (control), Treatment 2, Treatment 3, Treatment 4 and Treatment 5 registered significantly ($P \leq 0.05$) higher leaf chlorophyll content (SPAD values) over Treatment 6, Treatment 7 and Treatment 8. This was because Treatment 6, Treatment 7, and Treatment 8 received the lower amount of nutrient especially nitrogen compared to the rest of the treatments.

5.3.6 Leaf gas exchange

Data (Figure 5.6a-d), show there were no significant differences at any stages of bell pepper's growth among treatments on the leaf gas exchange parameters: photosynthetic capacity (μmol $m^{-2}\ s^{-1}$), transpiration rate (mmol $m^{-2}\ s^{-1}$), sub-stomatal CO_2 (vpm), and stomatal conductance (mmol $m^{-2}\ s^{-1}$). This can be attributed to relatively large variability in data. However, there appear to be some trends: photosynthetic capacity, transpiration rate and sub-stomatal conductance tended to decrease at every growth stage while sub-stomatal CO_2 tended to increase. Most probably this is due to the reduced light and temperature towards the end of the experiment.

Table 5.12 Leaf chlorophyll (SPAD values) of bell pepper at various stages affected by different treatment (bottom leaves)

Treatment	Leaf chlorophyll (SPAD values)		
	Stage 1	Stage 2	Stage 3
	35-DAT	61-DAT	89-DAT
T1 (control)	57.83	63.72a	62.28a
T2	62.08	66.48a	63.57a
T3	57.56	66.39a	62.26a
T4	59.81	70.27a	67.76a
T5	65.02	72.44a	68.59a
T6	59.99	56.23b	56.81b
T7	62.70	57.58b	58.61b
T8	62.77	60.93b	56.99b

Means in each column, followed by different letters are significantly different at $p \leq 0.05$ by Tukey's test

5.3.7 Uptake of NPK

There were no significant differences observed in NPK uptake by bell pepper plants in the first stage (S1) (details in Appendix 2) because nutrient treatments were similar in the first stage. However there were significant differences in the second (S2) and third (S3) stage. Treatment 2, Treatment 3, Treatment 4 and Treatment 5 did not show significant differences in the total nitrogen, total phosphorus and total potassium over the control (Treatment 1) in second and third stages. In contrast, Treatment 6, Treatment 7 and Treatment 8 had less total nitrogen, total phosphorus and total potassium over Treatment 1 (control) in both second and third stages.

In the second stage (Table 5.13), Treatment 6 (809mg plant^{-1}), Treatment 7 (867mg plant^{-1}) and Treatment 8 (926mg plant^{-1}) registered significantly ($P \leq 0.01$) less total nitrogen uptake over the control (T1, 1552mg plant^{-1}) which amounted to a decrease of 48%, 44%, and 40% respectively. In terms of the total phosphorus uptake: Treatment 6 (43mg plant^{-1}), Treatment 7 (46mg plant^{-1}) and Treatment 8 (44mg plant^{-1}) registered significantly less ($P \leq 0.05$) over the control (Treatment 1, 58mg plant^{-1}) which amounted to a decrease of 27%, 22% and 25% respectively. A similar pattern was observed in total potassium uptake whereby Treatment 6 (1378mg plant^{-1}), Treatment 7 (1502mg plant^{-1}) and Treatment 8 (1528mg plant^{-1}) registered significantly ($P \leq 0.05$) less total potassium uptake over the control (T1, 2320mg plant^{-1}). This was a decrease of 41%, 35% and 34% respectively.

In the third stage (Table 5.14), Treatment 2, Treatment 3, Treatment 4 and Treatment 5 showed no significant differences over the control (T1) in the total nitrogen, phosphorus and potassium uptake. However Treatment 6 (2238mg plant^{-1}), Treatment 7 (3036mg plant^{-1}) and Treatment 8 (2785mg plant^{-1}) registered significantly ($P \leq 0.05$) less in the total nitrogen uptake over the control (T1, 4371mg plant^{-1}) which amounted to a decrease of 49%, 31%, and 36% respectively. A similar pattern was observed in total phosphorus uptake whereby Treatment 6 (85mg plant^{-1}), Treatment 7 (92mg plant^{-1}) and Treatment 8 (90mg plant^{-1}) registered significantly ($P \leq 0.05$) less in the total potassium uptake over the control (T1, 117mg plant^{-1}). This was a decrease of 28%, 21% and 23% respectively. The total potassium uptake also followed a similar pattern, whereby Treatment 6 (2373mg plant^{-1}), Treatment 7 (3249mg plant^{-1}) and Treatment 8 (2941mg plant^{-1}) registered significantly ($P \leq 0.01$) lower values than Treatment 1 (control, 4745mg plant^{-1}). This was a decrease of 52%, 34% and 40% respectively.

The higher total nitrogen, total phosphorus and total potassium uptake of plants in Treatment 1 (control), Treatment 2, Treatment 3, Treatment 4, and Treatment 5 in the second (S2) and third (S3) stage was a result of significantly higher dry matter production at (Table 5.10).

5.3.8 Nutrient concentration in leaves

The concentration of micro-nutrients in the fertiliser treatments varied considerably (Table 5.4). Therefore, it was expected that plants growth might be affected by the various levels of micro-nutrients as well as NPK. Leaf nutrient analysis at final harvest (Table 5.15) indicated that plants in Treatment 6 exhibited the lower range of micro-nutrient content while Treatment 4 exhibited the higher range of micro-nutrient content when compared with the micro-nutrient ranges considered necessary for bell pepper (Hochmuth, 2003a) (details in Appendix 7). These micro-nutrient differences in Treatment 6 and in Treatment 4 might explain the reduced plant's growth (Table 5.7 and Table 5.8) and yield (Table 5.9 and Table 5.10) in these treatments.

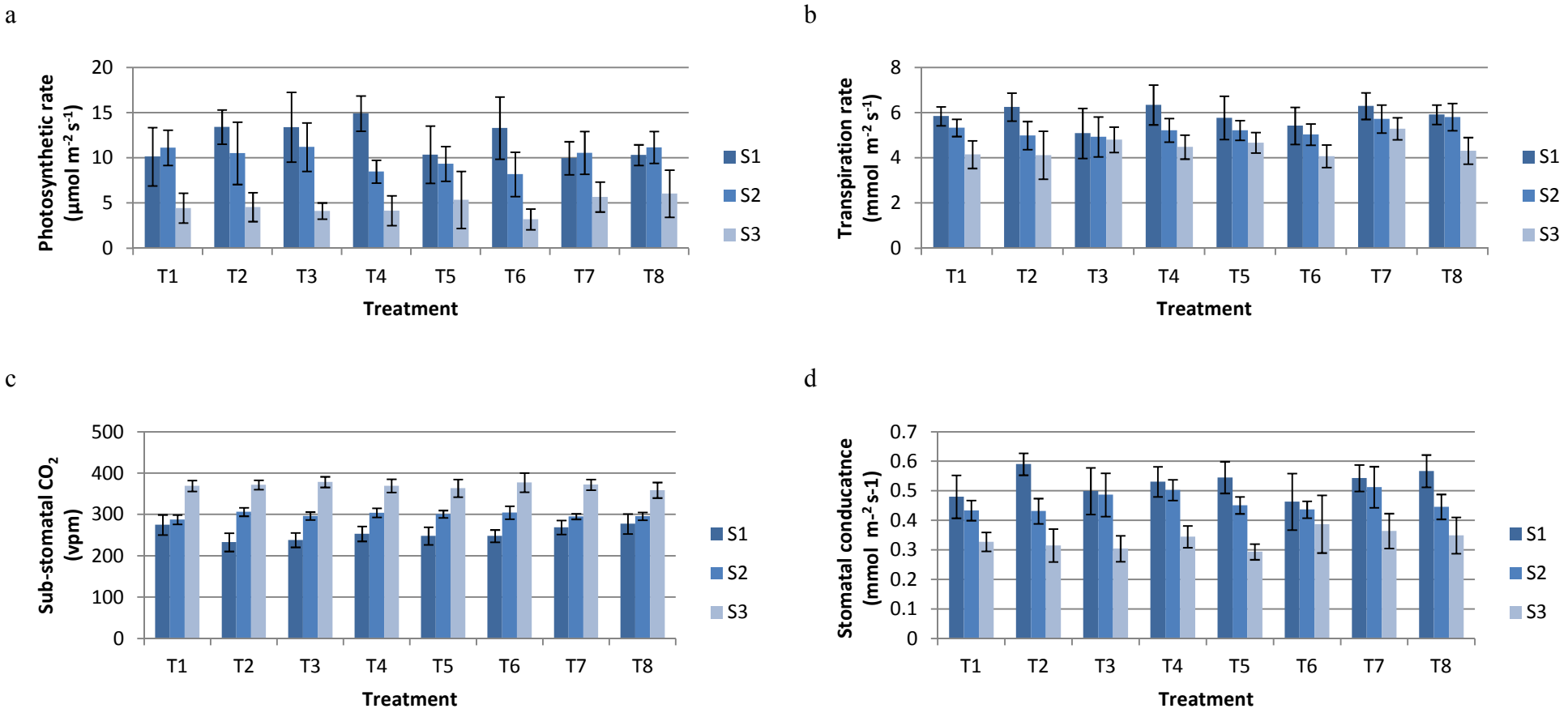


Figure 5.6 Leaf gas exchange parameters: (a) photosynthetic rate; (b) transpiration rate; (c) sub-stomatal CO_2; and (d) sub-stomatal conductance of bell peppers as affected by different treatments at various growth stages

Table 5.13 Effects of varying N and K rates on NPK uptake of nutrients in bell pepper at Stage 2 (34 to 61-DAT)

Treatment	Nitrogen			Phosphorus			Potassium		
	mg plant^{-1}								
	Leaf	Stem	Total	Leaf	Stem	Total	Leaf	Stem	Total
T1 (control)	1002.8	549.5	1552.3a	36.3	22.2	58.4a	1128.8	1191.4	2320.2a
T2	980.7	454.0	1434.7a	34.9	19.5	54.5a	1036.0	1117.8	2153.8a
T3	1498.5	709.8	2208.3a	40.5	25.4	65.8a	1462.5	1329.9	2792.4a
T4	1552.1	712.5	2264.6a	46.4	22.5	68.9a	1591.5	1306.6	2898.1a
T5	1642.4	754.8	2397.2a	45.0	19.9	64.9a	1566.6	1245.3	2811.9a
T6	529.9	279.4	809.3b	24.8	18.1	42.9b	553.3	824.5	1377.8b
T7	554.2	313.2	867.3b	26.8	19.0	45.8b	580.9	920.6	1501.5b
T8	611.9	313.6	925.6b	26.1	17.7	43.7b	630.8	897.6	1528.4b

Means in each column, followed by different letters are significantly different at $p \leq 0.05$ by Tukey's test

Table 5.14 Effects of varying N and K rates on NPK uptake of nutrients in bell pepper at Stage 3 (62 to 95-DAT)

Treatment	Nitrogen				Phosphorus				Potassium			
	mg plant^{-1}											
	Leaf	Stem	Fruit	Total	Leaf	Stem	Fruit	Total	Leaf	Stem	Fruit	Total
T1 (control)	1013.0	535.1	2822.4	4370.5a	30.2	21.6	65.5	117.3a	1007.1	1138.8	2792.2	4938.1a
T2	1215.7	744.3	2789.7	4749.7a	31.7	19.9	63.2	114.8a	1096.9	1261.7	2935.5	5294.1a
T3	1249.8	582.8	2697.6	4530.2a	31.1	22.6	59.5	113.2a	1292.1	1114.8	2729.7	5136.6a
T4	1544.8	764.9	2676.9	4986.6a	38.6	18.3	52.9	109.8a	1458.1	1213.3	2756.3	5427.7a
T5	1181.1	748.9	2250.9	4180.9a	40.6	19.4	53.3	113.3a	1214.2	1090.3	1849.1	4153.5a
T6	526.9	351.5	1359.4	2237.9b	20.7	18.6	45.6	84.9b	473.6	787.5	1111.7	2372.8b
T7	734.8	455.9	1845.0	3035.7b	23.4	19.2	49.6	92.2b	569.4	845.7	1833.6	3248.7b
T8	695.6	403.6	1685.3	2784.5b	22.5	20.6	47.3	90.4b	542.6	719.9	1678.0	2940.6b

Means in each column, followed by different letters are significantly different at $p \leq 0.05$ by Tukey's test

Table 5.15 Mineral concentration in leaves at final harvest in bell pepper as influenced by varying nitrogen and potassium rates

Treatment	Micronutrient concentration (mg g^{-1})						
	Mg	Fe	Mn	Zn	Cu	B	Mo
T1 (control)	0.03	0.040	0.033	0.027	0.051	0.021	0.0001
T2	0.03	0.092	0.033	0.034	0.073	0.028	0.0001
T3	0.03	0.093	0.035	0.037	0.075	0.032	0.0001
T4	0.04	0.147	0.099	0.078	0.093	0.039	0.0001
T5	0.03	0.090	0.031	0.029	0.064	0.029	0.0001
T6	0.02	0.020	0.021	0.017	0.022	0.014	0.0001
T7	0.03	0.035	0.025	0.020	0.036	0.018	0.0001
T8	0.03	0.031	0.023	0.020	0.034	0.019	0.0001

5.4 Discussion

The effect of fertiliser nitrogen and potassium concentration during the first stage was not significantly different due to all the plants receiving the same nutrient treatment (126-55-106 mg l^{-1} of N, P and K respectively). However in the second and third stages, data showed significant differences generally favouring the treatments subjected to 126-55-106 and 500-55-625mg l^{-1} of NPK (Treatment1 – control, Treatment 2, Treatment 3, Treatment 4, and Treatment 5) out performing treatments subjected to the low end of NPK concentration (42-55-71 mg l^{-1} of NPK) i.e. Treatment 6, Treatment 7 and Treatment 8).

Data on growth parameters (Table 5.7 and Table 5.8) shows that increasing nutrient NPK concentration from 42-55-106mg l^{-1} to 126-55-106mg l^{-1} increases growth parameters (plant height, stem diameter and leaf area), however a further increase to 500-55-625mg l^{-1} did not significantly affect growth rate. Significantly greater growth rate was recorded in Treatment 1 (control), Treatment 2, Treatment 3, Treatment 4, and Treatment 5 over Treatment 6, Treatment 7 and Treatment 8 in the second and third stages, which was attributed to taller plants with thicker stems (Table 5.7) and greater leaf area (Table 5.8). Better growth rate of plants subjected to 126-55-106mg l^{-1} and 500-55-625mg $l^{-1}$of NPK over those plants subjected to 42-55-72mg l^{-1} could be because the amount of nitrogen available to the latter plants was deficient. Nitrogen is the mineral element that plants require in the greatest amounts and it serves as a constituent of many plant cells components, including amino acids, proteins, and nucleic acids (Taiz and Zeiger, 2010). Nitrogen deficiency therefore can inhibit plant growth.

Significantly higher yield (Table 5.9) was recorded Treatment 1 (control), Treatment 2, Treatment 3, Treatment 4, and Treatment 5) mainly through increased growth parameters (Table 5.7 and 5.8) and NPK uptake (Table 5.11 and 5.12). Treatment 1 (control), Treatment 2, Treatment 3, Treatment 4, and Treatment 5 (556g plant^{-1}) gave a significantly higher fresh fruit weight above Treatment 6, Treatment 7, and Treatment 8. Treatment 6, Treatment 7, and Treatment 8 registered lower yield over the control (Treatment 1) by 24%, 17% and 15% respectively. This yield increase in Treatment 1 (control), Treatment 2, Treatment 3, Treatment 4, and Treatment 5 over Treatment 6, Treatment 7 and Treatment 8 can be attributed to greater fruit size (Table 5.9).

Yield of plants in Treatment 7 (126-106; 42-71; and 126-106mg l^{-1} of N, P and K respectively) was significantly different from Treatment 2 (126-106; 126-106; and 500-625mg l^{-1} of N, P and K respectively) even though the difference in nutrient supply between the two treatments can be considered minimal, which suggests it is low level of nutrient supply particularly at second stage (S2) which seems to be a limiting factor (Table 5.9).

Total fruit yield (fresh weight) per plant of Treatment 2, Treatment 3, Treatment 4, and Treatment 5 did not show significant difference over Treatment 1 (control), however fruits of plants from Treatment 1 (control) registered higher value. Reduction in fruit fresh weight in Treatment 2, Treatment 3, Treatment 4 and Treatment 5 over the control (Treatment 1) can be attributed to high solution electrical conductivity as reported by other researchers (Ehret and Ho, 1986). Uptake of water into the fruits is reduced by a high osmotic pressure of the nutrient solution and as a result the fruit size becomes smaller (Ling Li et al., 2001).

Fruits in Treatment 4 (subjected to 500-55-615mg l^{-1} of NPK at second and third stages) were significantly more affected by BER which reduce the yield (not significantly) over the control (Treatment 1) and other Treatments (T2, T3, T5, T6, T7 and T8) (Table 5.9). The higher incidence of BER in fruits in Treatment 4 can be attributed to higher electrical conductivity (EC) in the nutrient solution (500-55-615 mg l^{-1}; EC= 2.6dS m^{-1}). It has been suggested that EC of more than 2.5dS m^{-1} may have detrimental effect of the plant (Sarooshi and Cresswell, 1994). This could be associated with a reduction in calcium supply as well as distribution to the fruit (Ehret and Ho, 1986). The reduction

of yield in high EC treatment due to high percentage of BER in the fruits which was also reported by other researchers (Tabatabaie et al., 2004).

The total dry matter (TDM) production in both second stage and third stage (Table 5.10) was significantly higher in Treatment 1 (control), Treatment 2, Treatment 3, Treatment 4, and Treatment 5, over Treatment 6, Treatment 7 and Treatment 8. The greater dry matter production in Treatment 1, Treatment 2, Treatment 3, Treatment 4, and Treatment 5 in second and third stage can be ascribed to greater leaf area production (Table 5.8). Significantly higher leaf area was recorded in Treatment 1, Treatment 2, Treatment 3, Treatment 4, and Treatment 5 over Treatment 6, Treatment 7 and Treatment 8. Higher leaf area contributed to more carbohydrate synthesis and higher yield (Silber et al., 2003). The difference can also be ascribed to other growth parameters in Treatment 1, Treatment 2, Treatment 3, Treatment 4, and Treatment 5 where plants were taller with thicker stems compared to Treatment 6, Treatment 7 and Treatment 8 in the second and third stage and consequently affected growth (Table 5.7 and Table 5.8), yield (Table 5.9) and NPK uptake (Table 5.11 and 5.12).

Treatment 1 (control), Treatment 2, Treatment 3, Treatment 4, and Treatment 5 recorded significantly higher NPK uptake (Table 5.13 and Table 5.14) over the Treatment 6, Treatment 7 and Treatment 8. The higher NPK uptake in Treatment 1 (control), Treatment 2, Treatment 3, Treatment 4, and Treatment 5 was associated with higher dry matter production (Table 5.10).

The study suggest that NPK concentration 44-55-71 mg l^{-1} was inadequate for plant growth, and increasing concentration to 126-55-106 mg l^{-1} increased growth and yield. On the other hand, 500-55-625 mg l^{-1} NPK was an excess amount as no further increase in growth and yield were recorded. In fact it had detrimental effects on the plants e.g. greater incidence of BER and reduction in fruit size (Table 5.9) and may also have posed environmental pollution problems as substantial amount of nutrients were wasted in the leachate (Table 5.6).

5.5 Conclusion

In soil-less culture, the growth and the yield of bell pepper respond differently to different levels of NPK concentrations. In good agreement with previous studies, the

current study found that increasing the NPK concentration from low concentration (44-55-71 mg l^{-1}) to intermediate concentration (126-55-106mg l^{-1}) significantly increased growth and yield of bell pepper however no further increases were recorded when fertiliser concentration increased to 500-55-625mg l^{-1}. Plants subjected to high NPK concentration of 500-55-615mg l^{-1} in the second and third stage (Treatment 4) had greater fruits with BER and less efficient in the use of fertiliser which resulted in substantial amounts of nutrients were being wasted in the leachate.

The present study also revealed that, in soil-less culture, growth and yield of bell pepper respond differently to different levels of salinity (EC). The use of different ranges of NPK rates in the current study also resulted in a wide range in the fertigation solution's electrical conductivity (EC). Potentially, crop growth reduction may occur when fertigation solution has both low and high EC. The present study demonstrated that at low EC, not enough nutrients may be available to the plants resulting in a decrease in crop growth. At high EC, although ample nutrients are available, a decrease in water uptake may occur due to osmotic effects in fertigation water (highly negative osmotic potential), which may result in reduced crop growth and yield (Marcelis et al., 2003). The present study clearly demonstrated that the detrimental effects of high EC on the yield of soil-less grown bell pepper are due to a decreased mean fruit weight and higher incidence of BER. Similar findings were obtained by other researchers (Adams, 1991). The detrimental effects of high EC on the yield rather than on the vegetative organs in bell pepper can be attributed to a restriction of water accumulation in the fruit (Johnson et al., 1992).

This study was taken further (Chapter 6) in order to investigate the effect of varying fertigation frequency in bell pepper production grown in rockwool. This was considered necessary in view of the potential fertigation frequency in bell pepper growth, and yield.

Chapter 6

Effects of varying fertigation frequency on growth and development of bell peppers

6.0.1 Introduction

In previous chapters (Chapter 4 and 5), the studies of different nitrogen (N) and potassium (K) rates in greenhouse bell pepper production grown in rockwool are presented. However, the fertigation frequency of both experiments was maintained the same (five irrigation events per day). Previous studies have shown yield improvement in bell pepper with increased fertigation frequency (Silber, 2005). Thus, the effect of fertigation frequency needs to be investigated in order to find out the effect of varying fertigation frequency at different growth stages for greenhouse bell pepper production grown in rockwool.

In modern irrigated agricultural systems, especially in greenhouses using soil-less culture technique, water and nutrients are supplied simultaneously (fertigation), mainly by drip irrigation (Bar-Yosef, 1999). Frequent application of water and nutrients ensures that the root surface and its vicinity are well supplied with fresh nutrient solution during fertigation events and subsequent distributions (Silber et al., 2005). These frequent replenishments prevent the formation of depletion zone in the vicinity of the root surface by uptake of nutrients between successive events, decrease the concentration gradient between the medium solution and the root-medium interface and diminish the role of diffusion in transporting nutrients toward the root (Silber et al., 2003).

Bell pepper grown under protected cultivation (greenhouse) in artificial substrate is a valuable crop worldwide (Silber et al., 2005). Efforts to increase crop yields has led to frequent fertigation and, therefore, the time scale between successive fertigation events has diminished to hours or even less. Under these circumstances, the mechanism of nutrient movement towards the roots may differ from that considered in the traditional approach. As the period between successive irrigation events becomes longer, the nutrient concentration in the vicinity of the roots may be high or even excessive immediately after irrigation but may fall to deficit levels as time proceeds. Reducing the

time interval between successive irrigations in order to maintain constant, optimal water content in the root zone may reduce the variations in nutrient concentration, thereby increasing their availability to plants and reducing their leaching beneath the root zone.

Removal of leaves (defoliation) of plants is a practice used by plant growers due to the perceived positive influence on the yield (Decoteau, 1990). Defoliation may be a useful tool in improving water and fertiliser use efficiency in bell pepper production (HDC, 2009). However there is a potential risk that defoliation may resulted in yield reduction (Ramirez et al., 1988).

Relatively little is known about the effect of fertigation frequency applied at different growth stages of bell pepper. The present study investigated the effects of fertigation frequency on bell pepper growth, development, yield, leaf chlorophyll, and photosynthesis in two different experiments. These are presented in two sections in this chapter:

- Chapter 6.1: Effect of varying fertigation frequency at different growth stages on growth and development of bell pepper grown in rockwool.
- Chapter 6.2: Effect of varying fertigation frequency and defoliation on growth and development of bell pepper grown in rockwool.

6.0.2 Materials and Methods

A detailed description on the methodology and materials employed in both experiments can be found in Chapter 3.

6.0.2.1 Condition and Crop Details

Two experiments were conducted concurrently in the spring to summer season (4 May to 26 August 2009): effects of varying fertigation frequency at different growth stages (main experiment) and effects of defoliation with varying fertigation frequency (ancillary experiment) respectively.

Bell peppers (*Capsicum annuum* L. var. Ferrari) were supplied by a plant-raiser at about 4 weeks old. The bell pepper seedlings were raised in peat plugs. They were transplanted to rockwool 10x10cm blocks (Grodan) on 22 April 2010 and then transferred to 1m rockwool slab (Grodan) in the greenhouse on 4 May 2010.

Temperature and evaporation rate data were recorded from thermometer and evaporating pan inside the greenhouse. During the entire growth period the maximum air temperature varied between 25 and 51^{o}C and minimum between 10 and 16^{o}C with estimated evaporation rate between 0.6 and 5mm. (Details included in the Appendix 3).

6.0.2.2 Experimental Set Up

The experimental layout for both experiments is shown in Figure 6.1. In both experiments, a completely randomised design with three replicates was used and bell pepper plants were subjected to treatments at three different growth stages: S1: 1 to 43-DAT (days after transplanting); S2: 44 to 64-DAT and S3: 65 to 84-DAT. Each experimental unit consisted of one 1m rockwool slab containing 3 plants.

6.0.2.3 Fertigation Set Up

In both experiments, plants were fertilized with the complete nutrient solution as shown in Table 6.1. The fertigation nutrient treatments were the same for all treatments. The nutrients solution was prepared from commercial fertiliser (Scotts 20N-20P_2O_5-20K_2O, professional water soluble fertiliser). Tap water was used to prepare all nutrient solution and was used as irrigation water. The mineral composition of the nutrient solution and irrigation water is shown in Table 6.1.

Table 6.1 Elemental composition (mg l^{-1}) of the nutrient solution and irrigation water used in the experiment

	mg l^{-1}									
	N	P	K	Ca	Zn	Mg	Fe	Mn	Cu	Mo
20N-20P_2O_5-20K_2O	126	55	106	46.1	6.4	6.4	0.9	0.4	0.1	0.02
Irrigation water	1.22	18.0	14.6	33.2	0.02	5.8	0.01	0.01	0.01	0.002

In both experiments, nutrient solution was pumped from three independent tanks (one tank of 20L per experimental unit) through drip irrigation. The nutrient solution was administrated through one emitter per plant (flow rate 2L h^{-1}) and the excess was drained out. Fertilisers were injected through the non-electrical proportional injector from Dosatron International (Model DI.1500) at a rate of 1% (1:100). Irrigation scheduling was performed using irrigation controller (Heron, M*i*-4).

The fertigation uniformity was checked at the beginning of the experiment (1 May 2010). The uniformity coefficient (Uc) of fertigation system used in the study was

found to be 94.5% (Table 6.2) which is an excellent rating for drip irrigation uniformity when compared to statistical uniformity of drip irrigation provided by ASAE (Table 3.2 in Chapter 3). The high values of uniformity coefficient indicated excellent performance of fertigation system in this study in supplying nutrient solution throughout the emitters during the experiment

Table 6.2 Uniformity coefficient of the fertigation system

Mean volume (ml, in 5 minutes)		Discharge rate (q) ml min^{-1}		Mean deviation (Δq)	Uniformity coefficient (%)	SE mean (σM)
Mean	SEM	Mean	SEM			
149.8	0.72	30.0	0.14	1.65	94.5	0.32

6.0.3 Measurements

The detailed description measurement of parameters in the study is similar to that explained in previous experiments (Chapter 4 and Chapter 5).

6.0.3.1 Growth and Development

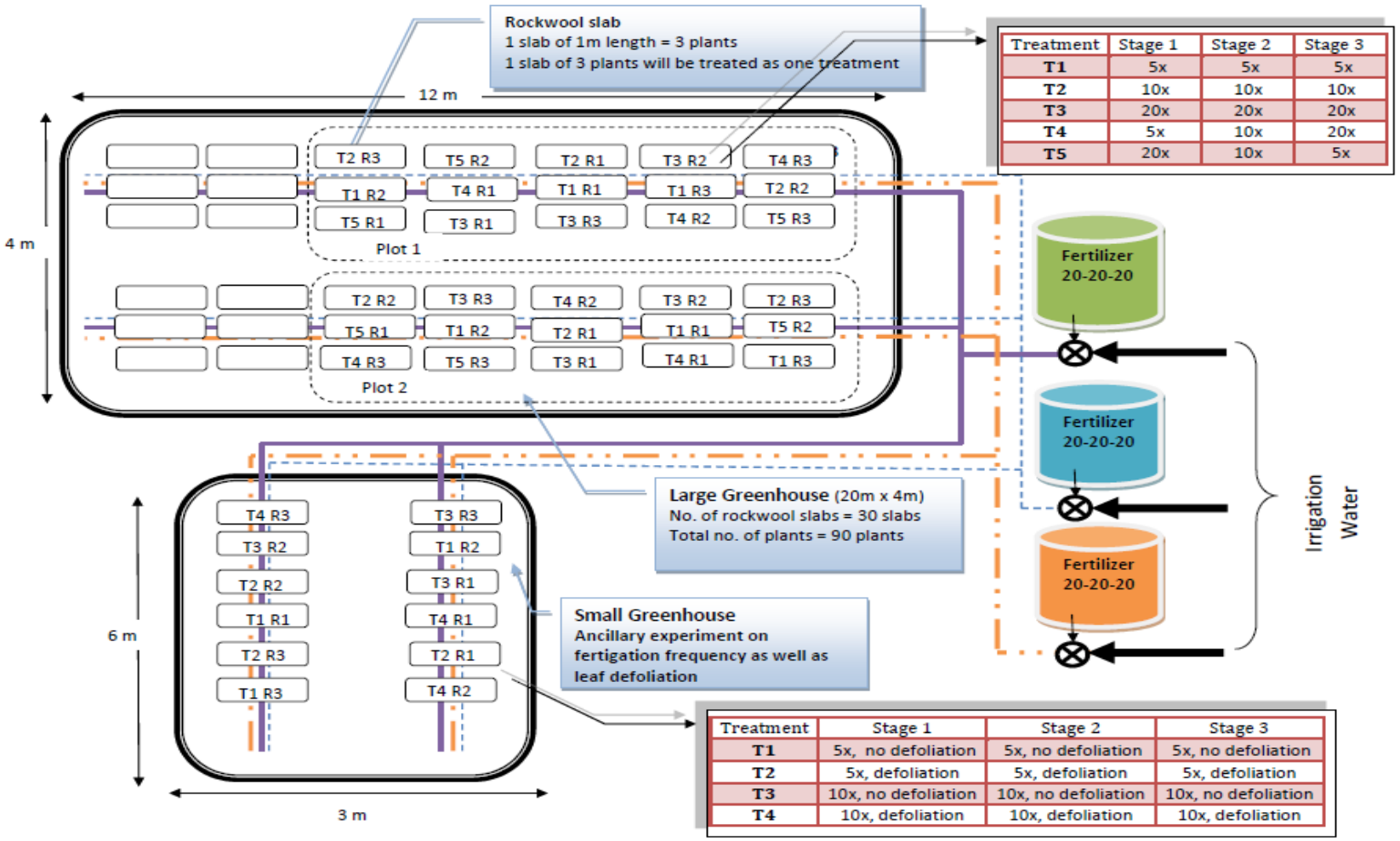
Growth and development parameters such as plant height, stem, diameter, and leaf area were recorded at every growth stage. Plant height (cm) and stem diameter (mm) were measured at 35-DAT (S1), 56-DAT (S2), and 79-DAT (S3) while leaf area (cm^2) was measured at the end of every growth stage i.e. 43-DAT (S1), 64-DAT (S2), and 84-DAT (S3) using the method as described in previous chapters.

6.0.3.2 Leaf Gas Exchange

Photosynthetic, transpiration rate, sub-stomatal CO_2 and stomatal conductance were measured on the apical leaflet using LC*i* infrared gas analyser (ADC BioScientific Ltd, Hertfordshire, UK) at 29-DAT (S1); 52-DAT (S2); and 83-DAT (S3). Infrared gas analyser (IRGA) measurements were made on three youngest fully expanded exposed leaves per treatment on each occasion on a cloudless day.

6.0.3.3 Leaf Chlorophyll Determination

The leaf chlorophyll concentration was measured on one fully expanded leaf per plant using the SPAD-502 chlorophyll meter (Konica, Minolta), at 13-DAT (S1); 48-DAT (S2); and 78-DAT (S3).



Treatment	Stage 1	Stage 2	Stage 3
T1	5x	5x	5x
T2	10x	10x	10x
T3	20x	20x	20x
T4	5x	10x	20x
T5	20x	10x	5x

Treatment	Stage 1	Stage 2	Stage 3
T1	5x, no defoliation	5x, no defoliation	5x, no defoliation
T2	5x, defoliation	5x, defoliation	5x, defoliation
T3	10x, no defoliation	10x, no defoliation	10x, no defoliation
T4	10x, defoliation	10x, defoliation	10x, defoliation

Figure 6.1 The layout of the experimental design and treatment allocation

6.0.3.4 Leaf weight ratio and specific leaf area

Leaf weight ratio (LWR; g g^{-1}) is the ratio of leaf dry biomass to total plant dry biomass and thus a measure of the proportion of the plant dry biomass in the leaf material. LWR was calculated as proportion of the total leaf dry weight to the total above-ground dry weight of the sample plants at harvest (Harrington et al., 1997).

Specific leaf area (SLA; leaf area (cm^2)/leaf dry biomass (g)) is the ratio of leaf area to leaf plant dry biomass and thus a measure of leaf thickness (Garnier et al., 2001). For SLA, leaf area was determined using the WinDIAS 3 image analysis system (Delta-T Devices, Cambridge, UK) (Figure 3.17), recorded and leaves were weighed using an analytical balance after drying for 24 hours in an oven at 80° C. Specific leaf area (SLA) was expressed in cm^2 leaf area g^{-1} dry weight.

6.0.3.5 Yield and Yield Components

At final harvest, fruit number, total fresh mass of fruit for each individual plant and fruit quality (fruit diameter and length) were recorded. Fruit from individual plants were examined for blossom-end rot (BER) incidence. The plants were divided into leaves, stems and fruits, and then were oven dried at 80^oC for up to 48 hours for aboveground biomass determination.

6.0.3.6 Plant sample analysis for nutrients

The dried leaves, stems, and fruits were pooled for each treatment and for nutrient analysis. The dried leaves, stems, and fruits were ground to fine powder and stored in a sealed plastic bag until nutrient (nitrogen, phosphorus, and potassium) content was determined as described in Chapter 3.

6.1

A greenhouse study of the effects of varying irrigation frequency at different growth stages on production of bell pepper

6.1.1 Treatment details

The key hypothesis of this investigation was that by increasing frequency with which, water and nutrients (i.e. of fertigation) are supplied would increase growth and yield of bell pepper by enhancing water and nutrients uptake.

The experiment was laid out in completely randomised design having five treatments as shown in Table 6.3. Each treatment was replicated three times. The growing period of bell pepper was divided to three growth stages: Stage 1: 1 to 43-DAT; Stage 2: 44 to 64-DAT; and Stage 3: 65 to 84-DAT. Treatments consisted of three varying fertigation frequencies in the order of the growth stages (S1, S2, and S3). Three irrigation frequencies were 5, 10 and 20 times daily, designated as low (I1), high (I2) and very high (I3) frequency respectively.

Table 6.3 Treatment details of varying fertigation frequency at different growth stages

Treatment	S1 (1 to 43-DAT)	S2 (44 to 64-DAT)	S3 (64 to 84-DAT)
	Irrigation events day^{-1}		
T1 (control)	5 (I1)	5 (I1)	5 (I1)
T2	10 (I2)	10 (I2)	10 (I2)
T3	20 (I3)	20 (I3)	20 (I3)
T4	5 (I1)	10 (I2)	20 (I3)
T5	20 (I3)	10 (I2)	5 (I1)

Irrigation schedules were set up by an irrigation controller (Heron M*i*-4) and were scheduled according to the different fertigation frequency (Table 6.4). An identical daily amount of water was used in all the treatments. Identical amounts of nutrient feed were delivered to the plants in total day (Table 6.1). However the volume of nutrient solution delivered to the plants per irrigation events varied at different stages (S1-800ml; S2-1000ml; and S3-1500ml for 5, 6 and 9 minutes respectively) in response to plant growth and development. Table 6.5 shows the treatment irrigation frequency cycles and volume of irrigation on daily basis.

Table 6.4 Scheduling of fertigation events used in the study

Fertigation events day^{-1}	Scheduling	Irrigation volumes (ml plant^{-1})		
		S1	S2	S3
5 x daily	08:00; 10:00; 12:00; 14:00; and 16:00 hrs			
10 x daily	08:00 and then every 1 hour until 17:00 hrs	800	1000	1500
20 x daily	08:00 and then every 30 min until 18:00 hrs			

Table 6.5 Irrigation frequency cycles and volume of irrigation on daily basis.

a) Stage 1

Fertigation events day^{-1}	Nutrient solution cycle^{-1} litres cycle^{-1}	Irrigation duration cycle^{-1} seconds cycle^{-1}	Nutrient solution day^{-1} litres day^{-1}	Irrigation duration day^{-1} seconds day^{-1}
5x daily	0.16	60	0.8	300
10x daily	0.08	30	0.8	300
20x daily	0.04	15	0.8	300

b) Stage 2

Fertigation events day^{-1}	Nutrient solution cycle^{-1} litres cycle^{-1}	Irrigation duration cycle^{-1} seconds cycle^{-1}	Nutrient solution day^{-1} litres day^{-1}	Irrigation duration day^{-1} seconds day^{-1}
5x daily	0.20	72	1.0	360
10x daily	0.10	36	1.0	360
20x daily	0.05	18	1.0	360

c) Stage 3

Fertigation events day^{-1}	Nutrient solution cycle^{-1} litres cycle^{-1}	Irrigation duration cycle^{-1} seconds cycle^{-1}	Nutrient solution day^{-1} litres day^{-1}	Irrigation duration day^{-1} seconds day^{-1}
5x daily	0.30	108	1.5	540
10x daily	0.15	54	1.5	540
20x daily	0.075	27	1.5	540

Diagrammatic representation of fertigation treatments to indicate how fertigation frequency applications changed over the three growth stages is shown in Figure 6.2.

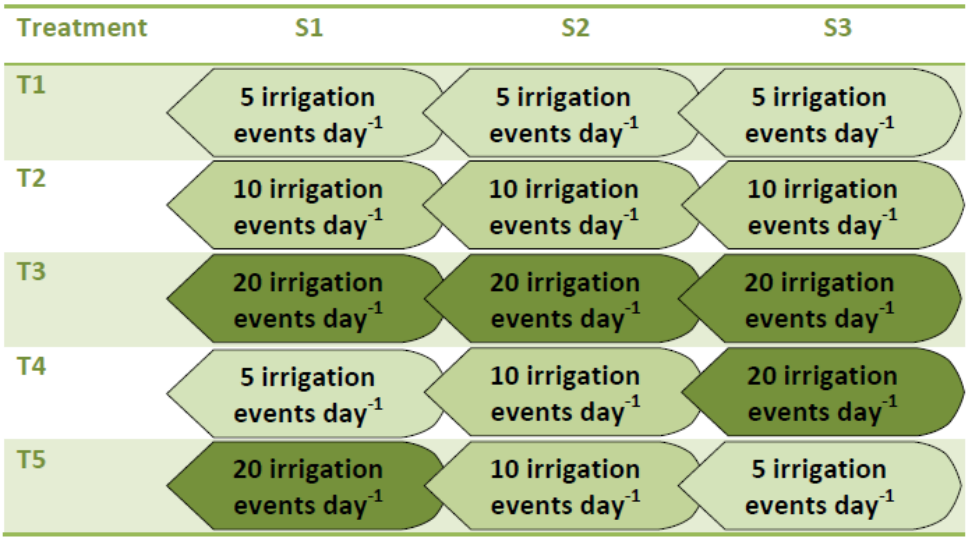


Figure 6.2 Diagrammatic representations of fertigation treatments. The colour scheme represents the fertigation frequencies at different stage, the frequencies increases from light (low) to darker (high) colour.

6.1.2 Results and Discussion

6.1.2.1 Plant growth characteristics

Figure 6.3 and 6.4 shows the difference in plant height and stem diameter between treatments at various growth stages. Increased irrigation frequency increased plant height and stem diameter of bell pepper plant.

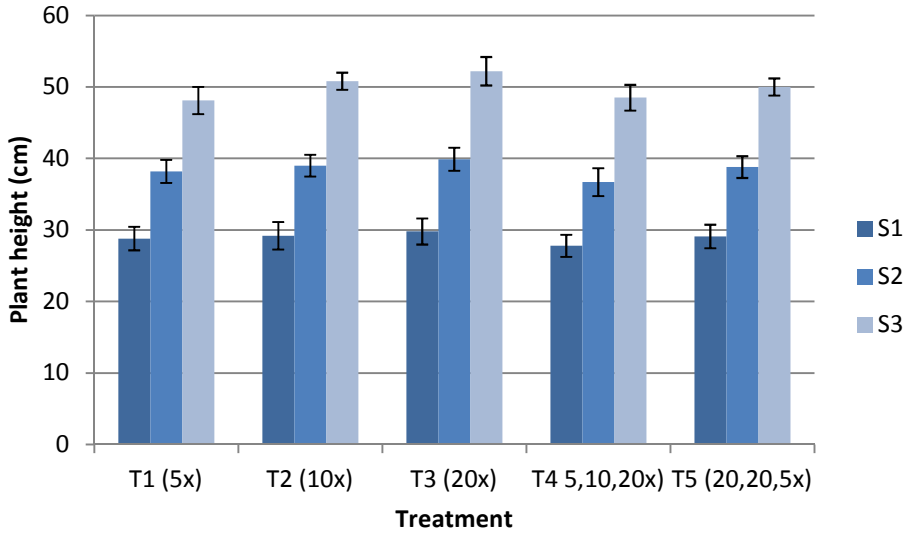


Figure 6.3 Plant heights as affected by different treatments at various growth stages

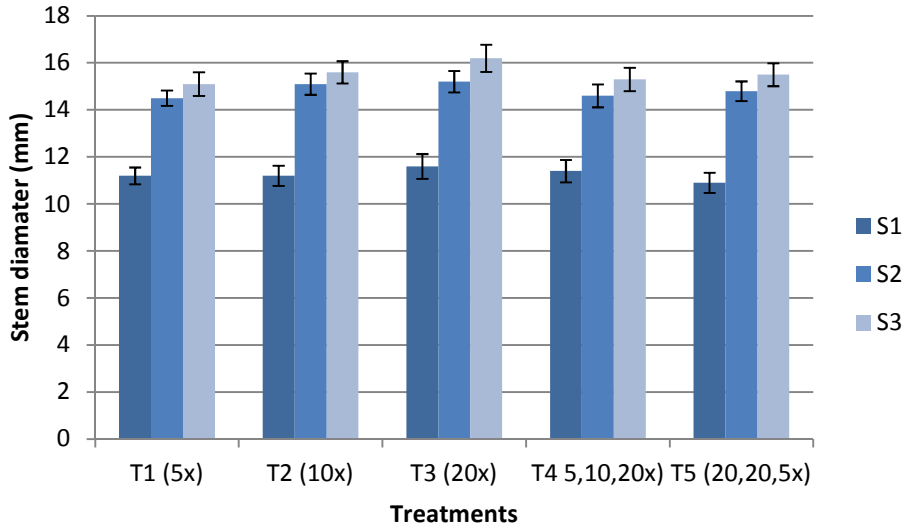


Figure 6.4 Stem diameter as affected by different treatments at various growth stages

However, there were no marked differences in plant height and stem diameter between treatments at any growth stages. However a trend was observed whereby Treatment 3 (20 irrigation events day^{-1} throughout the season) produced the tallest plants and thickest stems. Treatment 3 gave taller plants with thicker stems (plant height: 52.2cm; stem diameter 16.2mm) than the control (Treatment 1; 5 irrigation events day^{-1} throughout the season; plant height: 48.1cm and stem diameter: 15.1mm) by 8% and 7% respectively. Plants from Treatment 2 (10 irrigation events day^{-1} throughout the season), Treatment 4 (5, 10, and 20 irrigation events day^{-1} in S1, S2, and S3 respectively) and Treatment 5 (20, 10, and 5 irrigation events day^{-1} in S1, S2 and S3 respectively) were also taller with thicker stems than the control (Treatment 1). However differences were not significant.

Increasing fertigation frequency also increased leaf area per plant primarily (Table 6.6). There were no significant differences in the leaf area production of plants in the first (S1) and second (S2) stage. In the third stage Treatment 3 produced the biggest leaf area per plant (Table 6.6) and was 3531cm^2 and significantly greater than the control, Treatment 1 (2561cm^2) by 27%. Values for Treatment 2 (2913cm^2), Treatment 4 (2793cm^2) and Treatment 5 (2802cm^2) were also greater than the control (Treatment 1) by 12%, 8% and 9% respectively but were not statistically significant.

Table 6.6 Leaf area production of bell pepper as affected by different fertigation frequency treatments at different growth stages

Treatment	Leaf area (cm^2)		
	S1	S2	S3
T1 (control)	909.0	1622.0	2561.0b
T2	985.4	1993.0	2913.0ab
T3	1070.8	2224.9	3531.0a
T4	996.0	1949.0	2793.0ab
T5	992.2	1621.8	2802.2ab

Means in each column, followed by different letters are significantly different at $p \leq 0.05$ by Tukey's test.

6.1.2.2 Yield and yield components

There were no significant differences in numbers of fruits per plant between treatments (Table 6.7). This can be attributed to the removal of flower buds by pruning to control the number of fruits set per plant to ensure that they achieved marketable size. Bell peppers total fruit fresh weight per plant (Figure 6.5) indicates increasing fertigation frequency increased yield of bell pepper. However there were no significant differences between treatments.

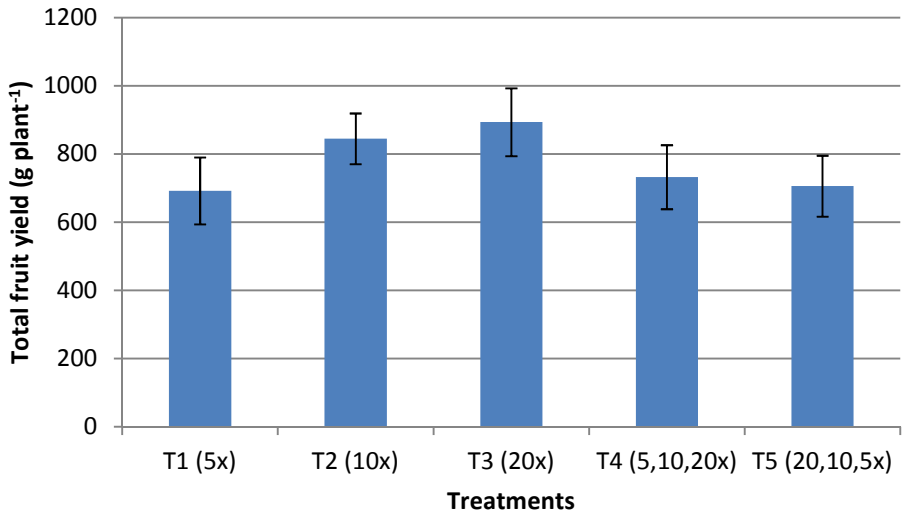


Figure 6.5 Total fruit yield (fresh weight) as affected by different fertigation frequency

At the same time the percentage of fruits affected with BER decreased with increasing fertigation frequency (Figure 6.6).

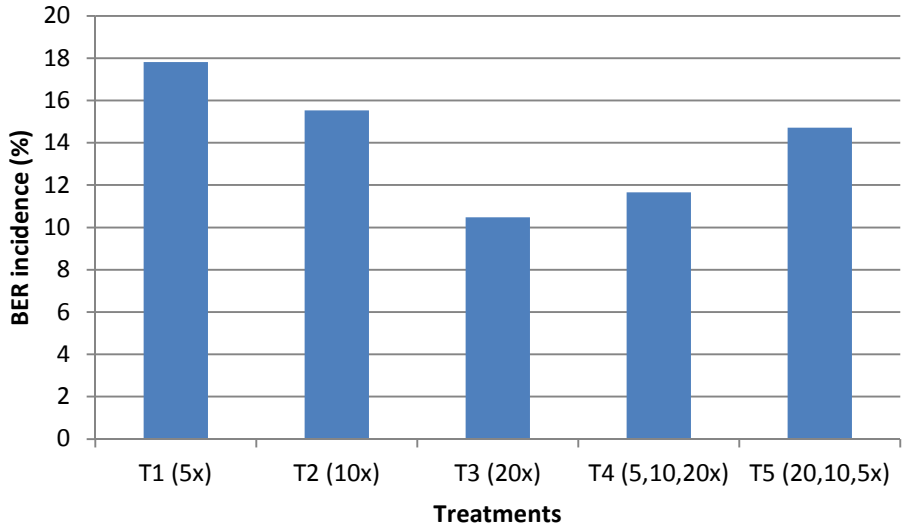


Figure 6.6 Percentage of fruits affected with BER by different fertigation frequency

Bell pepper marketable fruit fresh weight per plant (Table 6.7) on the other hand showed that bell pepper fertigated with 20 irrigation events day^{-1} through the season (Treatment3, 786.7g) increased fruit yield significantly (P≤0.05) per plant by 30% over the control (Treatment 1, 550.0g) (Table 6.7). This was because Treatment 3 (1.1 fruits plant^{-1}) had significantly (P≤0.05) less fruits affected with BER than the control (Treatment 1, 1.8 fruits plant^{-1}) by 39%. This significantly fewer fruits with BER in Treatment 3 can be attributed to better nutrient supply during the fertigation events (Silber et al., 2005). Treatment 2, Treatment 4 and Treatment 5 had fewer fruits with BER than Treatment 1 (control), but not significantly so. Furthermore, the higher yield in Treatment 3 was because fruits were 10.9mm (15%) longer and 6.9mm (12%) wider than the control (Treatment 1). Fruits from Treatments 2, 4 and Treatment 5 were also bigger than those from the control (Treatment 1) but none of the differences were significant.

6.1.2.3 Dry matter production and partitioning

The total dry matter (TDM) production of above ground plant material (leaf + stem + fruit) based on marketable fruit yield in the final harvest (Table 6.8) was higher in Treatment 3 (which provided 20 irrigation events day^{-1} throughout the season) when compared with other treatments. Treatment 3 (96.4g plant^{-1}) recorded significantly (p≤0.05) higher above ground dry matter production over the control (Treatment 1, 71.3g plant^{-1}) an increase of 26%.

Treatment 2 (92.7g plant^{-1}), Treatment 4 (77.8g plant^{-1}) and Treatment 5 (75.6g plant^{-1}) also registered higher above ground dry matter over the control (Treatment 1), however, there were no significant differences recorded in these treatments. The difference in dry matter production between treatments was associated with greater leaf area production (Table 6.6). Significantly higher leaf area production was recorded in Treatment 3 over the control (Treatment 1). High leaf area contributed to more solar radiation interception, carbohydrate synthesis (Silber et al., 2003) and resulted in higher yield (Table 6.7).

6.1.2.4 Harvest Index (HI)

Harvest index (HI) was greatest for Treatment 3 (61.5) and significantly ($p \leq 0.05$) higher than the control (Treatment 1; 58.8). The higher HI in Treatment 3 was because of higher fruit dry matter production in Treatment 3 (Table 6.8). There were no further significant differences between other treatments (T2, T4 and T5).

6.1.2.5 Specific leaf area (SLA) and leaf weight ratio (LWR)

Specific leaf area (SLA) tended to increase with increased irrigation frequency. Specific leaf area of Treatment 3 (160.5cm^2 g^{-1}) effect was significantly ($p \leq 0.05$) higher than the control (Treatment 1, 146.6cm^2 g^{-1}) (Table 6.7) by 9%. Whilst Treatment 2 (150.1cm^2 g^{-1}), Treatment 4 (156.0cm^2 g^{-1}) and Treatment 5 (154.0cm^2 g^{-1}) had higher SLA values than the control (Treatment 1) these differences were not significant. Leaf weight ratio (LWR) was unaffected by fertigation frequency (Table 6.8) indicating that the proportion of the plant dry biomass in the leaf material was similar in all treatments.

Table 6.7 Yield and yield components of bell pepper at the final harvest as affected by different fertigation frequency

Treatment	Total yield	Marketable Yield		Nos. fruits	BER	Fruit Quality	
	kg	g plant^{-1}	kg	Fruit plant^{-1}	Nos. plant^{-1}	Fruit width (mm)	Fruit length (mm)
T1 (control)	2.07	550.0	1.65b	10.1	1.8a	59.1	49.4
T2	2.53	713.3	2.14ab	10.3	1.6ab	64.8	53.9
T3	2.68	786.7	2.36a	10.5	1.1b	70.5	56.3
T4	2.12	650.0	1.95ab	10.3	1.2ab	60.1	51.2
T5	2.20	603.3	1.81ab	10.2	1.5ab	64.3	53.4

Means in each column, followed by different letters are significantly different at p≤0.05 by Tukey's test.

Table 6.8 Dry matter production, harvest index, specific leaf area, and leaf weight ratio of bell pepper at the final harvest as affected by different fertigation frequency

Treatment	Leaves	Stem	Fruit	Aboveground biomass	HI	SLA	LWR
	g plant^{-1}					cm^2 g^{-1}	g g^{-1}
T1 (control)	16.1b	13.3	41.9b	71.3b	58.8b	146.6b	0.23
T2	21.4ab	15.9	55.4ab	92.7ab	59.8ab	150.1ab	0.23
T3	22.0a	15.1	59.3a	96.4a	61.5a	160.5a	0.23
T4	17.9ab	15.0	44.9ab	77.8ab	57.7ab	156.0ab	0.23
T5	18.2ab	14.0	43.4ab	75.6ab	57.4ab	154.0ab	0.24

Means in each column, followed by different letters are significantly different at p≤0.05 by Tukey's test.

Table 6.9 Leaf photosynthesis, leaf transpiration and stomatal conductance as affected by different fertigation frequency treatments in bell pepper

Treatment	Net leaf rate of Photosynthesis (µmol m^{-2} s^{-1})			Leaf transpiration rate (mmol m^{-2} s^{-1})			Stomatal conductance (mmol m^{-2} s^{-1})		
	S1 (29-DAT)	S2 (52-DAT)	S3 (83-DAT)	S1 (29-DAT)	S2 (52-DAT)	S3 (83-DAT)	S1 (29-DAT)	S2 (52-DAT)	S3 (83-DAT)
T1 (control)	9.4	12.4	13.6	4.32	6.06	6.99	0.53	0.57	0.59
T2	11.8	14.2	14.4	5.10	6.42	7.61	0.60	0.61	0.63
T3	12.2	15.1	15.9	4.66	5.62	6.83	0.52	0.55	0.60
T4	10.6	13.0	14.4	5.12	6.32	6.81	0.52	0.60	0.61
T5	10.2	12.8	14.5	4.36	5.92	7.11	0.56	0.55	0.59

Values are the mean of 3 plants $treatment^{-1}$. Results were not significantly different between treatments

Table 6.10 Leaf chlorophyll content at different growth stages as affected by different fertigation frequency treatments in bell pepper

Treatment	Leaf chlorophyll content (SPAD unit)					
	Upper leaf			Lower Leaf		
	S1 (13-DAT)	S2 (48-DAT)	S3 (78-DAT)	S1 (13-DAT)	S2 (48-DAT)	S3 (78-DAT)
T1 (control)	52.93	61.27	55.06	64.33	78.43	75.74
T2	53.29	61.83	53.10	58.46	77.77	73.74
T3	53.39	60.74	54.57	65.33	78.11	75.96
T4	54.44	61.27	57.79	60.39	72.75	69.76
T5	51.59	62.13	54.47	63.55	75.73	71.69

Values are the mean of 18 plants, 15 plants and 12 plants in S1, S2 and S3 respectively. Results were not significantly different between treatments.

6.1.2.6 Leaf Gas Exchange

Net rate of leaf photosynthesis increased with increasing fertigation frequency (Table 6.9). Treatment 3 exhibited higher net leaf rate of photosynthesis compared to other treatments and was higher than the control (Treatment 1). Treatment 3 (12.2, 15.1, and 15.9 μmol m^{-2} s^{-1}) showed higher leaf photosynthesis rates than the control (Treatment 1: 9.4, 12.4, and 13.6 μmol m^{-2} s^{-1}) by 23%, 18% and 14% in S1, S2 and S3 respectively. Higher rate of leaf photosynthesis was also recorded in Treatments 2, 4 and 5 than the control (Treatment 1) in every growth stage but the differences were not significant. No significant differences were observed in other leaf gas exchange parameters: leaf transpiration rate and stomatal conductance. This may be due to large variability in data. However a trend was observed whereby photosynthesis rate, leaf transpiration, and stomatal conductance increased at every growth stage (Table 6.9).

6.1.2.7 Leaf Chlorophyll

No significant differences of the leaf chlorophyll content (SPAD values) among the treatments were observed in any stages of plant growth on both top and bottom leaves (Table 6.10). However there seems to be some trends indicating the leaf chlorophyll (SPAD values) increased from stage 1 to stage 2 but decreased again in stage 3 and the lower leaf registered higher leaf chlorophyll value compared to the upper leaf.

6.1.2.8 Leaf- nitrogen (N), phosphorus (P) and potassium (K) concentration

Figure 6.7, 6.8, and 6.9 shows the leaf- nitrogen (N), phosphorus (P) and potassium (K) concentration at different growth stages (S1, S2, and S3).

The concentration of N in leaves declined (Figure 6.7) at every growth stage for all treatments. Over all three growth stages, the concentration of P in tissues increased as irrigation frequency increased from 5 to 10 and to 20 irrigation events day^{-1} (Figure 6.8). Leaf P concentration in higher irrigation frequency (10 and 20 irrigation events day^{-1}) increased in S2 (peaked) and S3 over the lower irrigation frequency (5 irrigation events day^{-1}) which declined at every growth stage. The K concentration in the leaf tissues was greatest during the vegetative growth stage (S1) and flowering initiation stage (S2) and declined as plant maturity progressed (Figure 6.9). The concentration of K in leaf peaked at S2 and was lowest at S3.

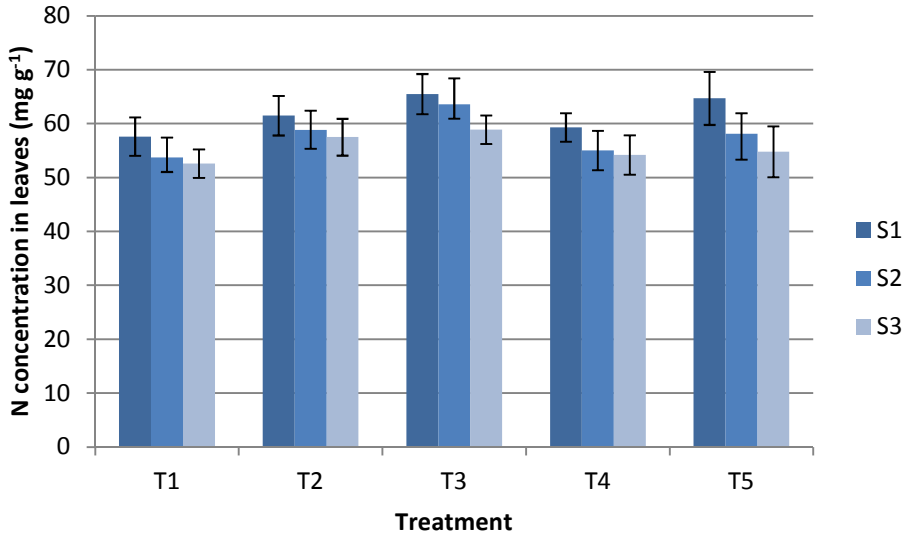


Figure 6.7 Nitrogen concentrations of the leaves as a function of different treatments and plant development stage

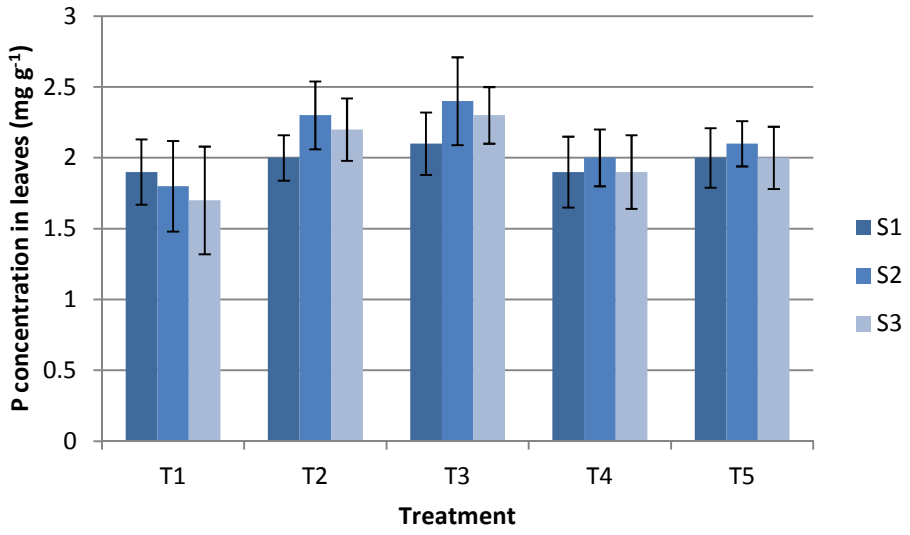


Figure 6.8 Phosphorus concentrations of the leaves as a function of different treatments and plant development stage

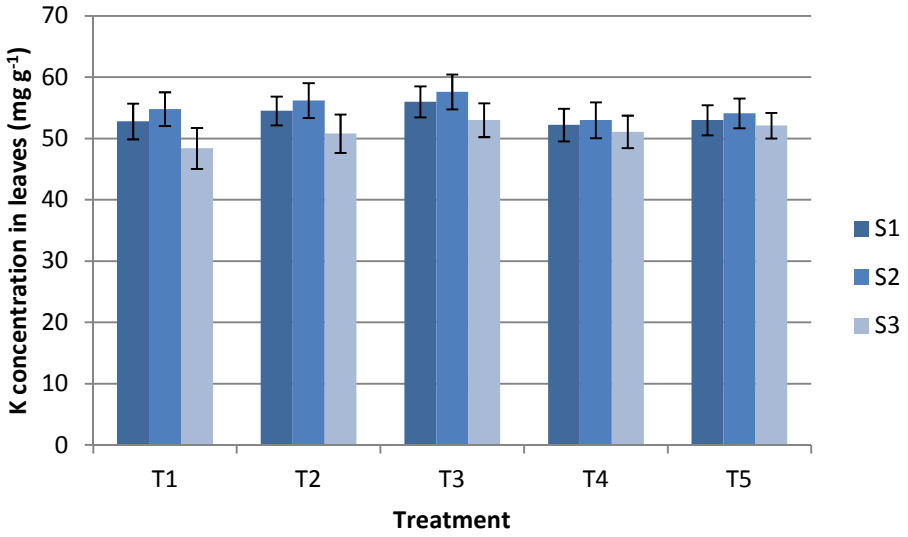


Figure 6.9 Potassium concentrations of the leaves as a function of different treatments and plant development stage

There were no significant differences between treatments in the concentration of leaf – nitrogen (N), phosphorus (P), and potassium (K) in the first and second stage were detected (Figure 6.7, 6.8 and 6.9 respectively).

Table 6.11 shows the leaf- nitrogen (N), phosphorus (P) and potassium (K) concentration at the final harvest. The leaf-P concentration in the control (Treatment 1) was lower compared to other treatments. Leaf-P increased with increasing fertigation frequency and was highest in the 20 irrigation events day^{-1} treatment throughout the season (Treatment 3, 2.3mg g^{-1} dry matter) and significantly higher ($p \leq 0.05$) than the control (Treatment 1, 1.6mg g^{-1} dry matter) by 30%. No other differences were observed among other treatments (Treatment 2, 4 and 5). There were negligible differences in concentration of nitrogen (N) and potassium (K) in leaf. This indicates that the differences in bell pepper performance subjected to different fertigation frequency can be attributed to better uptake of phosphorus (P) in Treatment 3 over the control (Treatment 1).

Table 6.11 Leaf NPK concentration at final harvest as affected by different fertigation frequency treatments in bell pepper

Treatment	N	P	K
	mg g^{-1} dry matter		
T1	52.6	1.6b	48.4
T2	57.5	2.2ab	50.8
T3	58.9	2.3a	52.0
T4	54.2	1.9ab	51.1
T5	54.8	2.0ab	50.1

Means in each column, followed by different letters are significantly different at $p \leq 0.05$ by Tukey's test

6.1.2.9 Nitrogen (N), phosphorus (P), and potassium (K) uptake

There were no significant differences observed in NPK uptake by bell pepper plants in the first (S1) and second (S2) stage (details in Appendix 3). This can be attributed to non-significant differences in NPK concentration in leaf, stem and fruit in these stages. However, there were significant differences in third (S3) stage (Table 6.12) where the total nitrogen (N) uptake of Treatment 3 (4655mg $plant^{-1}$) was significantly higher ($P \leq 0.05$) than Treatment 1 (control, 3139mg $plant^{-1}$) by 33%. The total potassium (K) uptake of Treatment 3 (5083mg $plant^{-1}$) was also registered significantly ($P \leq 0.05$) higher compared with Treatment 1 (control, 3481mg $plant^{-1}$), an increase of 24%. The phosphorus (P) uptake was also affected by different treatments. Significantly ($P \leq 0.05$) higher P concentrations were observed in Treatment 3 (159mg $plant^{-1}$) than the control (Treatment 1, 84mg $plant^{-1}$), an increase of 47%.

The higher N and K uptake in the third stage (S3) was a result of higher dry matter production in Treatment 3 (Table 6.8). As the dry matter increased in different plant parts and concentration of the nutrients in the plant parts also followed the trend of total uptake (Table 6.12). The higher phosphorus (P) uptake in third stage could be attributed to better availability of phosphorus in the leaf (Table 6.11).

Table 6.12 Total NPK uptake at final harvest as affected by different fertigation frequency treatments in bell pepper

	mg plant^{-1}		
	Nitrogen	Phosphorus	Potassium
T1 Control)	3138.7b	84.3b	3480.6b
T2	4477.6ab	146.5ab	4893.8ab
T3	4655.2a	159.0a	5083.4a
T4	3590.0ab	111.2ab	4120.8ab
T5	3530.2ab	106.4ab	3939.3ab

Means in each column, followed by different letters are significantly different at $p \leq 0.05$ by Tukey's test

6.1.3 Discussion

The effect of fertigation frequency during the first stage and second stage was not significant. Possibly this was because similar nutrient concentrations were received by all treatments and nutrient requirements are relatively low at the early stage (details in Appendix 3). However, at the later growth stage (Stage 3), as water and nutrient demands increased, fertigation frequency affected growth. In the third stage (65 to 84-DAT), there were significant differences with Treatment 3 (20 irrigation events day^{-1} throughout the season) out performing Treatment 1 (control, 5 irrigation events day^{-1} throughout the season).

Fertigation frequency affects bell pepper growth by increasing plant height, stem diameter and leaf area. It was apparent that increasing the fertigation frequency from 5 to 10 and to 20 irrigation events day^{-1} increased bell pepper growth. Treatment 3 (20 irrigation events day^{-1} throughout the season) produced plants with significantly greater leaf area over the control (Treatment 1, 5 irrigation events day^{-1} throughout the season) (Table 6.6). Higher leaf area contributed to more carbohydrate synthesis and higher yield (Silber et al., 2003). The difference can also be ascribed to other growth parameters in Treatment 3 where plants were taller with thicker stems compared with the control (Treatment 1) but not a significant different. Better plant growth in higher fertigation frequency was also observed by other researchers (Al-Jaloud and Ongkingco, 1999, Silber, 2005, Silber, 2008).

Total dry matter production is an important determinant of the economic yield (Hebbar et al., 2004). The total dry matter production (Table 6.8) was higher in Treatment 3, receiving 20 fertigation events day^{-1} throughout the season by 26% in the third stage over Treatment 1 (control). The difference in dry matter production in Treatment 3 can

be ascribed to greater leaf area production (Table 6.6).

The better performance of Treatment 3 may be attributed to maintenance of better nutrient status in the root's zone which in turn helped the plants to utilize nutrients more efficiently (Phene and Beale, 1976). As expected, the increasing fertigation frequency strategy adopted in this study significantly increased dry matter production, a result which is consistent with numerous other reports (Medrano et al., 2005). This increase may be ascribed to the increase in fruit yield. This observation confirms that, when fruit load is high and represents the strongest sink strength (Marcellis, 1993), and dry matter gain induced by increased irrigation events day^{-1} is mainly allocated to the growing fruits (Marcellis, 1993) .

Growth and yield of bell pepper plants was enhanced by higher fertigation frequency (20 irrigation events day^{-1}), mainly through increased growth (Figure 6.3, 6.4, 6.5), yield (Table 6.7) and nutrient uptake (Table 6.12). This may be attributed to better availability of nutrients throughout the growth stages in Treatment 3 leading to better uptake of nutrients. Treatment 3 had higher N, P, and K uptake over the control (Treatment 1) associated with higher dry matter production (Table 6.8). Better yield was also observed in higher fertigation frequency over low fertigation frequency in cucumber (Al-Jaloud and Ongkingco, 1999), bell pepper (Silber, 2008), and lettuce (Silber et al., 2003, Xu et al., 2004).

NPK concentration measurements in the leaves in the third stage (Table 6.11) showed that yield gains under high irrigation frequency can be primarily related to increased nutrient availability, especially that of phosphorus (P). Significantly higher Leaf-P concentration was recorded in Treatment 3 over the control (Treatment 1). Similar observations were made in other studies (Silber, 2005).

Data from this study seems to indicate blossom-end rot (BER) incidence decreased with increasing fertigation frequency. Significantly ($P \leq 0.05$) fewer fruits with BER were recorded in Treatment 3 (20 irrigation events day^{-1} throughout the season) over the control (Treatment 1, 5 irrigation events day^{-1} throughout the season). Similar positive effects were also reported by other researchers (Silber et al., 2005). The cause of high BER incidence under low fertigation frequency is unclear (Silber et al., 2005).

However, it is generally accepted that BER incidence may be associated with water stress e.g. substrate water deficit, high osmotic pressure or high salinity (Saure, 2001) and increasing the fertigation frequency enhanced the water uptake which decreased BER incidence (Silber, 2005). Despite extensive researches worldwide, the opinions on the causes of BER incidence in bell pepper and tomato remain complex, confusing and ambiguous (Saure, 2001). It is clear that in the present study increased fertigation frequency reduced BER, but the mechanism by which this occurred is still uncertain. BER has also been related to calcium (Ca) deficiency and, especially, to low Ca transport to the fruits, particularly to the distal fruit tissue (Ho and White, 2005). However, unlike BER incidence, fruit Ca concentrations were almost unaffected by the fertigation frequency (Ho and White, 2005).

To optimise the productivity, plants should never be subjected to conditions that cause stress and reduce plant growth. Plants should never be allowed to run out of readily available water since this may delay the crop, cause death of root tissues, or even the entire plant (Raviv and Lieth, 2008). High irrigation frequency may be very advantageous to agricultural crops especially under fertigation management. High frequency can serve as an efficient means of enhancing crop yield, by improving water availability and the uptake by plants of less mobile nutrients. Yield improvement is primarily related to enhanced uptake of nutrients, especially phosphorus (P). It is suggested that the reduced yield obtained in low frequency resulted from deficiency of nutrients rather than of water and that high irrigation frequency can compensate for nutrient deficiency (Silber, 2005).

The results from this study suggest that adequate management of irrigation scheduling (in this case fertigation frequency) could have important positive effects on overall growth and yield of the greenhouse bell pepper production system. From a practical point of view, this study confirms the potential interest of using high irrigation frequencies strategies in greenhouses where the horticultural sector is facing scarce and declining water resources, and needs to drastically reduce the contamination due to fertiliser emission to ensure the sustainability of greenhouse production.

The increases in the nitrogen, phosphorus, and potassium uptake in the bell pepper leaves, stem and fruits that followed the increase in the irrigation frequency in the

experiment can be attributed to both direct and indirect effects of irrigation frequency on the nitrogen, phosphorus, and potassium concentration in the leaves, stems, and fruits. The direct effect is the frequent elimination of the depletion zone at the root surface by the supply of fresh nutrient solution during and soon after the irrigation events.

Moreover, a higher irrigation frequency maintains a higher dissolved nitrogen, phosphorus and potassium concentration in the substrate solution, by shortening the period during which nitrogen, phosphorus, and potassium retention takes place (Silber, 2008). The indirect effect of irrigation frequency on nitrogen, phosphorus and potassium availability is manifested through the higher convective flux of dissolved phosphorus (P) from the substrate solution to the root surface, which increases with increased irrigation frequency (Silber, 2008). The increase of nitrogen, phosphorus and potassium concentration in the irrigation water increased its concentration both at the root surface and in the substrate solution and consequently increased nitrogen, phosphorus, and potassium uptake by the bell pepper (Silber et al., 2005).

The finding that increased irrigation frequency resulted in systematic enhancement of plant nitrogen, phosphorus, and potassium nutrient uptake (Table 6.12) may indicate that the main effect of fertigation frequency was related to an improvement in nutritional status, mainly in phosphorus (P). Thus, increasing the irrigation frequency would compensate for certain nutrient deficiencies, and the lower yields of plants fertigated at low frequency might be a result of nutrient shortage.

Water and nutrients acquisition by plants, and the formation of depletion zone in the immediate vicinity of the roots are the driving forces for solute movement towards the roots. (Silber et al., 2003). Nutrient transport from the substrate solution to the root surface takes place by two simultaneous processes: convection in the water flow (mass flow) and diffusion along the concentration gradient (Jungk, 1996). The main mechanism by which fertigation frequency enhanced nutrient acquisition by the plant in the present experiment was the frequent replenishment of nutrient solution in the depletion zone adjacent to the root surface, and the enhancement of mass flow transport (Silber, 2005).

6.1.4 Conclusion

Increasing fertigation frequency could serve as an effective means of enhancing crop growth and yield, by improving the nutrient uptake by plants. This study showed that fertigation with high irrigation frequency (20 irrigation events day^{-1}) increased yield of bell pepper significantly over low fertigation frequency (5 irrigation events day^{-1}). This accounted for 22% increase in yield. Higher yield with high fertigation frequency was brought about by higher leaf area and higher total dry matter production which resulted in higher NPK uptake. Increasing fertigation frequency could serve as an efficient means of enhancing crop yield, by improving the uptake by plants, of less mobile nutrients such as phosphorus. The main mechanisms by which irrigation frequency enhanced nutrient acquisition by the plant in the experimental setup were the frequent replenishments of nutrient solution in the depletion zone adjacent to the root surface, and the enhancement of mass flow transport.

6.2

A greenhouse study of the effects of irrigation frequency and defoliation on production of bell pepper

6.2.1 Treatment details

In a second and simultaneous experiment, bell pepper plants were grown under irrigation schedules of 5 and 10 irrigation events per day. Furthermore this experiment also examined the effect of defoliation on growth of bell pepper. The key hypothesis of this investigation was that some degree of defoliation would not have detrimental effect bell pepper production because it was found that many lower leaves were respiring more than they were photosynthesising and appeared to be net sinks, rather than sources of assimilates (HDC, 2009). Removing some lower, older, less photosynthetically active leaves from bell pepper plants (defoliation) may be beneficial for yield because the net supply of assimilates for fruit growth (sink) might increase. The horticultural practice of removing leaves (defoliation) as a tool by growers to improve yield has been reported in literature (Decoteau, 1990).

During the first stage of bell pepper development (35-DAT), lower leaves (not yet senesced) were removed and only about 30 uppermost leaves are kept (20% defoliation). The supplementary experiment consisted of four treatments with two fertigation frequency (5 and 10 irrigation events); three growth stages (S1: 1 to 43-DAT; S2: 44 to 64-DAT and; S3: 65 to 84-DAT) and two defoliation strategies (20% defoliation and 0% defoliation) (Table 6.13).

Table 6.13 Treatment details at different growth stages

Treatment	S1: 1 to 43-DAT	S2: 44 to 64-DAT	S3: 65 to 84-DAT
T1 (control)	5 irrigation events day^{-1}, 0% defoliation throughout		
T2	5 irrigation events day^{-1}, 20% defoliation throughout		
T3	10 irrigation events day^{-1}, 0% defoliation throughout		
T4	10 irrigation events day^{-1}, 20% defoliation throughout		

6.2.2 Results and Discussions

6.2.2.1 Plant growth characteristics

Table 6.14 shows that there were no significant differences between treatments for plant height and stem diameter records at final harvest (79-DAT). However a strong trend was observed in treatments with higher frequency (Treatment 3 and Treatment 4) exhibiting greater plant height and thicker stem compared with treatments with 5x irrigation events day^{-1} (Treatment 1 and Treatment 2). At the same time, it was also observed that undefoliated treatments (Treatment 1 and Treatment 3) produced taller plants with thicker stems than treatments whose lower leaves were removed (Treatment 2 and Treatment 4).

Table 6.14 Bell pepper plant and leaf characteristics as affected by different fertigation frequency and defoliation treatments at final harvest

Treatment	Plant height	Stem diameter	Leaf area	Leaves per plant	SLA	LWR
	cm	mm	cm^2	no. $plant^{-1}$	$cm^2\ g^{-1}$	$g\ g^{-1}$
T1 (control)	46.7	15.9	3607a	70a	146.0	0.27
T2	45.3	15.3	3017b	50b	143.7	0.27
T3	48.3	16.2	4228a	78a	153.7	0.27
T4	46.8	15.9	3173b	51b	149.0	0.26

Means in each column, followed by different letters are significantly different at $p \leq 0.05$ by Tukey's test.

Leaf area in the third stage (Table 6.14), Treatment 1 ($3607cm^2$) and Treatment 3 ($4228cm^2$) exhibited greater ($P \leq 0.01$) leaf surface area than Treatment 2 ($3017cm^2$) by $590cm^2$ (16%) and $1121cm^2$ (29%) respectively, and over Treatment 4 ($3173cm^2$) by $434cm^2$ (12%) and $1055cm^2$ (25%) respectively. The greater leaf area in Treatment 1 and Treatment 3 compared to Treatment 2 and Treatment 4 can be attributed to removal of lower leaves in the latter treatments. Similar patterns were seen in the leaf area production in S1 and S2 (details in Appendix 3).

On the other hand, defoliation increased the size of leaf area per leaf (total leaf area/number of leaves) (Figure 6.10). This seems to indicate that the remaining leaves try to compensate for the removal of some leaves by increasing their size.

There was also a trend for specific leaf area (SLA) (Table 6.14) to increase with increasing irrigation frequency, and SLA was also higher in 0% defoliated treatments

(Treatment 1 and Treatment 3) over 20% defoliated plants (Treatments 2 and Treatments 4). However no significant differences were recorded among the treatments. Data on leaf weight ratio (LWR) on the other hand were unaffected by fertigation frequency or defoliation (Table 6.14). This would indicate that the proportion of the plant dry biomass present in the leaves in all treatments was similar.

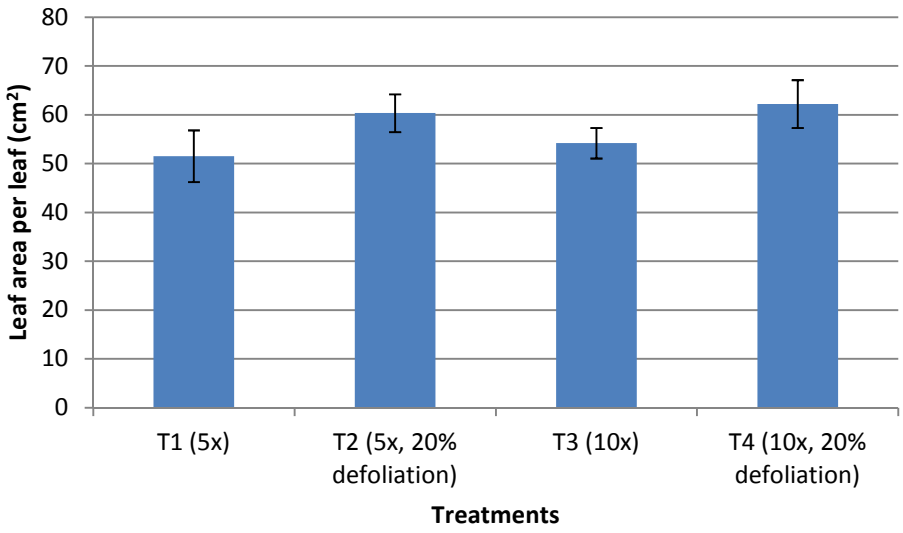


Figure 6.10 Leaf area per leaf as affected by defoliation and fertigation frequency

6.2.2.2 Yield and dry matter partitioning

There were no significant differences in the yield parameters of bell peppers among the treatments (Table 6.15). However a trend was observed, whereby plants subjected to 0% defoliation i.e. Treatment 1 (725g plant^{-1}) and Treatment 3 (796g plant^{-1}) produced greater yield than treatments subjected to 20% defoliation i.e. Treatment 2 (639g plant^{-1}) and Treatment 3 (679g plant^{-1}). This represented increases of 12% (Treatment 1 over Treatment 2); 6% (Treatment 1 over Treatment 4); 20% (Treatment 3 over Treatment 2); and 15% (Treatment 3 over Treatment 4).

Table 6.15 Yield, dry matter partitioning, and harvest index of bell pepper as affected by different fertigation frequency and defoliation treatments

Treatment	Yield		Dry matter partitioning				HI
	Fruit fresh weight	Total Fruit fresh weight	Leaves	Stem	Fruit	Aboveground biomass	
	g plant^{-1}	kg	g plant^{-1}				
T1 (control)	725.1	2.18	24.7a	14.9	52.5	92.1a	57.0
T2	639.0	1.92	21.0b	13.9	42.5	77.4b	54.9
T3	795.9	2.39	27.5a	15.1	57.5	100.1a	57.4
T4	679.3	2.04	21.3b	14.5	47.2	83.0b	56.9

Means in each column, followed by different letters are significantly different at $p \leq 0.05$ by Tukey's test.

Table 6.16 Leaf chlorophyll content and gas analyser parameters of bell peppers as affected by different fertigation frequency and defoliation treatments at final harvest

Treatment	Leaf chlorophyll content (SPAD unit)		Net leaf rate of Photosynthesis	Leaf transpiration rate	Stomatal conductance	Sub-stomatal CO_2
	Upper leaf	Lower Leaf	µmol m^{-2} s^{-1}	mmol m^{-2} s^{-1}	mmol m^{-2} s^{-1}	vpm
T1 (control)	60.49	71.87	13.38	7.49	0.50	268.80
T2	61.89	72.70	15.96	8.40	0.67	265.07
T3	60.22	73.63	11.26	8.02	0.67	258.93
T4	60.54	74.62	17.46	7.60	0.53	283.90

Values of means in each column. Results were not significantly different between treatments

Leaf dry matter production in defoliated (by 20%) and non-defoliated was similar for both 5 and 10 fertigation events day^{-1} treatments. However, Treatment 3 (27.5g plant-^{1}, 10 irrigation events day^{-1} with 0% defoliation) had significantly ($P \leq 0.05$) greater leaf dry matter production than Treatment 2 (21.0g plant^{-1}, 5 irrigation events day^{-1} with 20% defoliation) by 24%. As a result the total dry matter (TDM) production was significantly higher ($P \leq 0.05$) in Treatment 3 (100.1g plant^{-1}) than Treatment 2 (77.4g plant^{-1}) by 23% (Table 6.15).

Harvest indices (HI) were greater in plants without defoliation (Treatment1 and Treatment 3) than in plants whose lower leaves were removed (Treatment 2 and Treatment 4) irrespective of fertigation frequency. However no significant differences among the treatments were recorded. The higher HI in Treatment 1 and Treatment 3 can be attributed to higher fruit dry matter production in both treatments (Table 6.15).

6.2.2.3 Leaf Chlorophyll and Gas Analyser

There were no significant differences in the leaf chlorophyll content (SPAD values) of both upper and lower leaves between treatments (Table 6.16). However trends indicated that leaf chlorophyll (SPAD values) decreased at later growth stage (details in Appendix 3) and lower leaves had higher values compared to the top leaves. Higher SPAD values with 10 fertigation events day^{-1} (Treatment 3 and Treatment 4) compared with 5 fertigation events day^{-1} (Treatment 1 and Treatment 2) were recorded in third stage (S3) only in the lower leaves.

Net rate of leaf photosynthesis seemed to increase with defoliation (Figure 6.11). Plants with 20% leaf defoliated (Treatment 2 and Treatment 4) had higher net leaf rate of photosynthesis compared with plants without (0%) defoliation (Treatment 1 and Treatment 3) (Table 6.16). However no significant differences were recorded among other treatments. Data on other leaf gas exchange parameters: transpiration rate; sub-stomatal CO_2 and stomatal conductance, showed no significant differences or particular trend among the treatments. This can be attributed to relatively large variability in data.

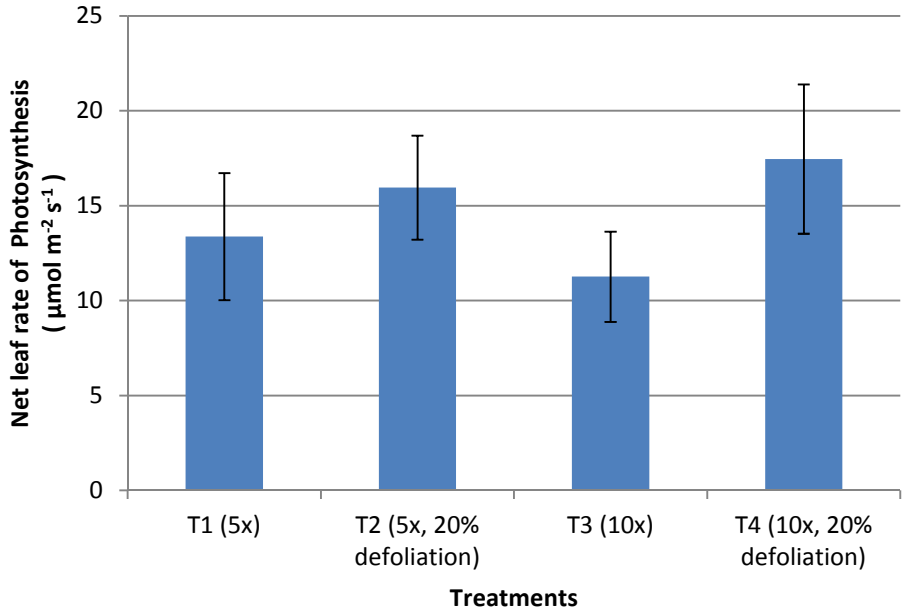


Figure 6.11 Photosynthetic rates as affected by defoliation and fertigation frequency

6.2.2.4 Nitrogen, phosphorus, potassium uptake

Significant differences in nitrogen (N), phosphorus (P), and potassium (K) uptake were observed at final harvest (Table 6.17). In all cases, treatments with no defoliation (Treatment 1 and Treatment 3) showed higher nitrogen (N), phosphorus (P) and potassium (K) uptake over treatments subjected to 20% defoliation (Treatment 2 and Treatment 4). However no significant differences were observed between the treatments.

The total nitrogen (N) uptake for Treatment 3 (5629mg plant^{-1}) and Treatment 1 (5270 mg plant^{-1}) exceeded Treatment 2 (4048mg plant^{-1}) by 28% and 23% respectively and over Treatment 4 (4372 mg plant^{-1}) by 22% and 17% respectively. The total potassium (K) uptake in Treatment 3 (5561mg plant^{-1}) and Treatment 1 (4826 mg plant^{-1}) was higher than in Treatment 2 (4105mg plant^{-1}), an increase by 26% and 15% respectively and over Treatment 4 (4451 mg plant^{-1}), an increase by 20% and 8% respectively. The higher nitrogen, phosphorus and potassium uptake in non-defoliated plants was a result of higher dry matter production in Treatment 1 and Treatment 3 (Table 6.17).

Total phosphorus (P) uptake was higher in plants with higher irrigation frequency (10 irrigation events day^{-1}) over plants with lower irrigation frequency (5 irrigation events day^{-1}) irrespective of defoliation treatments. Treatment 3 (150mg plant^{-1}) and Treatment

4 (119 mg plant^{-1}) took more phosphorus than Treatment 1 (114 mg plant^{-1}) by 24% and 4% respectively and over Treatment 2 (98 mg plant^{-1}) by 35% and 18% respectively. The higher phosphorus uptake in treatments with higher irrigation frequency (10 irrigation events day-1) over treatments with lower irrigation frequency (5 irrigation events day-1) could be due to better availability of phosphorus in the root zone as explained in Chapter 6.1.

Table 6.17 Total NPK uptake of bell peppers as affected by different fertigation frequency and defoliation treatments at final harvest

Treatment	mg plant^{-1}		
	N	P	K
T1	5270.2	113.9	4826.2
T2	4047.5	97.9	4104.8
T3	5628.6	149.9	5561.3
T4	4371.8	118.9	4450.6

Values of the mean in each column. Results were not significantly different between treatments

6.2.3 Discussion

Surprisingly, the effect of defoliation in the current study was detrimental irrespective of the varying fertigation frequency. The fact that 20% reductions in leaf area caused some restriction in fruit suggests that the growth of fruit (size of sink) in the bell pepper plant is limited by the amount of leaf area (size of source). Defoliation in bell pepper plants decreased total plant weight and the fresh and dry weight of the fruits. Leaf area per fruit has been found to a limiting factor for fruit growth (Ramirez et al., 1988).

Plants with no defoliation (Treatment 1 and Treatment 3) outyielded plants with 20% defoliation (Treatment 2 and Treatment 4) (Table 6.15). Their better performance of Treatment 1 and Treatment 3 may be attributed to higher leaf area (Table 6.14), higher dry matter production (Table 6.15). However, none of the results were significantly different. The result of this study also indicated that 20% defoliation of bell pepper plants stimulated the leaf area per leaf and photosynthetic rates of the remaining leaves. Similar findings were also observed by other researchers (Ramirez et al., 1988). This is evidence that net photosynthetic rate is controlled by the level of assimilates (mainly starch) in the leaves by a feedback control system (Thorne and Koller, 1974).

Overall this study indicated reduction in yield with defoliation over non-defoliated plants; however the difference was small and not significant. In another study by Ramirez et al (1988) 25 to 50% defoliation resulted in yield reduction of tomato plants whereby yield restriction resulted from a reduction in either flower number or fruit set. The fact that even 20% reductions in leaf area caused a significant restriction in fruit suggests that the growth of fruit (size of sink) in the bell pepper plant is limited by the amount of leaf area (size of source). Defoliation of plants significantly decreases total plant weight and the fresh and dry weight of the fruits (Ramirez et al., 1988). Leaf area per fruit has been found to be a limiting factor for fruit growth in cucumber (Ramirez et al., 1988). A study by Adeniyi and Ayandiji (2011) found out that defoliation could also lead to abscission of flowers and abortion of fruits and the intensity of these effects increases with increase in the degree of defoliation.

6.2.4 Conclusion

This study has shown that defoliation reduced yield of bell pepper irrespective of fertigation frequency. This accounted for up to 20% decrease in yield. Lower yield in leaf defoliated plants was brought about by lower leaf area and total dry matter production which resulted in lower NPK uptake. The practice of defoliation with the perceived better growth and yield should be done carefully as they might have negative effects that exceed the positive ones as shown in this study. It is very important to maintain a substantial leaf area throughout the growth period of bell pepper as it plays an important part in photosynthesis, transpiration and dry matter accumulation. Leaf loss may affect many processes of the plant, not only after flowering but also in the early vegetative phase and it may alter the flowering pattern and storage of assimilate in the vegetative structures (Adeniyi and Ayandiji, 2011). The removal of some leaves on plant's foliage when it is still actively growing may reduce the growth activities of the plant and may cause appreciable yield loss (Adeniyi and Ayandiji, 2011)

Chapter 7
General Discussion, Conclusion and Future Research

7.1 Introduction

The conclusions of the findings of this research work are presented in this chapter and include conclusions drawn from the extensive literature review carried out in this study as well as each set of experiments presented earlier in Chapters 4, 5, and 6. This study also raised many issues which require further scientific investigation, since it is obvious that issues pertaining to fertigation are enormous. Finally, the practical implications of the findings from the study for bell pepper growers as well as implications for agriculture production in Brunei are discussed.

Literature review (Chapter 3) shows that fertigation results in yield increases in most cases and an improved fertiliser and water use by plants. The interest in fertigation arose due to the potential advantages: higher yield, improved quality of produce, improved efficiency of fertiliser recovery, minimal fertiliser losses due to leaching, control of nutrient concentration in substrate solution and flexibility in timing of fertiliser application in relation to crop demand based on development and growth stage of crops (Papadopoulos, 1984). Scheduling fertiliser applications on the basis of needs reduces nutrient element losses associated with conventional application methods that depend on the soil as a reservoir for nutrients. The management of watering and nutrition is focused on the optimal delivery of water and nutrients over the various growth stages of the plant, through the changing growing environment over the growing season, in order to maximise yield. In order to support optimum growth, development and yield of the crop, the fertiliser feed solution has to continuously meet the nutritional requirements of the plants. In addition, fertigation reduces fluctuations of substrate solution salinity due to fertilisers, thereby improving substrate solution conditions particularly for salt sensitive crops. In general, with fertigation protection of substrate and water from fertilisers on a sustainable basis can be achieved (Papadopoulos, 1997).

The general aim of the current study was to demonstrate the contribution of nitrogen (N) and potassium (K) rates as well as fertigation frequency to the growth and yield of

greenhouse-grown bell pepper (*Capsicum annuum* L.). The potential to increase bell pepper production's efficient use of fertiliser by meeting the crop's requirements at different growth stages was also investigated. In this chapter, the major findings presented in Chapter 4 – 6 are summarised and discussed, and their implications for greenhouse bell pepper production and potential research are outlined, in reference to the main research questions as outlined at the commencement of this thesis (Chapter 1):

1. Are there differences in the production of bell pepper (*Capsicum annuum* L.) under different nitrogen (N) and potassium (K) concentration (126-106; 256-214 and 385-321mg l^{-1}) fertigated into drip irrigation water according to different growth stages?
2. What are the effects of too high and too low nitrogen (N) and potassium (K) concentration (42-71mg l^{-1}; 126-106; and 500-625) fertigated into drip irrigation water according to different growth stages on the growth, yield and incidence of BER in greenhouse bell pepper (*Capsicum annuum* L.)?
3. What are the effects of different fertigation frequency (5, 10 and 20 irrigation events day^{-1}) on growth, yield, and incidence of BER in bell pepper (*Capsicum annuum* L.) with fertigation regimes in a greenhouse?
4. What are the effects of defoliation (0% and 20% defoliation) under different fertigation frequency (5 and 10 irrigation events day^{-1}) on bell pepper (*Capsicum annuum* L.)?
5. Are there differences in production of bell pepper (*Capsicum annuum* L.) with different seasonal growing condition (summer-autumn and spring-summer)?
6. Are there differences in the effects of different varieties (California Wonder and Ferrari) on the production of bell pepper (*Capsicum annuum* L.) with fertigation regimes in greenhouse condition?

7.2 Discussions and Conclusions

The conclusions of this study are presented in sections representing the main research questions presented in sections 7.2.1 to 7.2.6.

7.2.1 *Are there differences in the production of bell pepper (Capsicum annuum L.) under different nitrogen (N) and potassium (K) concentration (126-106; 256-214 and 385-321mg l^{-1}) fertigated into drip irrigation water according to different growth stages?*

The main features of vegetable fruits such as bell pepper that distinguish them from leafy crops are the distinct stages of growth development, starting with a vegetative period, followed by flowering, and fruit development and growth. Each of these growth stages may require nutrients in different quantities, ratios and rate of supply (Bar-Tal et al., 2003). The experiment and results presented in Chapter 4 provided an understanding on the effect of varying amount of nitrogen (N) and potassium (K) at various growth stages of bell pepper grown in rockwool.

There were no significant differences between the treatments in the first (1 to 44-DAT) and second (45 to 69-DAT) stage. Therefore plants responded similarly to all nutrient treatments in these stages. Differences among plants were observed only in the third stage (70 to 122-DAT). These experimental data are consistent with those found for tomato (Garcia Lozano et al., 2005) showing that even in soil-less system the margins of treatment are broad and that minor changes in nutrient solution do not tend to have significant effects on growth, development, and yield.

The nutrient feed target of N and K for greenhouse bell pepper suggested by Calpas (2002) is 200 and 318 mg l^{-1} respectively. However extrapolation of known NPK uptake data to different environmental conditions should be done carefully and treated only as a first approximation (Xu et al., 2001, Bar-Yosef, 1999). In this study the results showed varying N and K levels only resulted in significant differences from the control treatment (126-106 mg l^{-1} of N and K respectively throughout the season) when they were applied at 126-106 mg l^{-1} to 265-214 mg l^{-1} and finally 385-321 mg l^{-1} (Treatment 1), when N and K were applied from 126-106 mg l^{-1} to 385-321 mg l^{-1} and finally 265-214 mg l^{-1} (Treatment 2) at the three different growth stages. Other permutations of N and K at different growth stages did not cause significant differences compared with the control treatment. In practice, over-applications could lead to substantial waste in fertiliser, increased cost and environmental contamination. Clearly results indicate that the doses of nutrients in soil-less culture should change according to the growth stage of the crop with fertigation program being adjusted during the growing season according to plant development. The result of this study also demonstrates that applying varying N and K at different growth stages is essential to achieve higher yield of greenhouse bell pepper grown in a soil-less medium.

Similar observations in bell peppers was also made by Jovicih et al (2004). However their study recommended N and K concentration of 70 and 119 mg l^{-1} at the beginning of transplanting stage and increasing to 160 and 200 mg l^{-1} at full production. While results of a study on soil-less greenhouse tomato in Israel by Imas (1999) recommended the N and K concentration to increase from 120-150 mg l^{-1} and 180-200 mg l^{-1} (at planting and establishment stage) to 150-180 and 220-270 mg l^{-1} (at flowering stage) and finally 180-200 and 270-300 mg l^{-1} (at ripening and harvest stage). The difference in the results can be attributed to different climatic conditions, different substrates and different plant species, but the principle is the same.

Higher yield in Treatment 1 and Treatment 2 were associated with the higher leaf area, total dry matter production, better quality fruits and higher nutrient uptake. This is an agreement with the work of Marschner (1995) who concludes that positive yield response (sink) for the reproductive organs (fruits) are the result of an increase in leaf area and net photosynthesis (source). In this study no significant treatment effects on the photosynthetic capacity were found. However plants given 126-106mg l^{-1} to 265-214mg l^{-1} and finally 385-321mg l^{-1} exhibited highest photosynthetic rate followed by those plants given 126-106mg l^{-1}, 385-321mg l^{-1} and finally 265-214mg l^{-1}.

Greater yield in plants given 126-106mg l^{-1} to 265-214mg l^{-1} and finally 385-321mg l^{-1} as well as those given 126-106mg l^{-1} to 385-321mg l^{-1} and finally 265-214mg l^{-1} was also attributed to higher nutrient uptake at the final harvest. This was due to greater dry matter production in these plants. All these factors led to more efficient use of fertiliser in these plants. The result of this study suggests the importance of greater synchrony between crop demand and nutrient supply is necessary.

The result of the study also suggests that the consumption function was not monotonic and exhibited sharp changes at critical growth stages. Ignoring the change in uptake rate with time may lead to periods of over- and under- fertilisation. Over-fertilisation may enhance salinity within the system and environmental contamination caused by redundant nutrient solution, whereas under-fertilisation may result in nutrient deficiency and yield reduction (Bar-Yosef, 1999).

7.2.2 *What are the effects of too high and too low nitrogen (N) and potassium (K) concentration (42-71mg l^{-1};126-106; and 500-625) fertigated into drip irrigation water according to different growth stages on the growth, yield and incidence of BER in greenhouse bell pepper (Capsicum annuum L.)?*

In view of yield results of the first experiment (Chapter 4), the author tested the effects extending the range of fertiliser N and K concentration beyond that in the first experiment in the second experiment (Chapter 5). Therefore, the author undertook the second experiment (Chapter 5), the results of which confirmed what had been expected that too low and too high N and K concentration have greater negative effect on bell pepper plant growth than the first experiment.

Increasing N and K concentration from low concentration (44-71mg l^{-1}) to moderate concentration (126-106mg l^{-1}) significantly increased growth and yield but with no further increase up to 500-625mg l^{-1}. Increases were attributed to increase in leaf area and net photosynthesis (effects of source) which resulted in increased in fruit yield (effects of sink) in common with Bar-Tal et al (2003) and Marschner (1995). It is well known that N deficiency induces many morphological and growth modifications in plants, resulting in strong inhibition of growth (Guidi et al., 1997). In the current study, reducing N supply well below the recommended rate (44mg l^{-1}) substantially decreased leaf N concentration, leaf area, leaf chlorophyll content and dry matter accumulation. The decline in chlorophyll content in N-deficient plants is widely reported in literature ((Hubber et al., 1989, Khamis et al., 1990, Ciompi et al., 1996, Guidi et al., 1997).

The result for this study also suggests increase in fertiliser concentration will increase nutrient solution's electrical conductivity (EC) and is in agreement with findings of other researchers (Contreras et al., 2006, Savvas and Lenz, 2000). According to Savvas and Lenz (2000) the effects of increasing EC by raising nutrient concentration was similar to increasing salinity by adding NaCl suggesting that any effects were osmotic potential in origin and not salt specific. In this study (Chapter 5), the results demonstrate that the effects of increasing electrical conductivity (EC) as a result of increasing N and K concentration are significantly important in order to raise yield of greenhouse bell pepper grown in a soil-less medium.

This study shows that growth of bell pepper is affected at high EC (2.6 dS m^{-1}). This confirmed the findings of previous authors, which indicated that bell pepper is a salt sensitive plant species (Sonneveld, 1988, Navarro et al., 2002). The present study clearly demonstrated the detrimental effects of high electrical conductivity (EC) on the yield of greenhouse bell pepper lead to a decrease in mean fruit weight, although number of fruits per plant is not affected. Similar observation was made by Adams (1991), Cuartero and Fernandez-Munoz (1999) and Savvas and Lenz (2000). The study also showed that decrease in total yield to high EC was mainly due to a decrease in fruit fresh weight in agreement with many studies (Sonneveld and Welles, 1988, Adams and Ho, 1989, Willumsen et al., 1996). In this study, the differences in the fruit fresh weight between high EC treatment and the control may simply because of differences in water content as there were no differences in fruit dry weight. This concurs with the observation made by Rubio et al (2008).

The study also indicated that unlike the fruit fresh weight, the dry weight of fruits, vegetative parts (stem and leaves) and leaf area were not significantly reduced by high EC (2.6 dS m^{-1}). However in a study by Savvas et al (2000) with a higher EC of 8 dS m^{-1}, the leaf area and dry weight of leaves and stems per plant were also restricted, and the fruit dry weight was reduced almost as much as the vegetative growth, whereas the fruit fresh weight was even more severely depressed. Consequently, the detrimental effects of high EC on the yield can be attributed to restriction of water accumulation in the fruit. Therefore the reduction in bell pepper fruit weight with high EC in this study can be attributed to reduced water transport to the fruit, since dry weight was not affected. This conclusion is supported by Ehret and Ho (1986) Adams (1991) and Willumsen et al (1996).

The result from this study also indicated that marketable yield was reduced at higher electrical conductivity (EC). In general, the reduction in marketable yield in the high EC treatment was due to a high percentage of BER in the bell pepper fruits. High EC caused by nutrient solution content and salinity have been shown to have a strong impact on the incidence of BER (Adams and Holder, 1992, Adams, 2002, Ho et al., 1995, Saure, 2001, Bar-Tal et al., 2003, Ehret and Ho, 1986). While most of the literature on BER relates this growth disorder to fruit calcium (Ca) deficiency, many inconsistencies exist in the Ca concentrations reported for normal fruit and affected by

BER (Cerda et al., 1979, Murray et al., 1972). In this study high EC reduced bell pepper total yield mainly due to a decrease in fruit fresh weight not to differences in fruit dry weight which can be attributed to restriction of water accumulation in the fruit. This is similar to the findings of several authors (Cerda et al., 1979, Adams and Ho, 1989, Pill and Lambeth, 1980, Shaykewich et al., 1971), which showed higher incidence of BER with increased plant water stress.

7.2.3 *What are the effects of different fertigation frequency (5, 10 and 20 irrigation events day^{-1}) on growth, yield, and incidence of BER in bell pepper (Capsicum annuum L.) with fertigation regimes in a greenhouse?*

The first two experiments reported in Chapter 4 and Chapter 5 investigated effects of different nitrogen (N) and potassium (K) rates in greenhouse bell pepper production grown in rockwool. However, the fertigation frequency of both experiments was maintained at five irrigation events per day. The literature reported in Chapter 3 showed yield improvement in bell pepper with increased fertigation frequency. Thus, it was considered that the effect of fertigation frequency at different growth stages for greenhouse bell pepper production grown in rockwool needed to be investigated.

Chapter 6.1 provided an understanding of the effect of varying irrigation frequency at various growth stages of bell pepper grown in rockwool. The key hypothesis tested in this investigation was that more frequent irrigation would increase bell pepper production because it would enhance water and nutrient uptake.

Results indicated that higher irrigation frequency (20 irrigation events day^{-1}) gave higher yield than lower irrigation frequency as also observed by other researchers (Silber, 2008, Silber, 2005, Silber et al., 2005, Xu et al., 2004). According to Silber et al (2005), the main mechanism by which fertigation frequency enhanced nutrients acquisition is the frequent replenishment of nutrient solution in the vicinity of the roots and the enhancement of mass flow transport. Reducing the period between successive irrigations and supplying water and nutrients at rates that match the plant requirement may be an effective tool for improvement of water and fertiliser use and yield enhancement.

This study indicated that the better growth and yield with higher irrigation frequency

was because of improved phosphorus (P) mobilisation and uptake and in agreement with the works of other researchers (Silber et al., 2003, Silber et al., 2005, Xu et al., 2004, Phene et al., 1990). The main indication is that the main effect of irrigation frequency was related to an improvement in P mobilisation and uptake. According to Xu et al (2004) and Silber et al (2003) the increase in the P concentration in the bell pepper leaves that followed the increase in the fertigation frequency resulted from the improved uptake of nutrients through two main mechanisms: continuous replenishment of nutrients in the depletion zone in the vicinity of the root-medium interface and enhanced transport of dissolved nutrients and mass flow, because of the higher time-averaged water content in the medium.

A important effect of irrigation frequency on blossom-end rot (BER) incidence has been reported by Silber et al (2005). The cause of high BER incidence under low fertigation frequency is unclear (Silber, 2005). Despite extensive research worldwide, opinions on the cause of BER incidence in bell pepper and tomato remain complex, confusing and ambiguous (Saure, 2001). It is clear that in the present study increased irrigation frequency reduced BER, which was also reported by other researchers (Saure, 2001, Silber, 2008, Silber, 2005, Silber et al., 2005, Xu et al., 2004). Whilst the mechanism by which this occurred is still uncertain, it could involve a direct effect, e.g. diminishing some kind of water stress, or enhancing the uptake of calcium (Ca) or magnesium (Mn), or an indirect effect, e.g. enhancing nutrient uptake as a result of improving its availability in the vicinity of the roots (Silber, 2005).

Results from experiment-2 (Chapter 5) indicated that that BER incidence may be associated with water stress due to high EC and this is supported by the work of Saure (2001). However, the relatively low electrical conductivity in this study (Chapter 6.1) ruled out the possibility of high salinity as a cause of BER incidence. BER has also been related to calcium (Ca) deficiency (Ho et al., 1993, Ho et al., 1995, Marcelis and Ho, 1999) however this study the calcium content of the nutrient solution were all similar to all treatments. This may ruled out direct effect of Ca deficiency for BER incidence. This is consistent with the conclusion of Nonami et al (1995) that BER in tomato may not be necessary related to Ca deficiency and the general remark of Saure (2001) that the role of Ca in BER should be reassessed.

7.2.4 *What are the effects of defoliation (0% and 20% defoliation) under different fertigation frequency (5 and 10 irrigation events day^{-1}) on bell pepper (Capsicum annuum L.)?*

The experiment and results presented in Chapter 6.2 provided an understanding of the effect of defoliation under varying irrigation frequency of bell pepper grown in rockwool. Leaf loss, according to Pandey (1983) interferes with many processes of the plant, not only after flowering but also in the early vegetative phase and it may alter the flowering pattern and storage of assimilate in the vegetative structures. In this study, defoliation at 20% resulted in lower growth and yield over the control treatment (0% defoliation), however no significant differences were observed and the magnitude of the difference was relatively small (6-20%). The reduction in yield as a result of defoliation in this study is in agreement with the findings of Adeniyi and Ayandiji (2011). However this is contrary to the findings of Decoteau (1990) who suggested the removal of mature leaves stimulate the growth of remaining leaves as well as stimulation of flowering and fruiting. No increases in fruiting followed the leaf removal in the current study. Possible explanations for this discrepancy may be the relatively early removal of these leaves and/or short interval from leaves removal to plant harvest. In the current study, the leaves were removed when still green and may have been fully functional and still influencing plant growth and development. The experiment was terminated six weeks after initiation of treatments (defoliation) which may be too short to take effect.

7.2.5 *Are there differences in the production of bell pepper (Capsicum annuum L.) with different seasonal growing condition (summer-autumn and spring-summer)?*

Even though the current study did not directly investigate the effects of seasonal conditions on the growth of bell pepper, comparisons between the control treatments in experiment-2, Chapter 5 (which took place during spring-summer) with that in experiment-3, Chapter 6 (summer-autumn) are possible. Both experiments had the same nutrient treatment (126-55-106 mg l^{-1} of N, P and K throughout the season) with the same bell pepper variety (Ferrari).

Table 7.1 shows that the leachate mean EC values were higher in the spring to summer season (1.1dS m^{-1}) compared with summer-autumn season (0.8dS m^{-1}). This may be due to higher evaporative demand in the spring-summer season (2.5mm day^{-1}) than in the summer-autumn (1.3mm day^{-1}). This is consistent with the findings of Rouphael and

Colla (2005) who stated that during spring-summer season the growing medium EC increases much more rapidly than during the summer to autumn season. So the implication is that with higher temperature and solar radiation (spring-summer season), less concentrated fertiliser solutions should be used to maintain the EC of the growing medium at the desired level to prevent yield reductions. The result of the study also indicated that significantly ($p \leq 0.05$) higher yield was recorded in the spring-summer (691.8g plant^{-1}) season over the summer-autumn season (533.1g plant^{-1}), a difference of 23% (Table 7.1).

Table 7.1 Effects of different seasonal condition on leachate EC, evaporation rate, and the yield of bell pepper at final harvest

Treatment	Leachate EC	Evaporation rate	Fruits fresh weight
	dS m^{-1}	mm day^{-1}	g plant^{-1}
Spring-summer	1.1	2.5	691.8a
Summer-autumn	0.8	1.3	533.1b

Means value in each column, followed by different letters are significantly different at $p \leq 0.05$ by Tukey's test

Another comparison was made between the results of experiment-2 (chapter 5) with the study by ALsodany (2011). Both experiments have similar nutrient treatment details, the difference was that experiment-2 (Chapter 5) was conducted in summer-autumn season while the study executed by ALsodany (2011) was conducted in spring-summer season (details of results in Appendix 4). The result of the study indicated that higher yield was recorded for all treatments in ALsodany's experiment compared with the experiment-2's result (Table 7.2). This was because there were more fruits per plant exhibited in ALsadony's work. However, there was no information on fruit size in ALsadony's work but the author suspected that the fruits were smaller. There was also no information on the number of fruits affected by BER, but Table 7.1 indicated that leachate mean EC values were higher in the spring to summer season compared with summer-autumn season. It was suspected that the number of fruits affected with BER was greater in ALsadony's work.

The higher yield of bell pepper in the spring to summer cropping season in comparison to the summer to autumn season in this study may be attributed to better temperature conditions and solar radiation. This is consistent with the findings of Adams (2002) and Rouphael and Colla (2005). The higher solar radiation due to high level of natural light

and long photoperiod was presumably responsible for the increased photosynthesis in the spring-summer with respect to the summer-autumn season.

However in the current study, the author had less opportunity to control the greenhouse temperature than some other experiment and commercial systems have. The temperature inside the greenhouse in the current study was erratic and reached up to more than 40^{o}C. The optimum temperature recommended for greenhouse bell pepper production is between 21 to 23^{o}C (Calpas, 2002). Temperature is known affect growth (Calpas, 2002) and to disturb flowering and fruit set (Bakker, 1989).

Table 7.2 Comparison in yield from experiment-2 and study by ALsadony (2011)

Treatment	Expt-2	ALsadony	Expt-2	ALsadony
	Total Fresh fruit weight plant^{-1}		Total no of fruits plant^{-1}	
T1 (control)	610.1a	817.5	5.0	11.3a
T2	592.2a	831.6	5.1	10.7a
T3	553.0a	913.1	5.2	11.3a
T4	544.1a	527.0	5.2	13.3a
T5	556.7a	861.2	5.0	12.0a
T6	461.5b	604.4	4.9	4.7b
T7	507.8b	899.1	5.0	8.7b
T8	516.3b	790.0	5.1	6.0b

Means value in each column, followed by different letters are significantly different at $p \leq 0.05$ by Tukey's test

7.2.6 *Are there differences in the effects of different varieties (California Wonder and Ferrari) on the production of bell pepper (Capsicum annuum L.) with fertigation regimes in greenhouse condition?*

Even though the current study did not directly study the effects of varietal differences on the growth of bell pepper, control treatments in experiment-1 (Chapter 4) and experiment-2 (Chapter 5) had the same nutrient treatment (126-55-106 mg l^{-1} of N, P and K throughout the season) and similar seasonal condition (summer to autumn) but different varieties. California Wonder was used in experiment-1, while variety Ferrari was used in experiment-2.

Result indicated bell pepper variety Ferrari (533.1g plant^{-1}) outperformed California Wonder (310.5g plant^{-1}) significantly ($p \leq 0.01$) by 42% (Table 7.3). However, both

varieties had similar numbers of fruits affected by BER indicating that both were susceptible to a similar degree.

Table 7.3 Effects of different variety on yield parameters of bell pepper at final harvest

Variety	Total fruits fresh weight	BER incidence
	g plant^{-1}	No fruits plant^{-1}
California Wonder	310.5b	1.2
Ferrari	533.1a	1.8

Means in each column, followed by different letters are significantly different at $p \leq 0.05$ by Tukey's test.

The difference in the performance of the two varieties however could not be attributed only to the effects of the varietal differences. Differences between the growth, the source and method of plant raising may have been involved. Experiment-2 plants (Ferrari) were more advanced; they were brought from commercial grower at the age of about 8 weeks old. On the other hand, experiment-1 plants were raised from seeds by the author and transplanted into the greenhouse 4 weeks after germination.

7.2.7 Conclusion

In conclusion, the study successfully addressed all specific objectives and provides answers to the research questions set out the beginning of the thesis. It may be concluded (i) that the nutrients should be applied to crops in amounts and at times to meet the changing demands of the plant; and (ii) high fertigation frequency enhances the time-averaged moisture content in the vicinity of the roots and therefore increases water availability to the plant which lead to optimisation of yield and quality through the exclusion of over-irrigation and improved the efficient use of fertiliser.

7.3 Critical Review of the Study

At the outset of the research programme, the author had to decide the source of nutrient to be used taking into account ease of handling, equipment requirement and management expertise for application and cost. Pre-mixed water soluble fertilisers were favoured over individual elemental nutrients. However, a limitation was that pre-mixed fertilisers offered less flexibility in changing the nutrient supply to meet the plants' demand. Also by changing the level or concentration of nitrogen (N), or phosphorus (P), or potassium (K), the concentration of the other nutrients also changed because of the fixed NPK ratios i.e. it was not possible to change the concentration of one nutrient

independent of the others. For instance, when phosphorus was set at 55mg l^{-1}, the 20N-$20P_2O_5$-$20K_2O$ provided 126 and 106 mg l^{-1} of N and K, while 21N-$7P_2O_5$-$21K_2O$ provided 385 and 321 mg l^{-1} of N and K. Therefore the effect of growth and yield of bell pepper might be affected by the various N and K concentrations, independently or in combination.

Another issue was because of the diverse nutrient analyses among the fertilisers, the concentrations of micronutrients also varied a great deal. Therefore it was expected that plant growth might also be affected by various levels of micronutrients. Micronutrient deficiency can lead to poor yield e.g. calcium stress during fruiting in tomato and bell pepper increases susceptibility to blossom-end rot (BER) (Adams and El-Gizawy, 1988, Ho et al., 1995, Sonneveld and Voogt, 1991). Another predicament posed with the use of pre-mixed fertilisers in this study was the variability of electrical conductivity (EC) of the nutrient solution which may affect the growth of plants as described in Chapter 5.

The fertigation system's uniformity in distribution was important. This was assessed using the volumetric method (Mahajan and Singh, 2006) at the beginning of each experiment. Uniformity coefficients (U*c*) were found to be at 94%, 95%, and 95% in first experiment (Chapter 4), second experiment (Chapter 5) and finally third experiment (Chapter 6) respectively which is an excellent rating for drip irrigation uniformity (ASAE, 1999). The high values of uniformity coefficient indicated excellent performance of the fertigation system in this study in supplying nutrient solution throughout the emitters during the three experiments.

The greenhouse environment i.e. temperature and transpiration rate varied markedly as explained in Chapters 4, 5 and 6. Heating was supplied to maintain the minimum temperature at 15^{o}C. However, despite ventilation, the maximum temperature on hot summer days reached over 40^{o}C; there was no shade curtain available. Furthermore, the plants were grown under natural light condition which may have been inadequate to support optimal growth during the short days at the beginning and end of the season.

7.4 Suggestions for Further Studies

With only three seasons available, there was a limit to what could be investigated. However, this study has provided conclusive information on many issues regarding

nitrogen (N) and potassium (K) rates and ratios as well as on fertigation frequency as presented earlier in section 7.2 of this chapter. Clearly many issues require further scientific investigation following this study.

1. Unless the control system of the greenhouse is ideal, consistency is difficult to ensure. Accurate determination and monitoring of fertigation uniformity, concentration of nutrient solution as well as maintaining ideal environmental condition is necessary. Therefore, there is a case to repeat these experiments in an environment and system that allows much more sophisticated control
2. Use of pre-mixed fertiliser poses restrictions and less flexibility to adjust the nutrient solution according to the plant's requirement. The micro-nutrients content of the various pre-mixed fertilisers can vary considerably and this may contribute to the differences in bell pepper performance. Effects of supplying nutrients individually with similar micro-nutrient content should be investigated in similar conditions.
3. Where nutrient concentrations in the leachate are substantial, poor efficient use of fertiliser occurs and may lead to environmental contamination. Recycling of the leachate solution is suggested as a possible improvement. A further study may be devised to look into recirculation of nutrients. Re-using drainage solution offers a good opportunity to reduce leaching to the environment as well as way to save water and nutrients. One of the main difficulties with this technique is the high risk of rapidly spreading plant disease from a few isolated plants to entire nurseries via the recycled water (Pettitt, 2003, Voogt, 2003a).
4. In these experiments, the production period did not match a full bell pepper growing season as practiced by commercial growers and should be repeated to determine if effects of the different treatments were similar.
5. Electrical conductivity (EC) of fertigation nutrient solution could pose a major problem to bell pepper production and require further study. For example, the potential impact of electrical conductivity in view of the effect of high water salinity on bell pepper if it is used for irrigation. The decreasing availability of water all over the world has forced horticulture to use water of marginal quality e.g. due to salinity (Silber, 2005). Previously it had been reported that high salinity induces oxidative stress in plant tissues (Bar-Tal et al., 2003) and has a strong impact of incidence of BER in tomato and bell pepper fruits (Adams and Holder, 1992).

6. In nutrient treatments reported in chapter 4, 5, and 6; the actual concentrations of nitrogen and phosphorus were lower than the target whilst potassium was higher than the target value. Possibly this could have been due to loss of nitrogen as a gas by volatization or denitrification (Prasad and Kumar, 2001) and formation of calcium phosphate precipitate (Dhakal et al., 2005) respectively. However this also could be as a result of sampling error, solubility factor of the pre-mixed fertiliser, as well as the mobility of N, P and K. A further study is required to provide more information on these issues.
7. Greenhouse experiments on the effects of fertigation frequency on bell pepper production at other nutrient concentrations would be interesting. In particular, future studies might incorporate a different range of N, P and K level and the study of the uptake of this and other nutrients on the responsiveness of bell pepper production to fertigation frequency. High irrigation frequency had also been associated with increased uptake of magnesium (Mg) (Silber et al., 2005) and may be associated with the incidence of BER (Silber, 2005).
8. In the current study, it was not possible to investigate the effects of treatments on plant's root development. It would be interesting to examine root growth and distribution as related to the aboveground growth. This is because alterations of growth conditions generally led to modifications of the root system (Silber, 2005) and thus water stress, nutrient deficiency and irrigation frequency may have an effect on the root system.
9. In all experiments in this study, nutrients and water were supplied only during daytime. There may be differences between day and night application which should be examined as this may affect fertiliser and water use efficiency (FUE & WUE). Night watering can help increase the rate of fruit development, but there is an associated risk of fruit splitting if too much water is taken up at night (Calpas, 2002).
10. In the current study, only nitrogen, phosphorus and potassium uptake was considered; it would be interesting to look at the effect of N & K rates, N: K ratios and fertigation frequency on the uptake of micronutrients. As with macronutrients, the demand of micronutrients also fluctuates dramatically during the crop growth (Voogt, 2003a).
11. It is clear that in the present study increased irrigation frequency reduced BER incidence whilst it increased electrical conductivity (EC) and increased BER

incidence in bell pepper. However the mechanism by which this occurred is still uncertain. Better understanding of the BER phenomenon is an important and essential challenge for future research as it has a major impact on marketable yields and consumer acceptability.

The lack of information on the performance of bell pepper, and on rockwool in relation to N and K application rates, prompted the current research. The results of the two-year greenhouse experiments comprising various N and K rates and fertigation frequency highlight the complexity of bell pepper production in the greenhouse. This was underpinned by different nutrient requirement of bell pepper at various stages which provided a significant improvement in the efficient use of fertiliser. Fertigation has tremendous potential to change the face of irrigation systems of the horticultural as well as broad-acre crops worldwide and most particularly contribute towards greater productivity and savings of fertiliser, whilst minimizing the negative environmental impacts of irrigation.

7.5 Relevance of findings to commercial bell pepper production

Practical applications of relevance for commercial bell pepper growers that emerge from this study are:

- Applications of higher nutrient concentrations at an early stage (vegetative) of growth have no substantial benefits on bell pepper production, owing to the relatively small nutrient requirements during this phase. The work presented also suggests that adjusting the feed concentration based on the nutritional requirement of the crop throughout the growing season according to the plant's growth development is important in improving the efficient use of fertiliser and consequently lessening the potential of environmental contamination by fertiliser leaching.
- From a commercial point of view, it appears that increasing irrigation frequency has substantial benefits on plant growth, efficient use of fertiliser and could also play an important role in reducing the occurrence and severity of blossom-end rot (BER) of soil-less grown bell pepper. However, higher irrigation frequency may be less favourable in soil-grown plants due to lower shoot/root ratio, shallower root system and spread of soil borne pathogens (Silber, 2005).
- Certain horticultural practices that are adopted to increase plant growth and yield

in bell pepper such as defoliation should be done carefully as they might have negative effects that exceed the positive ones as shown in this study. It is very important to maintain a substantial leaf area throughout the fruiting period since it is central parameter for photosynthesis, transpiration and dry matter accumulation. A report by HDC (2009) concluded that it would be safe to defoliate bell peppers providing that at least 1.6m of the plant stem is retained, and it might be beneficial to leave slightly more leaf in the summer than at other times of the year.

- Data also showed that spring-summer season planting was superior to summer-autumn season, primarily due to the effect of declining temperatures. Unless additional lighting and heating are provided, it is recommended to grow bell pepper in the spring-summer season. However, according to Rouphael and Colla (2005) growing in the summer-autumn season results in better water use efficiency (WUE) compared to the spring-summer season. From an environmental point of view, growing bell pepper during the summer-autumn season represents an important practice to improve WUE especially in regions where water supplies are limited.
- Data also showed that during the spring-summer season the growing medium EC (measured through leachate EC in the current study) increases much more than the summer-autumn season. So at higher temperature and solar radiation (spring-summer season), less concentrated fertiliser solution should be used to maintain the EC of the growing medium at the desired level to prevent yield reductions. Raising the feed EC during the cooler days (summer-autumn) will provide more nutrients to the plants, lowering the fertiliser EC on the hotter days (spring-summer) will provide a greater relative proportion of water to the plants (since the plants have greater demands for water).

7.6 Implication of the study towards Brunei Agriculture

Based on the experience and knowledge gained during the implementations of this study, the author believes the use of fertigation in Brunei Darussalam in order to realise its ambitions to achieve food self-sufficiency is essential.

Agricultural activity in Brunei is not high. The government has attempted to increase agricultural production in order to achieve self-sufficiency in food, but results have been

unsatisfactory. While land, finance, and irrigation facilities are available, agricultural activities lack manpower resources. The gap between wages in farming and the public sector is very large, and most Bruneians have little interest in agricultural production. The fact is, no matter how deeply-rooted it is in Brunei's culture, farming as a lifestyle and a viable means to earn a living has become a thing of the past. Only a tiny proportion of the population – retirees and members of older generation are currently maintaining the traditional way of life. Most of the younger generation are equipping and bracing themselves to earn a living in sectors such as oil and gas industry, civil service, banking and other private sectors.

Temporary and permanent crops are actively cultivated on an estimated 7,700 hectares of land which represents about 1.3% of total land area (Press, 2007). Agriculture employs about 2% of the total workforce in Brunei (Department of Agriculture, 2007). Urban migration and more profitable jobs in the oil industry and government sectors have led to a shortage in farm labour. The agricultural production activities in Brunei are dominated by a large number of small producers with smaller number of commercial entrepreneurs. For the most part, the commercial producers are concentrated in poultry production (Press, 2007).

According to the Brunei Darussalam Agriculture Statistics in Brief (2007), agriculture only makes up about 5% of Brunei's Gross Domestic Product (GDP). In fact up to 70 percent of food requirements in Brunei are imported from neighbouring countries. However with the recent and sudden increase in prices of agricultural products worldwide, the issue of food security has become very important to Brunei. The agriculture sector's contribution to the GDP has shown an increasing trend in the past 11 years (Press, 2007). In fact the contribution of the agriculture sector to the GDP in comparison to non-oil and gas sector increased from 3.1 percent to 3.7 percent in 2007 (Press, 2007).

However, despite an encouraging trend in the local poultry production, Brunei has yet to achieve sufficiency with the rest of the agricultural sectors. While in Brunei agriculture sector is small, the level of self-sufficiency achieved in the poultry sector demonstrates an important aspect of food security against the back drop of increase in global price of agricultural produce. Under the 9th National Development Plan (NDP) which runs from

2006 to 2011 (Press, 2007), a great emphasis has been put into agriculture with the aspiration for food self-sufficiency and food security for the people of Brunei as a whole.

Agriculture remains a priority sector in Brunei's economic development where there are considerable opportunities for increasing domestic production as well as potential for increased exports into specialised markets. In term vegetable industry, Brunei imported 7,125 tonnes in 2007, about 42% of Brunei's requirement and valued about £7 million. One of the major types of vegetable imported by Brunei is bell pepper (*Capsicum annuum L.*) with CIF value of about £256,000 in 2007 (Department of Agriculture, 2007) and has been increasing every year. Brunei still does not produce bell peppers in large enough amounts that can satisfy local demand.

In this context, traditional agriculture needs to transform towards modernisation. The author believes that, the use of fertigation can overcome some of the shortcomings by improving yield with better fertiliser and water use efficiency. With the use of greenhouse soil-less fertigation system, the production of bell pepper in Brunei can be increased beyond the current production (soil grown), without the use of methyl bromide but still avoiding problems with soil borne pests and diseases. Increase in bell pepper yield will require efficient use of water and fertiliser to sustain plant nutritional demands throughout the growing season while minimising nutrient losses to the environment. This can be achieved through proper scheduling of nutrient according to the growth stages of the plants and through increasing fertigation frequency as revealed in the current study.

Appendices

Appendix 1

(Chapter 4: A greenhouse study of the effects of fertiliser concentration (N and K rates) at different growth stages on bell pepper production)

Table 4.16 Fertigation uniformity

Amount collected in dripper^{-1} in five minutes (ml)			Amount collected dripper^{-1} minute^{-1} (ml)		
154	150	148	30.8	30.0	29.6
152	144	150	30.4	28.8	30.0
151	140	153	30.2	28.0	30.6
147	148	154	29.4	29.6	30.8
145	152	156	29.0	30.4	31.2
147	147	149	29.4	29.4	29.8
143	158	145	28.6	31.6	29.0
146	146	156	29.2	29.2	31.2
147	151	153	29.4	30.2	30.6
156	143	138	31.2	28.6	27.6
Mean = 148.2		SEM = 1.08	Mean = 29.6		SEM = 0.22

Table 4.17 Plant height at different growth stages as affected by different treatments

Treatments	Plant height (cm)		
	37-DAT	67-DAT	102-DAT
	S1	S2	S3
T1	22.4	33.4	43.3a
T2	22.7	34.9	38.0ab
T3	23.3	31.5	37.1ab
T4	23.0	33.9	36.9ab
T5	24.2	32.5	36.6ab
T6	23.9	32.6	36.0ab
T7 (control)	22.9	30.5	35.2b

Values of the mean of 18, 12, and 6 plants treatment^{-1} in S1, S2 and S3 respectively. Mean in each column, followed by different letters are significantly different $p \leq 0.05$ by Tukey's test

Table 4.18 Stem diameter at different growth stages as affected by different treatments

Treatments	Stem diameter (mm)		
	37-DAT	37-DAT	67-DAT
	S1	S1	S2
T1	8.2	12.8	16.7
T2	8.2	13.1	15.5
T3	8.7	12.2	14.6
T4	8.4	13.2	14.9
T5	8.7	12.3	14.8
T6	8.9	12.9	14.5
T7 (control)	8.1	11.2	14.3

Values of the mean of 18, 12, and 6 plants treatment^{-1} in S1, S2 and S3 respectively. Results were not significantly different between treatments

Table 4.19 Leaf area at different growth stages as affected by different treatments

Treatments	Leaves area per plant (cm^2)		
	43- DAT	72-DAT	126-DAT
	S1	S2	S3
T1	1442.2	2521.5	4251.3a
T2	1326.1	2782.5	4038.2a
T3	1575.8	2043.8	3689.4ab
T4	1479.3	2614.6	3275.1ab
T5	1458.6	2491.2	3389.4ab
T6	1532.1	2533.9	3249.8ab
T7 (control)	1382.9	2130.2	3085.8b

Values of the mean of 6 plants treatment^{-1} at each stage. Mean in each column, followed by different letters are significantly different $p \leq 0.05$ by Tukey's test

Table 4.20 Leaf chlorophyll content (SPAD values) of bottom leaves

Treatment	S1		S2		S3	
	Mean	SEM	Mean	SEM	Mean	SEM
T1	69.5	2.50	74.4	2.05	75.7	2.51
T2	67.9	3.15	74.1	2.59	80.0	2.13
T3	75.5	3.50	76.7	2.52	80.3	2.30
T4	70.8	2.83	71.9	2.66	77.8	2.63
T5	74.6	2.54	76.3	3.23	79.1	1.95
T6	69.6	2.20	75.2	2.68	77.2	2.75
T7 (control)	73.4	3.50	74.6	2.97	75.4	2.94

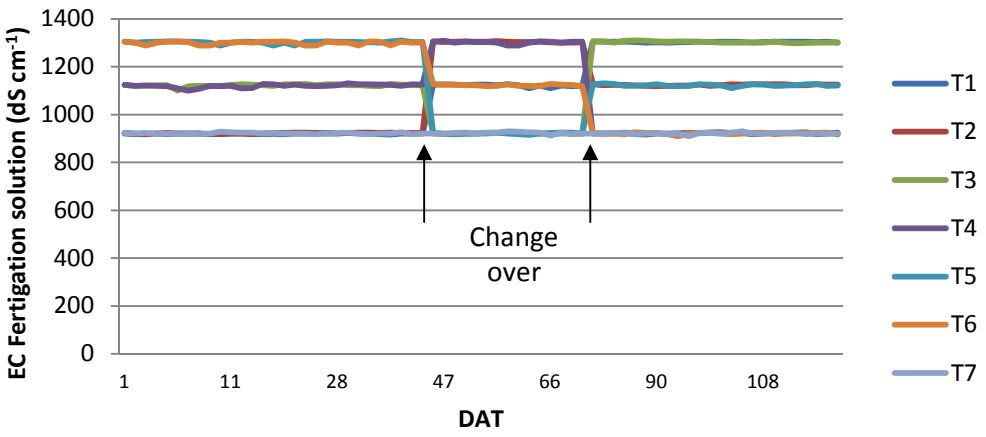
Means in each column. SEM is the standard error of means

Table 4.21 Leaf chlorophyll content (SPAD values) of top leaves

Treatment	S1		S2		S3	
	Mean	SEM	Mean	SEM	Mean	SEM
T1	56.7	2.47	60.6	3.45	67.2	2.45
T2	56.9	2.83	62.5	2.87	65.7	2.17
T3	57.6	2.63	59.9	2.55	64.6	2.55
T4	52.4	2.84	56.4	2.55	64.0	2.05
T5	50.8	2.97	59.2	2.77	64.4	3.27
T6	51.6	3.07	57.2	2.52	64.4	2.52
T7 (control)	52.3	2.50	55.4	3.83	63.4	3.31

Means in each column. SEM is the standard error of means

a



b

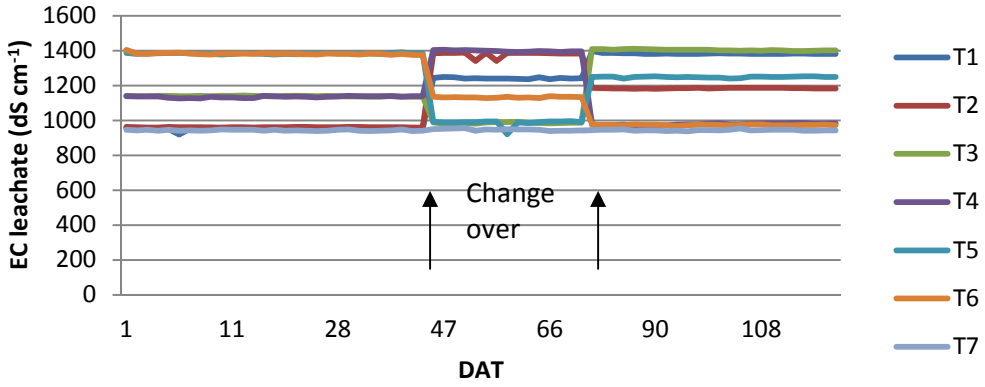
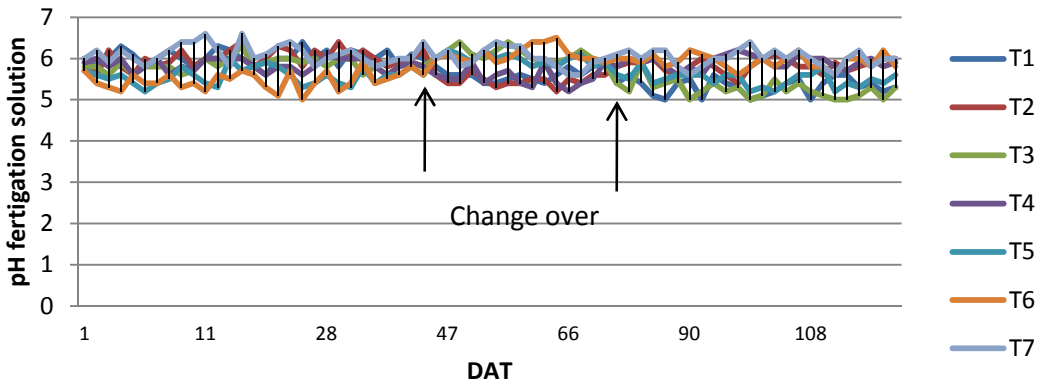


Figure 4.20 Electrical conductivity (EC) in (a) fertigation and (b) leachate solution at different days after transplanting (DAT)

a



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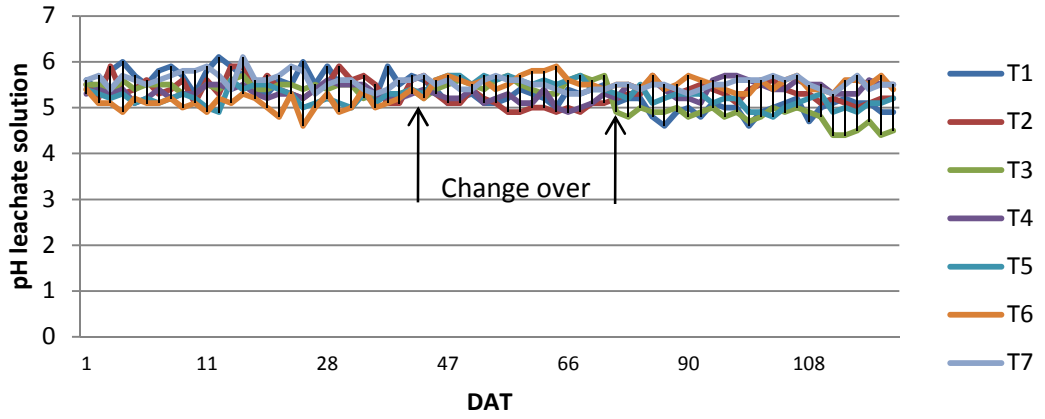

Figure 4.21 pH of (a) fertigation solution; (b) leachate solution at different growth stages

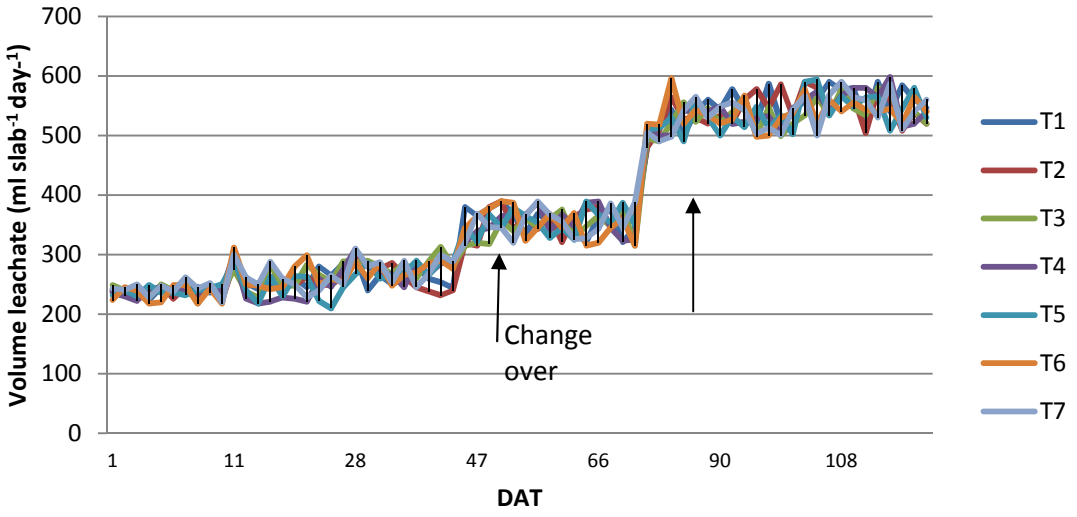

Figure 4.22 Amount of leachate solution at different growth stages

Table 4.22 NPK concentration in leaf, stem and fruit at Stage 1 (1 to 44-DAT)

Treatment	S1					
	N		P		K	
	Leaves	Stem	Leaves	Stem	Leaves	Stem
	mg g^{-1} dry matter					
T1	65.9	37.2	2.0	1.6	66.4	74.5
T2	67.3	37.4	2.0	1.8	64.0	73.1
T3	71.5	44.6	1.9	1.7	69.2	75.8
T4	69.4	47.6	2.1	1.8	67.8	76.9
T5	73.2	51.1	1.8	1.6	71.3	79.5
T6	73.7	51.0	1.9	1.6	70.5	79.1
T7 (control)	64.4	35.7	2.0	1.8	65.7	73.7

Values of means in each column. Results were not significantly different between treatments.

Table 4.23 NPK concentration in leaf, stem and fruit at Stage 2 (45 to 69-DAT)

Treatment	S2					
	N		P		K	
	Leaves	Stem	Leaves	Stem	Leaves	Stem
	mg g^{-1} dry matter					
T1	67.6	40.6	1.8	1.3	72.4	79.3
T2	69.1	44.2	1.8	1.4	73.6	76.0
T3	62.2	40.4	1.7	1.5	67.5	77.4
T4	70.1	43.5	1.9	1.4	72.9	75.4
T5	60.4	44.6	1.6	1.3	68.6	78.3
T6	64.1	46.8	1.7	1.3	71.6	76.1
T7 (control)	59.4	34.6	1.8	1.4	67.4	78.1

Values of means in each column. Results were not significantly different between treatments

Table 4.24 Effects of varying N and K rates on NPK uptake of nutrients in bell pepper at Stage 1 (1 to 44-DAT)

Treatment	Nitrogen			Phosphorus			Potassium		
	mg $plant^{-1}$								
	Leaf	Stem	Total	Leaf	Stem	Total	Leaf	Stem	Total
T1	1021.5	215.7	1237.2	27.9	9.2	37.1	1029.2	432.1	1461.3
T2	1029.7	228.1	1257.8	30.6	11.0	41.6	979.2	445.9	1425.1
T3	1158.3	298.9	1457.2	30.8	11.4	42.2	1121.0	507.9	1628.9
T4	1061.8	290.4	1352.2	32.1	11.0	43.1	1037.3	469.1	1506.4
T5	1185.8	321.9	1507.7	29.2	10.1	39.3	1155.1	500.9	1656.0
T6	1164.5	351.9	1516.4	30.0	11.0	41.0	1113.9	545.8	1659.7
T7 (Cntl)	985.3	214.2	1199.5	30.6	10.8	41.4	1005.2	442.2	1447.4

Values of the mean of 3 plants $treatment^{-1}$. Results were not significantly different between treatments

Table 4.25 Table Effects of varying N and K rates on NPK uptake of nutrients in bell pepper at Stage 2 (45 to 69-DAT)

Treatment	Nitrogen			Phosphorus			Potassium		
	mg plant^{-1}								
	Leaf	Stem	Total	Leaf	Stem	Total	Leaf	Stem	Total
T1	1304.7	393.8	1698.5	34.7	12.6	47.3	1397.3	769.2	2166.5
T2	1230.0	433.2	1663.2	32.0	13.7	45.7	1310.1	744.8	2054.9
T3	1007.6	371.7	1379.3	27.5	13.8	41.3	1093.5	712.1	1805.6
T4	1121.6	387.2	1508.8	30.4	12.5	42.9	1166.4	653.3	1819.7
T5	984.5	365.7	1350.2	26.1	10.7	36.8	1118.2	633.9	1752.1
T6	1044.8	388.4	1433.2	27.7	10.8	38.5	1167.1	615.0	1782.1
T7 (Cntl)	938.5	269.9	1208.4	28.4	10.9	39.3	1064.9	570.2	1635.1

Values of the mean of 3 plants treatment^{-1}. Results were not significantly different between treatments

Table 4.26 Gas analyser (photosynthetic rate)

Treatment	S1		S2		S3	
	μmol m^{-1} s^{-1}					
	Mean	SEM	Mean	SEM	Mean	SEM
T1	13.16	2.53	9.76	2.44	6.42	1.37
T2	12.61	2.30	8.39	2.34	5.14	1.05
T3	9.23	1.59	4.82	1.99	4.29	0.58
T4	9.61	1.36	4.76	1.73	3.78	1.07
T5	5.86	2.86	4.52	1.49	3.51	0.89
T6	8.84	1.56	6.66	1.63	5.39	0.78
T7	11.61	2.54	5.32	1.88	4.45	1.21

Means in each column. SEM is the standard error of means

Table 4.27 Gas analyser (transpiration rate)

Treatment	S1		S2		S3	
	mmol m^{-2} s^{-1}					
	Mean	SEM	Mean	SEM	Mean	SEM
T1	6.68	0.74	4.19	0.90	2.55	0.98
T2	7.04	0.65	5.02	0.85	3.64	0.54
T3	6.02	0.67	3.60	0.84	2.98	0.83
T4	4.87	1.21	3.50	1.01	2.72	0.78
T5	5.27	1.21	3.65	0.99	2.82	0.67
T6	5.42	1.21	2.97	1.21	2.65	1.01
T7	6.75	1.10	4.55	0.87	3.59	0.89

Means in each column. SEM is the standard error of means

Table 4.28 Gas analyser (sub-stomatal CO_2)

Treatment	S1		S2		S3	
	vpm					
	Mean	SEM	Mean	SEM	Mean	SEM
T1	275.63	18.99	255.87	24.10	277.47	23.1
T2	279.17	18.80	291.13	18.18	312.13	16.5
T3	281.60	17.90	291.83	9.67	298.55	21.0
T4	262.47	12.40	290.70	14.60	307.59	15.0
T5	298.90	17.12	298.80	18.74	295.55	12.5
T6	282.73	13.90	272.40	21.20	288.24	11.3
T7	276.77	17.49	301.03	21.13	306.01	11.1

Means in each column. SEM is the standard error of means

Table 4.29 Gas analyser (stomatal conductance)

Treatment	S1		S2		S3	
	mmol m^{-2} s^{-1}					
	Mean	SEM	Mean	SEM	Mean	SEM
T1	0.52	0.11	0.29	0.06	0.17	0.05
T2	0.51	0.10	0.37	0.09	0.25	0.06
T3	0.43	0.07	0.24	0.07	0.20	0.04
T4	0.38	0.11	0.22	0.09	0.16	0.03
T5	0.39	0.08	0.24	0.08	0.16	0.04
T6	0.36	0.09	0.18	0.11	0.15	0.06
T7	0.51	0.09	0.36	0.09	0.21	0.05

Means in each column. SEM is the standard error of means

Appendix 2

(Chapter 5: Further evaluation of the effects of fertiliser concentration – Effects of higher and lower fertiliser concentration (N and K rates) on bell pepper production

Table 5.16 Fertigation uniformity

Amount collected in dripper^{-1} in five minutes (ml)				Amount collected dripper^{-1} minute^{-1} (ml)			
154	140	156	153	30.8	28.0	31.2	30.6
152	148	149	148	30.4	29.6	29.8	29.6
151	152	145	156	30.2	30.4	29.0	31.2
147	147	156	149	29.4	29.4	31.2	29.8
145	158	153	145	29.0	31.6	30.6	29.0
147	146	138	156	29.4	29.2	27.6	31.2
143	151	152	160	28.6	30.2	30.4	32.0
146	143	149	152	29.2	28.6	29.8	30.4
147	148	151	149	29.4	29.6	30.2	29.8
156	150	145	150	31.2	30.0	29.0	30.0
150	153	160	142	30.0	30.6	32.0	28.4
144	154	150	156	28.8	30.8	30.0	31.2
Mean = 149.86		SEM = 0.70		Mean = 29.97		SEM = 0.14	

Table 5.17 Leaf chlorophyll content (SPAD values) of top leaves

Treatment	S1		S2		S3	
	Mean	SEM	Mean	SEM	Mean	SEM
T1	60.69	2.45	59.52	1.73	65.91	1.47
T2	62.06	1.35	60.49	1.08	64.14	1.84
T3	62.60	1.25	61.81	1.89	66.61	1.52
T4	60.39	2.09	62.98	1.84	66.02	1.41
T5	62.63	1.69	63.80	1.79	64.54	1.37
T6	62.22	1.42	54.61	1.04	58.64	1.64
T7	63.66	2.20	53.66	1.26	58.92	1.37
T8	59.38	2.44	55.55	1.21	59.65	0.99

Means in each column. SEM is the standard error of means

Table 5.18 Leaf chlorophyll content (SPAD values) of bottom leaves

Treatment	S1		S2		S3	
	Mean	SEM	Mean	SEM	Mean	SEM
T1	57.83	2.55	61.82	1.34	67.45	1.80
T2	62.08	3.16	64.21	2.09	67.46	1.15
T3	57.56	2.76	65.52	1.59	67.25	1.23
T4	59.81	2.57	67.24	1.33	71.16	1.47
T5	65.02	1.84	69.49	1.39	72.04	1.14
T6	59.99	3.66	53.94	2.09	58.34	1.19
T7	62.70	3.23	55.31	1.22	60.23	1.07
T8	62.77	2.78	56.16	1.09	60.89	1.23

Means in each column. SEM is the standard error of means

Table 5.19 Gas analyser (photosynthetic rate)

Treatment	S1		S2		S3	
	μmol m^{-2} s^{-1}					
	Mean	SEM	Mean	SEM	Mean	SEM
T1	10.13	3.23	11.11	1.95	4.44	1.65
T2	13.41	1.90	10.51	3.45	4.55	1.60
T3	13.39	3.86	11.20	2.68	4.12	0.90
T4	14.90	1.95	8.48	1.27	4.16	1.65
T5	10.35	3.17	9.34	1.92	5.35	3.15
T6	13.30	3.44	8.18	2.45	3.20	1.14
T7	9.96	1.83	10.56	2.37	5.68	1.66
T8	10.31	1.14	11.16	1.77	6.04	2.60

Means in each column. SEM is the standard error of means

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Table 5.20 Gas analyser (transpiration rate)

Treatment	S1		S2		S3	
	mmol m^{-2} s^{-1}					
	Mean	SEM	Mean	SEM	Mean	SEM
T1	5.84	0.42	5.33	0.38	4.14	0.61
T2	4.99	0.62	6.25	0.62	4.12	1.06
T3	4.93	1.11	5.09	0.88	4.80	0.56
T4	6.34	0.88	5.22	0.52	4.48	0.53
T5	4.66	0.96	5.77	0.44	5.22	0.45
T6	5.42	0.82	5.03	0.47	4.07	0.50
T7	5.72	0.59	6.29	0.62	5.29	0.49
T8	5.81	0.43	5.91	0.60	4.31	0.59

Means in each column. SEM is the standard error of means

Table 5.21 Gas analyser (sub-stomatal CO_2)

Treatment	S1		S2		S3	
	vpm					
	Mean	SEM	Mean	SEM	Mean	SEM
T1	274.8	24.4	287.6	11.1	369.2	13.3
T2	232.8	22.1	306.2	10.1	371.9	11.3
T3	238.3	17.5	296.5	9.6	378.6	12.9
T4	253.2	18.0	304.1	11.0	369.4	16.0
T5	248.0	21.4	301.0	9.0	363.6	21.2
T6	248.0	14.8	304.7	15.6	377.2	23.3
T7	268.7	17.0	295.3	6.7	372.1	12.8
T8	277.4	24.2	295.8	9.6	358.8	18.8

Means in each column. SEM is the standard error of means

Table 5.22 Gas analyser (stomatal conductance)

Treatment	S1		S2		S3	
	mmol m^{-2} s^{-1}					
	Mean	SEM	Mean	SEM	Mean	SEM
T1	0.42	0.07	0.48	0.03	0.43	0.03
T2	0.32	0.04	0.59	0.04	0.43	0.06
T3	0.30	0.08	0.49	0.07	0.50	0.04
T4	0.53	0.05	0.50	0.03	0.49	0.04
T5	0.26	0.05	0.55	0.03	0.45	0.03
T6	0.39	0.10	0.44	0.03	0.46	0.10
T7	0.36	0.04	0.54	0.07	0.51	0.06
T8	0.44	0.05	0.66	0.04	0.45	0.06

Means in each column. SEM is the standard error of means.

Table 5.23 NPK concentration in leaf, stem and fruit at Stage 1 (1 to 33-DAT)

Treatment	S1					
	N		P		K	
	Leaves	Stem	Leaves	Stem	Leaves	Stem
	mg g^{-1} dry matter					
T1	58.8	32.3	2.1	1.3	58.0	63.0
T2	59.6	31.1	2.1	1.2	55.4	61.5
T3	62.6	33.2	2.0	1.4	56.3	65.1
T4	62.9	31.5	2.3	1.4	54.1	64.5
T5	59.4	29.6	2.2	1.2	53.6	63.2
T6	58.2	30.0	2.1	1.4	54.4	62.2
T7	60.0	33.4	2.2	1.2	55.0	63.1
T8	58.1	28.3	2.1	1.3	56.2	62.8

Values of the mean in each column. Results were not significantly different between treatments

Table 5.24 NPK concentration in leaf, stem and fruit at Stage 2 (34 to 61-DAT)

Treatment	S2					
	N		P		K	
	Leaves	Stem	Leaves	Stem	Leaves	Stem
	mg g^{-1} dry matter					
T1	52.5a	29.7a	1.9	1.2	59.1a	64.4a
T2	53.3a	25.5a	1.9	1.1	56.3a	62.8a
T3	66.6a	36.4a	1.8	1.3	65.0a	68.2a
T4	66.9a	37.9a	2.0	1.2	68.6a	69.5a
T5	69.3a	41.7a	1.9	1.1	66.1a	68.8a
T6	38.4b	18.5b	1.8	1.2	40.1b	54.6b
T7	39.3b	19.7b	1.9	1.2	41.2b	57.9b
T8	42.2b	19.6b	1.8	1.1	43.5b	56.1b

Mean in each column, followed by different letters are significantly different $p \leq 0.05$ by Tukey's test

Table 5.25 NPK concentration in leaf, stem and fruit at Stage 3 (62 to 95-DAT)

Treatment	S3								
	N			P			K		
	Leaves	Stem	Fruit	Leaves	Stem	Fruit	Leaves	Stem	Fruit
	mg g^{-1} dry matter								
T1	50.4a	27.3a	56.0a	1.5	1.1	1.3	50.1a	58.1a	55.4a
T2	61.4a	37.4a	57.4a	1.6	1.0	1.4	55.4a	63.4a	60.4a
T3	56.3a	31.0a	58.9a	1.4	1.2	1.3	58.2a	59.3a	59.6a
T4	64.1a	41.8a	60.7a	1.6	1.0	1.2	60.5a	66.3a	62.5a
T5	49.5a	38.6a	54.9a	1.6	1.0	1.3	47.8a	56.2a	50.1a
T6	35.6b	20.8b	41.7b	1.4	1.1	1.4	32.0b	46.6b	34.1b
T7	42.1b	26.2b	48.3b	1.5	1.1	1.3	36.5b	48.6b	45.0b
T8	43.2b	23.6b	46.3b	1.4	1.2	1.3	33.7b	42.1b	46.1b

Mean in each column, followed by different letters are significantly different $p \leq 0.05$ by Tukey's test

Table 5.26 Effects of varying N and K rates on NPK uptake of nutrients in bell pepper at Stage 1 (1 to 33-DAT)

Treatment	Nitrogen			Phosphorus			Potassium		
	mg $plant^{-1}$								
	Leaf	Stem	Total	Leaf	Stem	Total	Leaf	Stem	Total
T1 (control)	1181.9	474.8	1656.7	42.2	19.1	61.3	1165.8	926.1	2091.9
T2	1168.2	444.7	1612.9	41.2	17.2	58.3	1085.8	879.5	1965.3
T3	1270.8	501.3	1772.1	40.6	21.1	61.7	1142.9	983.0	2125.9
T4	1295.7	488.3	1784.0	47.4	21.7	69.1	1114.5	999.8	2114.2
T5	1253.3	476.6	1729.9	46.4	19.3	65.7	1131.0	1017.5	2148.5
T6	1309.5	471.0	1780.5	47.3	22.0	69.2	1224.0	976.5	2200.5
T7	1158.0	484.3	1642.3	42.5	17.4	59.9	1061.5	915.0	1976.5
T8	1150.4	418.8	1569.2	41.6	19.2	60.8	1112.8	929.4	2042.2

Values of the mean in each column. Results were not significantly different between treatments

Appendix 3

(Chapter 6: A greenhouse study of the effects of irrigation frequency on bell pepper production)

Climatic record

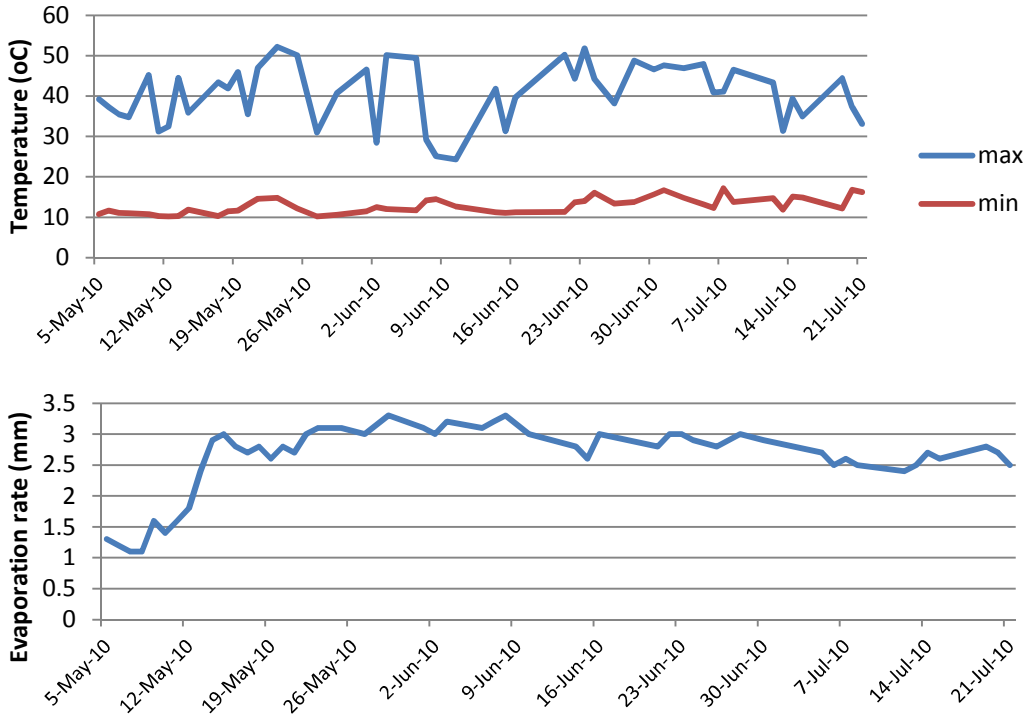

Figure 6.12 Variations with time of air temperature (maximum and minimum) and evaporation rate in the greenhouse throughout the study

Table 6.18 Fertigation uniformity

Amount collected in dripper^{-1} in five minutes (ml)				Amount collected dripper^{-1} minute^{-1} (ml)			
147	151	150	151	29.4	30.2	30.0	30.2
158	147	144	145	31.6	29.4	28.8	29.0
146	145	140	160	29.2	29.0	28.0	32.0
151	147	148	152	30.2	29.4	29.6	30.4
143	143	150	156	28.6	28.6	30.0	31.2
148	160	153	149	29.6	32.0	30.6	29.8
150	152	154	154	30.0	30.4	30.8	30.8
153	149	156	147	30.6	29.8	31.2	29.4
148	150	149	152	29.6	30.0	29.8	30.4
156	142	145	156	31.2	28.4	29.0	31.2
149	149	156	146	29.8	29.8	31.2	29.2
145	156	153	138	29.0	31.2	30.6	27.6
Mean = 149.77		SEM = 0.72		Mean = 29.95		SEM = 0.14	

Chapter 6.1

(Effects of varying irrigation frequency at different growth stages on the production of bell pepper)

Table 6.19 Plant heights and stem diameter as affected by varying fertigation frequency

Treatment	Plant height (cm)			Stem diameter (mm)		
	S1	S2	S3	S1	S2	S3
	42-DAT	56-DAT	79-DAT	42-DAT	56-DAT	79-DAT
T1	28.8	38.2	48.1	11.2	14.5	15.1
T2	29.2	39.0	50.8	11.2	15.1	15.6
T3	29.8	39.9	52.2	11.6	15.2	16.2
T4	27.8	36.7	48.5	11.4	14.6	15.3
T5	29.1	38.8	50.0	10.9	14.8	15.5

Means in each column. No significant differences were observed between treatments.

Table 6.20 NPK concentrations in leaf and stem at Stage 1 (1 to 33-DAT)

Treatment	S1					
	N		P		K	
	Leaves	Stem	Leaves	Stem	Leaves	Stem
	mg g^{-1} dry matter					
T1	57.6	48.5	2.1	1.6	52.8	60.3
T2	61.5	46.6	1.9	1.4	54.5	62.0
T3	65.5	52.1	2.1	1.7	58.0	63.0
T4	59.3	47.4	1.8	1.5	52.2	60.7
T5	64.7	52.2	2.2	1.7	53.0	62.4

Means in each column. No significant differences were observed between treatments.

Table 6.21 NPK concentrations in leaf and stem at Stage 2 (34 to 61-DAT)

Treatment	S2					
	N		P		K	
	Leaves	Stem	Leaves	Stem	Leaves	Stem
	mg g^{-1} dry matter					
T1	53.7	38.6	1.8	1.2	54.8	61.2
T2	58.8	40.8	2.3	1.5	56.2	62.6
T3	63.6	37.7	2.5	1.8	58.6	63.8
T4	55.0	45.0	2.0	1.4	53.0	61.0
T5	58.1	36.7	2.1	1.5	54.1	64.6

Means in each column. No significant differences were observed between treatments.

Table 6.22 NPK concentration in leaf, stem and fruit at Stage 3 (62 to 95-DAT)

Treatment	S3								
	N			P			K		
	Leaf	Stem	Fruit	Leaf	Stem	Fruit	Leaf	Stem	Fruit
	mg g^{-1} dry matter								
T1	52.6	29.3	53.9	1.6	1.1	1.3	48.4	52.1	58.8
T2	57.5	35.4	56.0	2.2	1.4	1.3	50.8	56.2	60.4
T3	58.9	38.5	56.1	2.3	1.6	1.5	52.0	58.3	61.8
T4	54.2	34.1	54.2	1.9	1.3	1.4	51.1	53.0	61.5
T5	54.8	31.1	55.6	2.0	1.3	1.3	50.1	54.6	59.6

Means in each column. No significant differences were observed between treatments.

Table 6.23 Leaf chlorophyll content (SPAD values) of top and bottom leaves

Treatment	S1		S2		S3	
	Top leaves					
	Mean	SEM	Mean	Mean	SEM	Mean
T1	53.86	1.11	55.06	1.32	61.27	1.15
T2	53.10	1.02	54.30	0.90	61.83	0.91
T3	54.07	0.78	54.57	1.39	60.74	1.00
T4	56.34	1.19	57.79	1.91	61.27	1.36
T5	53.97	1.07	54.47	1.34	62.13	1.08

Means in each column. SEM is the standard error of means.

Table 6.24 Leaf chlorophyll content (SPAD values) of top and bottom leaves

Treatment	S1		S2		S3	
	Bottom leaves					
	Mean	SEM	Mean	Mean	SEM	Mean
T1	72.33	1.82	78.43	1.57	80.96	0.70
T2	69.68	2.30	75.50	1.84	77.70	2.14
T3	74.77	1.72	78.11	1.79	79.92	1.81
T4	68.15	1.60	72.75	1.75	80.23	1.79
T5	72.81	2.16	75.73	1.91	77.99	1.31

Means in each column. SEM is the standard error of means.

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Table 6.25 Gas analyser (photosynthetic rate)

Treatment	S1		S2		S3	
	µmol m^{-2} s^{-1}					
	Mean	SEM	Mean	SEM	Mean	SEM
T1	9.4	2.78	12.4	1.20	13.6	1.31
T2	11.8	2.03	14.2	0.63	14.4	0.79
T3	12.2	1.54	15.1	0.70	15.9	0.52
T4	10.6	1.79	13.0	0.78	14.4	1.00
T5	10.2	1.80	12.8	1.51	14.5	2.05

Means in each column. SEM is the standard error of means.

Table 6.26 Gas analyser (transpiration rate)

Treatment	S1		S2		S3	
	mmol m^{-2} s^{-1}					
	Mean	SEM	Mean	SEM	Mean	SEM
T1	6.99	1.43	6.06	0.36	4.32	0.54
T2	7.61	1.21	6.42	0.47	5.10	0.29
T3	6.83	1.38	5.62	0.76	4.66	0.53
T4	6.81	1.38	6.32	0.51	5.12	0.45
T5	7.11	0.94	5.92	0.33	4.36	0.50

Means in each column. SEM is the standard error of means.

Table 6.27 Gas analyser (sub-stomatal CO_2)

Treatment	S1		S2		S3	
	vpm					
	Mean	SEM	Mean	SEM	Mean	SEM
T1	265.51	14.7	300.00	5.46	298.37	9.88
T2	274.12	10.4	285.23	2.37	296.78	7.64
T3	259.34	8.83	276.12	4.35	269.24	7.19
T4	274.91	9.37	291.43	4.76	285.27	5.16
T5	264.91	11.1	289.68	7.11	289.71	10.1

Means in each column. SEM is the standard error of means.

Table 6.28 Gas analyser (stomatal conductance)

Treatment	S1		S2		S3	
	mmol m^{-2} s^{-1}					
	Mean	SEM	Mean	SEM	Mean	SEM
T1	0.53	0.06	0.57	0.04	0.59	0.05
T2	0.60	0.04	0.61	0.03	0.63	0.04
T3	0.52	0.04	0.55	0.05	0.60	0.05
T4	0.52	0.05	0.60	0.04	0.61	0.04
T5	0.56	0.04	0.55	0.05	0.59	0.07

Means in each column. SEM is the standard error of means.

Table 6.29 Effects of varying fertigation frequency on biomass production, partitioning and harvest index (HI) of bell pepper

Treatment	Dry weight (g plant^{-1})											HI
	S1			S2				S3				
	Leaves	Stem	TDM	Leaves	Stem	Young fruits	TDM	Leaves	Stem	Fruit	TDM	
T1 (control)	5.9	3.9	9.8	11.3	9.3	13.1	33.7	16.1	13.3	41.9	71.3	58.8b
T2	5.9	4.2	10.1	13.6	9.9	13.6	37.1	21.4	15.9	55.4	92.7	59.8ab
T3	7.1	4.3	11.4	12.8	10.0	17.0	39.8	22.0	15.1	59.3	96.4	61.5a
T4	6.5	4.6	11.1	12.7	9.0	12.6	34.3	17.9	15.0	44.9	77.8	57.7ab
T5	6.4	4.1	10.5	11.0	9.0	14.4	34.4	18.2	14.0	43.4	75.6	57.4ab

Means in each column. Results were not significantly different between treatments.

Table 6.30 Effects of varying N and K rates on NPK uptake of nutrients in bell pepper at Stage 1 (1 to 43-DAT)

Treatment	Nitrogen			Phosphorus			Potassium		
	mg plant^{-1}								
	Leaf	Stem	Total	Leaf	Stem	Total	Leaf	Stem	Total
T1	339.8	189.2	529.0	12.4	6.2	18.6	311.5	235.2	546.7
T2	362.9	195.7	558.6	11.2	5.9	17.1	321.6	260.4	582.0
T3	465.1	224.0	689.1	14.9	7.3	22.2	411.8	272.2	684.0
T4	385.5	218.0	603.5	11.7	6.9	18.6	339.3	279.2	618.5
T5	414.1	214.0	628.1	14.1	7.0	21.1	339.2	255.8	595.0

Values of the mean of 3 plants treatment^{-1}. Results were not significantly different between treatments

Table 6.31 Effects of varying N and K rates on NPK uptake of nutrients in bell pepper at Stage 2 (44 to 64-DAT)

Treatment	Nitrogen			Phosphorus			Potassium		
	mg plant^{-1}								
	Leaf	Stem	Total	Leaf	Stem	Total	Leaf	Stem	Total
T1	606.8	359.0	965.8	20.3	10.2	30.5	619.2	569.2	1188.4
T2	799.7	403.9	1203.6	31.3	14.9	46.2	764.3	619.7	1384.0
T3	814.1	377.0	1191.1	32.0	18.0	50.0	750.1	638.0	1388.1
T4	698.5	405.0	1103.5	25.4	12.6	38.0	673.1	549.0	1222.1
T5	639.1	330.3	969.4	23.1	13.5	36.6	595.1	581.4	1176.5

Values of the mean of 3 plants treatment^{-1}. Results were not significantly different between treatments

Table 6.32 Effects of varying N and K rates on NPK uptake of nutrients in bell pepper at Stage 3 (65 to 84-DAT)

Treatment	Nitrogen				Phosphorus				Potassium			
	mg plant^{-1}											
	Leaf	Stem	Fruit	Total	Leaf	Stem	Fruit	Total	Leaf	Stem	Fruit	Total
T1	867.9	389.7	1881.1	3138.7	26.4	16.0	41.9	84.3	798.6	629.9	2052.1	3480.6
T2	1230.5	598.3	2648.8	4477.6	47.1	23.7	75.7	146.5	1087.1	949.8	2856.9	4893.8
T3	1295.8	581.4	2778.0	4655.2	50.6	24.2	84.2	159.0	1144.0	880.3	3059.1	5083.4
T4	872.6	511.5	2205.9	3590.0	30.6	19.5	61.1	111.2	822.7	795.0	2503.1	4120.8
T5	904.2	435.4	2190.6	3530.2	33.0	18.2	55.2	106.4	826.7	764.4	2348.2	3939.3

Values of the mean of 3 plants treatment^{-1}. Results were not significantly different between treatments

Chapter 6.2

(Effects of irrigation frequency and defoliation on the development of bell pepper)

Table 6.33 Plant heights and stem diameter as affected by varying fertigation frequency

Treatment	Plant height (cm)			Stem diameter (mm)		
	S1	S2	S3	S1	S2	S3
	42-DAT	56-DAT	79-DAT	42-DAT	56-DAT	79-DAT
T1	25.2	33.3	46.7	10.6	14.2	15.9
T2	25.6	33.5	45.3	11.0	14.6	15.3
T3	25.9	33.3	48.3	10.7	14.9	16.2
T4	26.0	34.5	46.8	11.1	14.3	15.9

Means in each column. Results were not significantly different between treatments

Table 6.34 Leaf area at different growth stages as affected by varying fertigation frequency

Treatments	Leaves area per plant (cm^2)		
	43-DAT	64-DAT	84-DAT
	S1	S1	S2
T1 (control)	1087a	2062a	3607a
T2	675b	1529b	3017b
T3	1055a	2156a	3828a
T4	770b	1450b	3173b

Means in each column, followed by different letters are significantly different at $p \leq 0.05$ by Tukey's test.

Table 6.35 NPK concentrations in leaf and stem at Stage 1 (1 to 33-DAT)

Treatment	S1					
	N		P		K	
	Leaves	Stem	Leaves	Stem	Leaves	Stem
	mg g^{-1} dry matter					
T1	67.6	54.0	1.9	1.4	51.0	61.8
T2	73.6	52.2	2.0	1.5	50.4	60.6
T3	66.5	51.9	2.1	1.6	54.3	63.6
T4	72.8	53.1	2.1	1.5	54.1	64.6

Means in each column. No significant differences were observed between treatments.

Table 6.36 NPK concentrations in leaf and stem at Stage 2 (34 to 61-DAT)

Treatment	S2					
	N		P		K	
	Leaves	Stem	Leaves	Stem	Leaves	Stem
	mg g^{-1} dry matter					
T1	61.0	46.2	1.3	1.2	52.1	62.0
T2	65.2	49.4	1.4	1.3	52.0	63.2
T3	65.1	51.0	1.5	1.5	56.4	64.5
T4	68.5	48.4	1.6	1.4	54.3	65.2

Means in each column. No significant differences were observed between treatments.

Table 6.37 NPK concentration in leaf, stem and fruit at Stage 3 (62 to 95-DAT)

Treatment	S3								
	N			P			K		
	Leaf	Stem	Fruit	Leaf	Stem	Fruit	Leaf	Stem	Fruit
	mg g^{-1} dry matter								
T1	60.2	44.4	59.8	1.1	1.0	1.3	50.8	60.2	71.4
T2	60.3	46.6	50.2	1.1	1.0	1.3	50.3	59.1	72.4
T3	58.9	43.1	58.4	1.3	1.3	1.5	53.5	61.8	74.9
T4	59.8	41.5	57.4	1.3	1.2	1.6	53.7	61.6	75.3

Means in each column. No significant differences were observed between treatments.

Table 6.38 Gas analyser (photosynthetic rate)

Treatment	S1		S2		S3	
	µmo m^{-2} s^{-1}					
	Mean	SEM	Mean	SEM	Mean	SEM
T1	13.02	1.56	12.40	2.75	13.38	3.35
T2	14.62	1.09	12.64	2.51	15.96	2.74
T3	17.38	0.94	16.93	3.35	17.26	2.38
T4	12.02	3.04	13.87	0.72	11.46	3.93

Means in each column. SEM is the standard error of means.

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Table 6.39 Gas analyser (transpiration rate)

Treatment	S1		S2		S3	
	mmol m^{-2} s^{-1}					
	Mean	SEM	Mean	SEM	Mean	SEM
T1	8.66	1.68	7.45	0.36	7.49	1.43
T2	9.30	0.67	7.17	0.40	8.40	0.84
T3	8.35	0.45	7.38	0.62	8.02	0.43
T4	10.81	1.68	6.73	0.73	7.60	0.79

Means in each column. SEM is the standard error of means.

Table 6.40 Gas analyser (sub-stomatal CO_2)

Treatment	S1		S2		S3	
	vpm					
	Mean	SEM	Mean	SEM	Mean	SEM
T1	252.2	27.0	268.5	20.3	268.8	12.2
T2	253.4	30.8	280.0	10.9	265.1	14.0
T3	211.5	26.9	259.1	23.9	258.9	12.9
T4	263.3	33.8	256.6	15.5	283.9	14.8

Means in each column. SEM is the standard error of means.

Table 6.41 Gas analyser (stomatal conductance)

Treatment	S1		S2		S3	
	mmol m^{-2} s^{-1}					
	Mean	SEM	Mean	SEM	Mean	SEM
T1	0.46	0.17	0.49	0.10	0.50	0.09
T2	0.52	0.14	0.59	0.05	0.67	0.12
T3	0.40	0.10	0.62	0.09	0.67	0.02
T4	0.67	0.27	0.52	0.10	0.53	0.08

Means in each column. SEM is the standard error of means.

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Table 6.42 Yield parameters in bell peppers as influenced by varying fertigation frequency and leaf defoliation at final harvest

Treatment	No of flowers plant^{-1} (59DAT)	Total fresh yield (kg)	Fruits (g plant^{-1})	Fruits number plant^{-1}	Fruits with BER plant^{-1}	Fruit quality	
						Fruit width (mm)	Fruit length (mm)
T1 (control)	3.1	2.18	725.1	7.4	1.9	64.2	55.5
T2	3.3	1.92	639.0	7.3	1.7	58.3	50.2
T3	3.2	2.39	795.9	7.9	1.3	62.1	54.4
T4	3.3	2.04	679.3	7.7	1.5	60.8	51.8

Means in each column. Results were not significantly different between treatments

Table 6.43 Effects of varying fertigation frequency and leaf defoliation on biomass production, partitioning and harvest index (HI) of bell pepper

Treatment	Dry weight (g plant^{-1})											HI
	S1			S2				S3				
	Leaves	Stem	TDM	Leaves	Stem	Young fruits	TDM	Leaves	Stem	Fruit	TDM	
T1 (control)	7.1a	4.3	11.4a	15.6a	10.0	13.7	39.3a	24.7b	14.9	52.5	92.1a	57.0
T2	4.5b	3.3	7.8b	12.1b	8.7	12.1	32.9b	21.0b	13.9	42.5	77.4b	54.9
T3	7.4a	4.0	11.4a	15.3a	9.6	13.4	38.3a	27.5a	15.1	57.5	100.1a	57.4
T4	5.2b	3.1	8.3b	10.0b	7.4	11.9	29.3b	21.3b	14.5	47.2	83.0b	56.9

Means in each column, followed by different letters are significantly different at $p \leq 0.05$ by Tukey's test.

Table 6.44 Effects of varying N and K rates on NPK uptake of nutrients in bell pepper at Stage 1 (1 to 43-DAT)

Treatment	Nitrogen			Phosphorus			Potassium		
	mg plant^{-1}								
	Leaf	Stem	Total	Leaf	Stem	Total	Leaf	Stem	Total
T1	480.0	232.2	712.2a	13.5	6.0	19.5a	362.1	265.7	627.8a
T2	331.2	172.3	503.5b	9.0	5.0	14.0b	226.8	200.0	426.8b
T3	492.1	207.6	699.7a	15.5	6.4	21.9a	401.8	254.4	656.2a
T4	378.6	164.6	543.2b	10.4	4.7	15.1b	281.3	200.3	481.6b

Values of the mean of 3 plants treatment^{-1}. Results were not significantly different between treatments

Table 6.45 Effects of varying N and K rates on NPK uptake of nutrients in bell pepper at Stage 2 (44 to 64-DAT)

Treatment	Nitrogen			Phosphorus			Potassium		
	mg plant^{-1}								
	Leaf	Stem	Total	Leaf	Stem	Total	Leaf	Stem	Total
T1	951.6	462.0	1413.6a	20.3	12.0	32.3a	812.8	620.0	1432.8a
T2	788.9	429.8	1218.7b	16.9	11.3	28.2b	629.2	549.8	1179.0b
T3	996.0	489.6	1485.6a	23.0	14.4	37.4a	862.9	619.2	1482.1a
T4	685.0	358.2	1043.2b	16.0	10.4	26.4b	543.0	482.5	1025.5b

Values of the mean of 3 plants treatment^{-1}. Results were not significantly different between treatments

Table 6.46 Effects of varying N and K rates on NPK uptake of nutrients in bell pepper at Stage 3 (65 to 84-DAT)

Treatment	Nitrogen				Phosphorus				Potassium			
	mg plant^{-1}											
	Leaf	Stem	Fruit	Total	Leaf	Stem	Fruit	Total	Leaf	Stem	Fruit	Total
T1	1486.9	643.8	3139.5a	5270.2	29.6	16.0	68.3	113.9a	1254.8a	872.9	2698.5	4826.2a
T2	1266.3	647.7	2133.5b	4047.5	27.3	15.3	55.3	97.9b	1056.3b	821.5	2227.0	4104.8b
T3	1619.8	650.8	3358.0a	5628.6	44.0	19.6	86.3	149.9a	1471.3a	933.2	3156.8	5561.3a
T4	1273.7	618.4	2479.7b	4371.8	32.0	17.8	69.1	118.9b	1143.8b	917.8	2389.0	4450.6b

Values of the mean of 3 plants treatment^{-1}. Results were not significantly different between treatments

Table 6.47 Leaf chlorophyll content (SPAD values) of top and bottom leaves

Treatment	S1		S2		S3		S1		S2		S3	
	Top leaves						Bottom leaves					
	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM
T1	58.45	1.00	61.25	1.15	60.49	1.48	69.94	2.60	72.33	2.51	71.87	4.02
T2	60.05	0.82	62.34	1.23	61.89	1.14	73.79	3.49	73.38	2.25	72.70	3.35
T3	59.80	0.55	60.45	0.92	60.22	1.27	74.34	2.33	74.73	2.30	73.63	3.04
T4	60.10	0.52	61.32	1.23	60.54	1.16	79.94	2.89	75.01	2.24	74.62	3.48

Means in each column. SEM is the standard error of means

Appendix 4

(Effects of fertiliser formulations on bell pepper (*Capsicum annuum* L.) plants grown in a soil-less greenhouse fertigation (ALsodany, 2011))

Table 7.4 Growth parameters of bell peppers affected by different treatment at the two different stages

Treatment	Plant height (cm)		Stem diameter (mm)		Leaf area (cm^2)		No of leaves per plant	
	S1	S2	S1	S2	S1	S2	S1	S2
T1 (control)	60.00a	79.33b	15.28a	16.257b	2906a	1954b	114.3a	111.7b
T2	57.00a	85.67a	15.74a	19.157a	2465a	3280a	100.56a	181.33a
T3	57.17a	78.33b	15.84a	17.217b	2047a	1938b	99.5a	100.67b
T4	57.16a	86.00a	16.71a	19.573a	2013a	3861a	143.38a	115.3a
T5	59.67a	77.00b	16.02a	17.323b	2105a	3288b	151.32a	107.0b
T6	43.66b	46.00c	14.43b	15.237c	1246b	1160c	52.75b	73.7c
T7	51.34b	78.67b	14.30b	16.657b	1087b	3717b	46.59b	121.7b
T8	52.067b	55.67c	14.51b	15.883c	1343b	1206c	56.84b	89.0c

Means in each column, followed by different letters are significantly different at $p \leq 0.05$ by Tukey's test.

Table 7.5 Leaf chlorophyll content (SPAD values) of bell pepper plants as affected by different treatment

Treatment	SPAD values			
	Lower marked leaves		Top leaves	
	S1	S2	S1	S2
T1 (control)	58.20a	48.23a	68.73a	70.30 a
T2	55.90a	57.17a	74.03a	77.53a
T3	55.97a	50.93a	71.50a	66.17a
T4	57.60a	44.40b	70.73a	68.53a
T5	59.50a	57.87b	65.97a	49.80b
T6	40.50b	36.07b	57.57b	52.00b
T7	41.67 b	59.27a	54.57b	75.10a
T8	40.43b	60.93a	58.77b	81.20a

Means in each column, followed by different letters are significantly different at $p \leq 0.05$ by Tukey's test.

Table 7.6 Yield parameters of bell peppers affected by different treatments

Treatment	No flowers plant/plant	Fruits (g/plant)	Fruits number / plant
T1 (control)	14.2	817.5	11.3a
T2	13.9	831.6	10.7a
T3	11.4	913.1	11.3a
T4	10.1	527.0	13.3a
T5	11.6	861.2	12.0a
T6	11.3	604.4	4.7b
T7	10.7a	899.1	8.7b
T8	11.9a	790.0	6.0b

Means in each column, followed by different letters are significantly different at $p \leq 0.05$ by Tukey's test.

Table 7.7 Dry matter distribution of bell pepper plants as affected by different treatments in stage 1 and S2

Treatment	g plant^{-1}			
	Leaves	Stem	Fruit	TDM
T1 (control)	23.64a	16.88a	4.57	46.41a
T2	21.41a	14.55a	3.78	41.17a
T3	18.20a	14.59a	2.37	36.14a
T4	25.22a	12.33a	1.56	40.13a
T5	26.12a	14.97a	2.64	44.80a
T6	11.66b	14.31a	1.58	28.56b
T7	9.81b	11.67ab	2.24	24.72b
T8	11.89b	12.34b	3.40	28.71b

Means in each column, followed by different letters are significantly different at $p \leq 0.05$ by Tukey's test.

Table 7.8 Dry matter distribution of bell pepper plants as affected by different treatments in stage 2

Treatment	g plant^{-1}			HI
	Leaves	Stem	Fruit	
T1 (control)	18.48 b	25.72b	35.42b	44.49
T2	33.02a	33.51a	40.23a	37.68
T3	17.46b	24.76b	35.25b	45.50
T4	33.32 a	34.52a	41.37a	37.88
T5	20.99b	27.19b	35.22b	42.23
T6	8.87c	12.26c	28.05c	43.03
T7	28.28b	23.71b	34.96b	40.21
T8	15.21c	16.19c	28.43c	47.52

Means in each column, followed by different letters are significantly different at $p \leq 0.05$ by Tukey's test.

Table 7.9 Nutrient uptake in leaf, stem and fruit of bell pepper as affected by treatments in stage 1

Treatment	Nitrogen				Phosphorus				Potassium			
	mg plant^{-1}											
	Leaf	Stem	Fruit	Total	Leaf	Stem	Fruit	Total	Leaf	Stem	Fruit	Total
T1 (control)	264.7	87.4	321.6	673.7a	14.5	8.1	23.1	45.7	328.6	230.7	559.3	1118.6a
T2	236.1	85.7	318.2	640.0a	14.8	8.0	22.8	45.6	325.3	225.7	551.0	1102.0a
T3	251.7	90.2	319.1	661.0a	14.2	8.6	22.3	45.1	320.7	231.5	552.2	1104.4a
T4	221.9	88.6	323.7	634.2a	13.9	8.2	23.4	45.5	330.3	225.4	555.7	1111.4a
T5	248.2	91.5	314.5	654.2a	14.5	8.1	22.1	44.7	326.4	220.6	547.0	1094.0a
T6	186.5	48.6	225.2	459.4b	13.5	8.0	22.5	44.0	221.6	181.5	403.1	806.2b
T7	174.3	50.2	254.4	478.9b	13.9	8.4	20.8	43.1	218.6	175.6	394.2	788.4b
T8	169.6	47.5	232.9	450.0b	14.8	8.2	21.9	44.9	234.5	181.2	415.7	831.4b

Means in each column, followed by different letters are significantly different at p≤0.05 by Tukey's test.

Table 7.10 Nutrient uptake in leaf, stem and fruit of bell pepper as affected by treatments in stage 2

Treatment	Nitrogen				Phosphorus				Potassium			
	mg plant^{-1}											
	Leaf	Stem	Fruit	Total	Leaf	Stem	Fruit	Total	Leaf	Stem	Fruit	Total
T1 (control)	541.86	110.83	857.54	1510.2b	31.42	15.63	134.26	181.31b	532.62	358.54	1231.83	2122.99b
T2	718.94	144.43	973.97	1837.3a	56.13	20.44	152.47	229.04a	702.43	467.13	1399.20	2568.76a
T3	473.31	106.72	853.40	1433.4b	29.68	15.10	133.60	178.38b	464.58	345.15	1226.00	2035.73b
T4	689.10	148.78	1001.57	1839.4a	56.64	21.06	156.79	234.49a	722.44	481.21	1438.85	2642.50a
T5	570.53	117.19	852.68	1540.4b	35.68	16.59	133.48	185.75b	500.03	379.03	1224.95	2104.01b
T6	296.06	52.84	679.09	1027.9c	15.08	7.48	106.31	128.87c	159.63	170.90	975.58	1306.11c
T7	591.42	102.19	846.38	1539.9b	48.08	14.46	132.50	195.04b	586.28	330.52	1215.91	2132.71b
T8	502.11	69.78	688.29	1260.1c	25.86	9.88	107.75	143.49c	314.51	225.69	988.80	1529.00c

Means in each column, followed by different letters are significantly different at p≤0.05 by Tukey's test.

Appendix 5

Technical analysis of Scotts Peters professional fertilisers (% by weight)

Fertilisers	N				P	K	Mg	S	Fe	Mn	Zn	Cu	B	Mo
	Total	NO_3	NH_4	Urea	(P_2O_5)	(K_2O)			DTPA	EDTA	EDTA	EDTA		
	% by weight													
20-20-20	20	4.5	2.4	13.1	20	20	0.7	1.5	0.12	0.06	0.015	0.015	0.02	0.01
20-10-20	20	12.0	8.0	-	10	20	1.0	1.7	0.12	0.06	0.015	0.015	0.02	0.01
21-7-21	21	6.3	1.4	18.3	7	21	3.1	6.2	0.12	0.06	0.015	0.015	0.02	0.01
20-5-30	20	9.0	1.0	10.0	5	30	0.7	1.5	0.12	0.06	0.015	0.015	0.02	0.01
10-30-20	10	5.2	4.8	-	30	20	2.0	4.2	0.12	0.06	0.015	0.015	0.02	0.01

Appendix 6 (Fertiliser calculation)

NPK 20-20-20

i) Elemental amount P_2O_5 in NPK 20-20-20 is 20%
ii) Conversion rule: %K equals to 2.3

Therefore the percentage of P in NPK 20-20-20

$$= \frac{\%\ P2O5}{2.3}$$

$$= \frac{20}{2.3}$$

= **8.7%** of P in NPK 20-20-20

i) Desired concentration in ppm = 55 ppm
ii) Injector ratio = 1:100; dilution factor 100
iii) Fertilizer analysis = 20-20-20 whereby P is 8.7%
iv) Conversion constant (C) = 10

$$\frac{Desired\ concentration\ (ppm) \times Dilution\ factor}{Nutrient\ content\ (\%) \times Conversion\ constant}$$

$$\frac{55\ ppm\ \times 100}{8.7\ \times 10}$$

$$\frac{5{,}500}{87}$$

= 63.2 g per litre

= 63.2g x 20 litres

= **1264g** of NPK 20-20-20 in 20 litres stock tank

What is the amount ppm of N and K in 63.2g per litre of NPK 20-20-20?
Nitrogen (N)

$$\frac{Desired\ concentration\ (ppm) \times Dilution\ factor}{Nutrient\ content\ (\%) \times Conversion\ constant} = \text{g of fertilizer litre}^{-1}$$

$$\frac{x\ ppm \times 100}{20 \times 10} = 63.2\text{g of } 20\text{-}20\text{-}20$$

$$\frac{100x}{200} = 63.2$$

$$x = \frac{63.2\ \times 200}{100}$$

$$x\ = 126\ ppm\ of\ N\ in\ 63.2g\ of\ 20-20-20$$

Potassium (K)

i) Fertilizer analysis 20-20-20, whereby 20% is K_2O
ii) Conversion rule: %K equals to 1.2

Therefore the percentage of K in NPK 20-20-20

$$= \frac{\% K2O}{1.2}$$

$$= \frac{20}{1.2}$$

= 16.7**%** of P in NPK 20-20-20

$$\frac{Desired\ concentration\ (ppm) \times Dilution\ factor}{Nutrient\ content\ (\%) \times Conversion\ constant} = \text{g of fertilizer litre}^{-1}$$

$$\frac{x\ ppm \times 100}{16.7 \times 10} = 63.2\text{g of 20-20-20}$$

$$\frac{100x}{167} = 63.2$$

$$x = \frac{63.2 \times 167}{100}$$

$$x = 106\ ppm\ of\ K\ in\ 63.2g\ of\ 20-20-20$$

Therefore 63.2g litre^{-1} of NPK 20-20-20 would contain:-

Nutrients	mg l^{-1}
Nitrogen	126
Phosphorus	55
Potassium	106

NPK 20-10-20

i) Elemental amount of P_2O_5 in NPK 20-10-20 is 10%
ii) Conversion rule: %K equals to 2.3

Therefore the percentage of P in NPK 20-10-20

$$= \frac{\%\ P2O5}{2.3}$$

$$= \frac{10}{2.3}$$

= **4.3%** of P in NPK 20-10-20

i) Desired P concentration in ppm = 55 ppm
ii) Injector ratio = 1:100; dilution factor 100
iii) Fertilizer analysis = 20-10-20 whereby P is 4.3%
iv) Conversion constant (C) = 10

$$\frac{Desired\ concentration\ (ppm) \times Dilution\ factor}{Nutrient\ content\ (\%) \times Conversion\ constant}$$

$$\frac{55\ ppm\ \times 100}{4.3\ \times 10}$$

$$\frac{5{,}500}{43}$$

= 127.9g per litre

= 127.9g x 20 litres

= **2,558g** of NPK 20-10-20 in 20 litres stock tank

What is the amount ppm of N and K in 127.9g per litre of NPK 20-10-20?

Nitrogen (N)

$$\frac{Desired\ concentration\ (ppm) \times Dilution\ factor}{Nutrient\ content\ (\%) \times Conversion\ constant} = \text{g of fertilizer litre}^{-1}$$

$$\frac{x\ ppm \times 100}{20 \times 10} = 127.9\text{g of } 20\text{-}10\text{-}20$$

$$\frac{100x}{200} = 127.9$$

$$x = \frac{127.9\ \times 200}{100}$$

$$x\ = 256\ ppm\ of\ N\ in\ 127.9g\ of\ 20-10-20$$

Potassium (K)

Elemental amount of K in K_2O

i) Fertilizer analysis 20-10-20, whereby 20% is K_2O

ii) Conversion rule: %K equals to 1.2

Therefore the percentage of K in NPK 20-10-20

$$= \frac{\% K2O}{1.2}$$

$$= \frac{20}{1.2}$$

= 16.7**%** of P in NPK 20-10-20

$$\frac{Desired\ concentration\ (ppm) \times Dilution\ factor}{Nutrient\ content\ (\%) \times Conversion\ constant} = \text{g of fertilizer litre}^{-1}$$

$$\frac{x\ ppm \times 100}{16.7 \times 10} = 127.9\text{g of } 20\text{-}10\text{-}20$$

$$\frac{100x}{167} = 127.9$$

$$x = \frac{127.9 \times 167}{100}$$

$$x = 214\ ppm\ of\ K\ in\ 127.9g\ of\ 20-10-20$$

Therefore 127.9 g litre^{-1} of NPK 20-10-20 would contain:-

Nutrients	mg l^{-1}
Nitrogen	256
Phosphorus	55
Potassium	214

NPK 21-07-21

i) Elemental amount of P_2O_5 in NPK 21-7-21 is 7%
ii) Conversion rule: %K equals to 2.3

Therefore the percentage of P in NPK 21-7-21

$$= \frac{\%\ P2O5}{2.3}$$

$$= \frac{7}{2.3}$$

= 3.0**%** of P in NPK 21-7-21

i) Desired concentration in ppm = 55 ppm
ii) Injector ratio = 1:100; dilution factor 100
iii) Fertilizer analysis = 21-07-21 whereby P is 3%
iv) Conversion constant (C) = 10

$$\frac{Desired\ concentration\ (ppm) \times Dilution\ factor}{Nutrient\ content\ (\%) \times Conversion\ constant}$$

$$\frac{55\ ppm\ \times 100}{3\ \times 10}$$

$$\frac{5{,}500}{30}$$

=183.3 g per litre

= 3,667 g x 20 litres

= **3,667g** of NPK 21-07-21 in 20 litres stock tank

What is the amount ppm of N and K in 183.3g per litre of NPK 21-07-21?

Nitrogen (N)

$$\frac{Desired\ concentration\ (ppm) \times Dilution\ factor}{Nutrient\ content\ (\%) \times Conversion\ constant} = \text{g of fertilizer litre}^{-1}$$

$$\frac{x\ ppm \times 100}{21 \times 10} = 183.3\text{g of 21-07-21}$$

$$\frac{100x}{210} = 183.3$$

$$x = \frac{183.3\ \times 210}{100}$$

$$x\ = 385\ ppm\ of\ N\ in\ 183.3g\ of\ 21-07-21$$

Potassium (K)

Elemental amount of K in K_2O

i) Fertilizer analysis 21-7-21, whereby 21% is K_2O

ii) Conversion rule: %K equals to 1.2

Therefore the percentage of K in NPK 21-7-21

$$= \frac{\% K2O}{1.2}$$

$$= \frac{21}{1.2}$$

= 17.5**%** of P in NPK 21-7-21

$$\frac{Desired\ concentration\ (ppm) \times Dilution\ factor}{Nutrient\ content\ (\%) \times Conversion\ constant} = \text{g of fertilizer litre}^{-1}$$

$$\frac{x\ ppm \times 100}{17.5 \times 10} = 183.3\text{g of 21-7-21}$$

$$\frac{100x}{175} = 183.3$$

$$x = \frac{183.3 \times 175}{100}$$

$$x = 321\ ppm\ of\ K\ in\ 183.3g\ of\ 21-7-21$$

Therefore 183.3g litre^{-1} of 21-07-21 would contain:-

Nutrients	mg l^{-1}
Nitrogen	385
Phosphorus	55
Potassium	321

NPK 20-05-30

i) Elemental amount of P_2O_5 in NPK 20-5-30 is 5%
ii) Conversion rule: %K equals to 2.3

Therefore the percentage of P in NPK 20-5-30

$$=\frac{\%\ P2O5}{2.3}$$

$$=\frac{7}{2.3}$$

= 2.2**%** of P in NPK 20-5-30

iii) Desired concentration in ppm = 55 ppm
iv) Injector ratio = 1:100; dilution factor 100
v) Fertilizer analysis = 20-05-30 whereby P is 2.2%
vi) Conversion constant (C) = 10

$$\frac{Desired\ concentration\ (ppm) \times Dilution\ factor}{Nutrient\ content\ (\%) \times Conversion\ constant}$$

$$\frac{55\ ppm\ \times 100}{2.2\ \times 10}$$

$$\frac{5{,}500}{22}$$

= 250g per litre

= 250g x 20 litres

= 5,000g of NPK 20-05-30 in 20 litres stock tank

What is the amount ppm of N and K in 250g per litre of NPK 20-05-30?

Nitrogen (N)

$\frac{Desired\ concentration\ (ppm) \times Dilution\ factor}{Nutrient\ content\ (\%) \times Conversion\ constant}$ = g of fertilizer litre^{-1}

$\frac{x\ ppm \times 100}{20 \times 10}$ = 250g of 20-05-30

$$\frac{100x}{200} = 250$$

$$x = \frac{250\ \times 200}{100}$$

$$x\ = 500ppm\ of\ N\ in\ 183.3g\ of\ 20-05-30$$

Potassium (K)

Elemental amount of K in K_2O

i) Fertilizer analysis 20-5-30, whereby 30% is K_2O

ii) Conversion rule: %K equals to 1.2

Therefore the percentage of K in NPK 20-5-30

$$= \frac{\% K2O}{1.2}$$

$$= \frac{30}{1.2}$$

= 25**%** of P in NPK 20-5-30

$$\frac{Desired\ concentration\ (ppm) \times Dilution\ factor}{Nutrient\ content\ (\%) \times Conversion\ constant} = \text{g of fertilizer litre}^{-1}$$

$$\frac{x\ ppm \times 100}{25 \times 10} = 250\text{g of 20-5-30}$$

$$\frac{100x}{250} = 250$$

$$x = \frac{250 \times 250}{100}$$

$$x = 625\ ppm\ of\ K\ in\ 250g\ of\ 20-5-30$$

Therefore 183.3g litre^{-1} of 20-05-30 would contain:-

Nutrients	mg l^{-1}
Nitrogen	500
Phosphorus	55
Potassium	625

NPK 10- 30-20

i) Elemental amount of P_2O_5 in NPK 10-30-20 is 30%
ii) Conversion rule: %K equals to 2.3

Therefore the percentage of P in NPK 10-30-20

$$=\frac{\%\ P2O5}{2.3}$$

$$=\frac{30}{2.3}$$

= 13**%** of P in NPK 10-30-20

iii) Desired concentration in ppm = 55 ppm
iv) Injector ratio = 1:100; dilution factor 100
v) Fertilizer analysis = 10-30-20 whereby P is 13%
vi) Conversion constant (C) = 10

$$\frac{Desired\ concentration\ (ppm) \times Dilution\ factor}{Nutrient\ content\ (\%) \times Conversion\ constant}$$

$$\frac{55\ ppm\ \times 100}{13\ \times 10}$$

$$\frac{5{,}500}{130}$$

= 42.3g per litre

= 42.3g x 20 litres

= 846**g** of NPK 10-30-20 in 20 litres stock tank

What is the amount ppm of N and K in 42.3g per litre of NPK 10-30-20?

Nitrogen (N)

$\frac{Desired\ concentration\ (ppm) \times Dilution\ factor}{Nutrient\ content\ (\%) \times Conversion\ constant}$ = g of fertilizer litre^{-1}

$\frac{x\ ppm \times 100}{10 \times 10}$ = 42.3g of 10-30-20

$$\frac{100x}{100} = 42.3$$

$$x = \frac{42.3\ \times 100}{100}$$

$$x\ = 42ppm\ of\ N\ in\ 42.3g\ of\ 10-30-20$$

Potassium (K)

Elemental amount of K in K_2O

i) Fertilizer analysis 10-30-20, whereby 20% is K_2O

ii) Conversion rule: %K equals to 1.2

Therefore the percentage of K in NPK 10-30-20

$$= \frac{\% K2O}{1.2}$$

$$= \frac{20}{1.2}$$

= 16.7**%** of P in NPK 10-30-20

$$\frac{Desired\ concentration\ (ppm) \times Dilution\ factor}{Nutrient\ content\ (\%) \times Conversion\ constant} = \text{g of fertilizer litre}^{-1}$$

$$\frac{x\ ppm \times 100}{16.7 \times 10} = 42.3\text{g of } 10\text{-}30\text{-}20$$

$$\frac{100x}{167} = 42.3$$

$$x = \frac{167 \times 42.3}{100}$$

$$x = 71\ ppm\ of\ K\ in\ 42.3g\ of\ 10-30-20$$

Therefore 183.3g litre^{-1} of 10-30-20 would contain:-

Nutrients	mg l^{-1}
Nitrogen	42
Phosphorus	55
Potassium	71

Conclusion

Fertilizer	Amount (g)		Nutrients (mg l^{-1})		
	1 litre	20 litre	Nitrogen	Phosphorus	Potassium
20-20-20	63.2	1,264	126	55	106
20-10-20	127.9	2,558	256	55	214
21-07-21	183.3	3,666	385	55	321
20-05-30	250.0	5,000	500	55	625
10-30-20	42.3	846	42	55	71

Appendix 7

Sufficiency nutrient ranges for bell pepper (Hochmuth, 2003a)

Macro and secondary plant nutrients contents in pepper plant leaves

Nutrient	Deficient	Normal	High
	% of dry matter		
N	2-2.5	3-4	4-5
P	0.25	0.3-0.4	0.4-0.6
K	2	3.5-4.5	4.5-5.5
Ca	1	1.5-2	5-6
Mg	0.25	0.25-0.4	0.4-0.6
Na	-	0.1	-

Micro plant nutrients contents in pepper plant leaves:

Nutrient	Deficient	Normal	High
	mg l^{-1} of dry matter		
Fe	50-100	200-300	300-500
Mn	25	80-120	140-200
Zn	25-40	40-50	60-200
Cu	-	15-20	24-40
B	-	40-60	60-100
Mo	-	0.4	0.6

Appendix 8

(Determination of Total Phosphorus after Peroxodisulfate Oxidation)

REAGENTS

Potassium peroxodisulfate solution

Add 5 g ± 0.1 g of potassium peroxodisulfate ($K_2S_2O_8$) to 100 ml ± 5 ml of water, stir to dissolve.

NOTE: *The solution is stable for at least 2 weeks, if the supersaturated solution is stored at room temperature in an amber borosilicate bottle, protected from direct sunlight.*

APPARATUS

Borosilicate flasks, 100 ml, with glass stoppers, tightly fastened by metal clips (for the determination of total phosphorus using the peroxodisulfate method in an autoclave); polypropylene bottles or conical flasks (screw capped) are also suitable.

Before use, clean the bottles or flasks by adding about 50 ml water and 2 ml sulphuric acid. Place in an autoclave for 30 min at operating temperature of between 115 ^{o}C and 120 ^{o}C, cool, and rinse with water, repeat the procedure several times and store covered.

SAMPLING AND SAMPLES

Preparation of the test sample

Add 1 ml of sulphuric acid per 100 ml of the unfiltered test sample. The acidity should be about pH 1, if not, adjust with sodium hydroxide solution or sulphuric acid.

Store in cool dark place until analysis.

If total soluble phosphorus is to be determined, the sample is to be filtered.

PROCEDURE

Test portion

The oxidation causing peroxodisulphate will not be effective in the presence of large quantities of organic matter; in this case oxidation with nitric acid-sulphuric acid is necessary.

Pipette up to a maximum of 40 ml of the test sample into a 100 ml conical flask. If

necessary dilute with water 40 ml ± 2 ml. Add 4 ml of potassium peroxodisulphate solution and boil gently for approximately 30 min. Periodically, add sufficient water so that the volume remains between 25 ml and 35 ml. Cool, adjust to between pH3 to 10 with sodium hydroxide solution or sulphuric acid and transfer to a 50 ml volumetric flask; dilute with water to about 40 ml.

1) Pipette 40 ml of deionised water, orthophosphate working standard solutions, sample and blank solutions into 50 ml volumetric flask
2) Add 1 drop of phenolphthalein indicator solution
3) Add sodium hydroxide (NaOH) drop wise till turns pink.
4) Add sulphuric acid (H_2SO4) drop wise till pink just goes.
5) Add to each flask, while swirling, 2.0 ml acid molybdate solution.
6) Add to each flask, while swirling 1.0 ml ascorbic acid solution.
7) Dilute to 50 ml with deionised water and mix well.
8) Allow the solutions to stand for between 10 and 30 minutes to allow complete development of the blue colour.
9) Measure the absorbance of the solutions at 880 nm.

CALCULATION

Plot a graph of absorbance (y-axis) against the orthophosphate-phosphorus concentration (x-axis) in mg/L of the calibration solutions. Read off the orthophosphate-phosphorus concentrations, mg/L, of the sample solutions. If a volume of sample, other than 40 ml, was taken for colour development, a dilution correction is made as follows:

Concentration orthophosphate phosphorus, mg/L = $\frac{(C).40}{V}$

where:

C is the orthophosphate phosphorus concentration, mg/L, of the samples

V is the volume of sample, ml, used for colour development

Appendix 9

(Wet Digestion of Plant materials)

1. A mixture of nitric acid (HNO_3), sulphuric acid (H_2SO_4) and perchloric acid ($HClO_4$) in the ratio of 9:4:1 is used for sample digestion. It is known as tri-acid digestion.
2. 1 g of ground plant sample is taken for analysis.
3. It is placed in 100 ml conical flask, and 14 ml of acid mixture is added and the contents are mixed by swirling.
4. The flask is placed in the hot plate in the fume hood and heated; starting at 80 – 90 ^oC and then the temperature is raised to about 150 – 200 ^oC.
5. Heating continues until the production of red NO_2 fumes ceases.
6. The contents are further heated until the volume is reduced to 3 – 4 ml and become colourless, but it should not be dried.
7. After cooling the contents, the volume is made up with distilled water and filtered through No.1 filter paper.
8. This solution should be used for nutrient estimation.

NOTE:

a) Perchloric acid ($HClO_4$) is used primarily for increasing the efficiency of oxidation of the sample as $HClO_4$ disassociates into nascent chlorine and oxygen at high temperature, which increases the rate of oxidation or the digestion of the sample. At times, perchloric acid causes an explosion when it comes into direct contact with the plant sample. Therefore, pre-digestion of the sample with HNO_3 is considered desirable, followed by treatment with the tri-acid mixture.

b) Tri acid digestion is preferred for P and K estimations.

Appendix 10

(Nutritional disorders in bell pepper)

Visual symptoms exhibited by pepper plants under nutritional disorders

Nutrient	Deficiency symptoms	Excess / Toxicity symptoms
Nitrogen	Plant development gradually slows down. Gradual drying, beginning at leaf margins, of the area between the lower leaf veins. The petioles bend and hang downwards, parallel to the stem. The plant develops few flowers and fruit setting is poor. The fruit receptacle is thin, and the ovary is small. Sometimes there is no fruit development on the plant at all, and on those plants that bear fruits, the fruit is deformed.	Plants are usually dark green in colour, have abundant foliage, but usually with a restricted root system. Flowering and seed production can be retarded.
Phosphorus	The plants display limited growth. The leaves are hard and brittle to the touch. Flower formation is defective. Few flowers develop, and in those that do develop, only one in every four or five develops a fruit. The fruit is underdeveloped, with a thin receptacle, and very few seeds. The root system is undeveloped.	No typical primary symptoms. Copper and zinc deficiencies may occur due to excessive phosphorus.
Potassium	Yellow chlorosis spots appear between leaf veins, firstly in the lower leaves. The veins and the areas adjacent to these spots do not change their colour. Later, the chlorotic spots become lighter. (This can be seen mainly in the upper parts of the plant). There is little fruit setting, and not much fruit, which is smaller than usual.	Usually not excessively absorbed by plants. Excessive potassium may lead to magnesium, manganese, zinc or iron deficiencies.
Sulphur	Causes leaves to become yellowish.	Reduction in growth and leaf size. Leaf symptoms often absent or poorly defined. Sometimes interveinal yellowing or leaf burning.

Nutrient	Deficiency symptoms	Excess / Toxicity symptoms
Magnesium	Is Common on pepper plants. Yellowing of the leaves is apparent in the interveinal areas and veins remain green. The oldest leaves are affected first. Sometimes magnesium deficiency occurs when excessive applications of potassium have been made. It may also show up under extremely hot dry weather.	Very little information available.
Calcium	The most common reason for Blossom End Rot of the fruit.	No consistent visible symptoms. Usually associated with excessive soil carbonate.
Iron	Symptoms show at the later stages of growth. The young leaves fade and then become yellow in the areas between the veins. The veins remain green.	Rarely evident in natural conditions. Has been observed after foliar iron sprays manifested as necrotic spots.
Chloride	Wilted leaves, which then become chlorotic bronze, and necrotic. Roots become stunted and thickened near tips.	Burning or firing of leaf tips or margins. Bronzing, yellowing and leaf abscission and sometimes chlorosis. Reduced leaf size and lower growth rate.
Manganese	Chlorotic spots between the upper leaf veins.	Sometimes chlorosis, uneven chlorophyll distribution. Reduction in growth. Lesions and leaf shedding may develop later.
Boron	The deficiency manifests itself very quickly. The lower leaves curl upwards. Growth is stunted. The plant develops a thick, short stem. The apex withers and the leaves become yellow from bottom to top of the plant. There is a reduced production of flowers, and fruit setting is poor.	Yellowing of leaf tip followed by progressive necrosis of the leaf beginning at tip or margins and proceeding toward midrib.
Zinc	The leaves become narrow and small in chilli.	Excessive zinc commonly produces iron chlorosis in plants.

Nutrient	Deficiency symptoms	Excess / Toxicity symptoms
Copper	Appear late in the vegetative stage. The leaf margins curl and dry up. The leaves and the fruit become narrow and rectangular.	Reduced growth followed by symptoms of iron chlorosis, stunting, reduced branching, thickening and abnormal darkening of rootlets.
Molybdenum	The foliage turns yellow-green and growth is somewhat restricted. The deficiency occurs most commonly on acidic substrates.	Rarely observed. Sometimes leaves turn golden yellow.

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