Controlled release fertiliser as a management tool for productivity of tunnel-grown tomatoes

by

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Declaration

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Summary

To be able to grow crops such as tomatoes on a commercial scale under stringent controlled conditions in what is termed controlled environment agriculture (CEA), requires a great amount of expertise and technology. Therefore, the aim of this study was to see if the use of controlled release fertilizer as an alternative low expertise and low technology-based fertilization method could produce the same yields and marketability than the conventional fertigation fertilization methods used in greenhouse tomato production. The study assessed this by (1) determining if the ratio of perlite to coco coir in the growth medium had any effect on the yield response to an industry recommended controlled release fertilization recommendation, (2) trying to establish an appropriate mixing ratio of controlled release fertilizer (CRF) and liquid fertilizer (LF) to determine if a follow up fertilization application of the pre-plant applied CRF can obtain improved yields. From the results it was evident that by applying a mixture of 80% CRF (based on the fraction of the total % nitrogen applied) and 20% LF with additional monthly manual application of calcium sulphate or calcium nitrate to each planting bag, CRF could potentially replace a 100% LF fertilization programme in greenhouse tomato production. Some results here indicate that a spike in temperature at the beginning of the growing season may have contributed to the premature release of nutrients from the CRF prill, causing a spike in EC. This stunted the growth of the plants for the rest of the season, which could have been attributed to an initial toxic level of salts in the rootzone and a prolonged deficit of other essential nutrients. The growth media trial for the determination of the optimal perlite: coco coir ratio revealed that a mix consisting of 20% perlite to 80% coco coir, or 40% perlite and 60% coco coir were the best ratios that yielded the highest. Thus, for tomato production the effect of CRF would be greatly improved if applied in an environment where the temperature and growth media properties are favourable for the slow release of the nutrients. The evidence here did not support the utilisation of 100% CRF as a replacement of the currently employed LF for commercial greenhouse tomato production. In addition, it is imperative that additional calcium (Ca^{2+}), Sulphate (SO_4^{2-}) and Nitrate (NO^{3-}) be supplemented to reap the full benefits of CRF due to the ongoing technological research into the ability to coat calcium-based fertilizer products as a CRF.

This thesis is dedicated to my wife Leandri Potgieter and my family who stood by me to persevere, and everyone one who did not give up on their dreams and passions despite adversities.

The keenest sorrow is to recognize ourselves as the sole cause of all our adversities

- Sophocles

Biographical sketch

Studied BScAgric (Soil Science and Horticulture) at the university of Stellenbosch from 2011-2014

2015 – Took a gap year from studies and gained experience in the pre- and postharvest primary agricultural industry working in Ceres where I gained vast experience and deeper understanding in how the pre-harvest crop production factors affect the export quality and post-harvest handling of stone and pome fruit.

2016 – After my gap year, I decided to pursue my passion for controlled environment agriculture by enrolling into the MSc Agric (Agronomy) – Greenhouse crop production program at the university of Stellenbosch. Due to bursaries and funding not materialising, I was compelled to seek a full-time job to fund my studies. This brought in the next phase of my career working for a precision farming consultancy in South Africa as a soil scientist and horticulturist mainly focusing on soil mapping for orchard development and better agricultural practices recommendation. Unfortunately, this job took me all over South Africa working many longs hours and my studies were neglected due to the workload and being home only two weekends a month at the most. I classified more than 13,000 hectares of soil in a year all over Southern Africa for which I am grateful for the vast experience and exposure I got to the soil types of Southern Africa (Botswana and South Africa).

2017/2018 – Although my job with the precision agriculture consultancy was fulfilling, it was not a healthy lifestyle and I decided to pursue my dreams and focus on training courses for the company I co-founded in 2015 as well as doing private soil mapping and horticultural consultancy on a small-scale base to make ends meet at the end of the month. This was a bold leap of faith, but it was a highly satisfying period in my career. During this time Elsenburg Agricultural Institute gave me the opportunity to lecture and present the B. Agric Agricultural engineering courses for the 2nd and 3rd year students. I lectured for Elsenburg up until before the 2nd semester of 2019. Here I have learned how the practical approach and development of our future farmers were more important than just giving farmers technical advice as a consultant. Apart from Elsenburg I presented short courses in topic specific on-site training for farm workers such as irrigation. This was also the year my company was accredited with the AgriSETA for the offering of the NQF level 1-3 for plant production. I also became a registered professional natural scientist with SACNASP in 2018.

2019 – A new chapter in my life as it brought about my travels to Angola for help with the problem citrus orchards regarding drainage. Also, I became involved with a 600-ha pilot project to establish the macadamia and avocado industry in Angola serving as the soil scientist and precision agriculture consultant for the project. This taught me a lot about perseverance. Also, this was the year my company finally reached a big milestone by becoming accredited with the AgriSETA for offering of the National Diploma in Plant Production.

2020 – I accepted a job offer from Yara to become their crop scientist and sales agronomist for the northern region for Zambia focussing on Lusaka-North, Chisamba and Mkushi onwards to Lake Tanganyika. This was a wonderful time and I gained vast experience in how farmers think and go about farming in difficult climates. I also got a better understanding of the commercial and small-scale agricultural industries. I was privileged to get experience on a wide range of crops from irrigation wheat and barley and other row crops, sugar cane, coffee, tea, bananas to mention a few.

2021 – Although I loved Zambia and would have liked to make it my new home, the pandemic made visits to family impossible and when Yara offered me an agronomist position for Northern Limpopo and the Lowveld I was just to glad to come back to South Africa especially to my childhood region. Since my move back to South Africa I enjoy working with farmers on a scientific approach to nutrient management and to economical farm more sustainable and to support Yara sales representatives with the 4R principle in responsible fertilization.

Sometimes I wonder if I would have gained all this experience and adventures if I had received funding to become a full time MSc student… although I am deeply ashamed and distraught because of the long period it took to get my MSc Agric, I can never be ashamed of the wealth of life's experience I gained so far…

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Preface

This thesis is presented as a compilation of 7 Chapters

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CHAPTER 1

Introduction

The investment in fixed greenhouse production improvements, which include automated irrigation and fertigation systems, greenhouse structures and automated ventilation and air conditioning systems in agriculture in South Africa for the period July 2016 to June 2017, were between R 5 000 million and R 7 000 million, but for machinery and implements varied between R 9 000 million and R 11 000 million (Department of Agriculture, 2017). One of the main costs incurred in CEA production set-ups is that of the fertigation system. The fertigation system encompasses a network of pumps and different nutrient tanks, which are automatically mixed and delivered to the plants through the irrigation supply. It is prohibitively expensive because the set-up also includes specialised software, and hardware that mix the different nutrients in the correct ratios and delivers it through the irrigation system at the correct electronic conductivity (EC) level and the correct pH, whilst continuously being monitored and adjusted as required. Hence, the consequences of mismanagement of the fertigation program might lead to failed harvests culminating in subsequent financial losses. Such mismanaging of expensive automation systems could often be attributed to inexperienced and under qualified operators rather than the outright failure of the operating system itself. For this reason, even experienced farmers are hesitant to use fertigation systems to produce crops.

To illustrate the need for specialised skills when using fertigation systems, an example of a case study of a commercial farmer in the Zebediela region of South Africa is given. His fertigation system was used incorrectly and high concentrations of nutrients in the root zone scorched his grape cuttings. Due to the poor results and financial losses the fertigation system was disbanded, and fertilizers are applied by hand in the form of controlled release fertilizers.

Hence an alternative fertilization method for greenhouse crop production should be investigated where the expertise and technology of application is much less sophisticated than for the conventional LF fertilization method.

In recent years a trend has emerged where controlled released fertilizers are being used for young tree fertilization in soil-based agriculture as well as in nursery tree and seedlings fertilization in soilless greenhouse crop production units (Oliet et al., 2004). There are only a few reported studies on the use of CRF in CEA (Blythe et al., 2002, 2006; Kinoshita et al., 2016; Merhaut et al., 2006; Xiao, Fan, Ni, Li, Xu, et al., 2017; Xiao, Fan, Ni, Li, Zou, et al., 2017)

Controlled Release Fertilizer is getting attention in recent years as a potential fertilization method for crop production. Due to the possibility of making a one-off initial fertilizer application at the beginning of the plant's growing season and releasing different rates of fertilizer at the different phenological stages of the crop. CRF is a viable option for production units with limited labour or mechanical capacity. The CRF technology is developed to control the release of the nutrients gradually over the whole growing period of the crop and at different rates correlating to the physiological needs of the crop in each growth stage. The release rate is controlled and determined by the thickness of the polymer coating and temperature. In theory, in the colder months a thinner polymer coating can be used to release the required amount of nutrients and in the summer a thicker polymer coating can be used to reduce the release rate with the higher temperatures over the pre-calculated period of the growing season.

1.1 Scope of study

1.1.1 Fertigation vs. Controlled Release Fertilizer

This study focused on controlled release fertilizers (CRF) as an alternative for the highly complex fertigation system. This alternative will potentially benefit small scale farmers as well as emerging farmers or any farmer wanting a simple fertilization method where the high-tech possibilities a LF system can provide is limited for various reasons. For commercial farmers, the use of a fertigation system will most probably stay the viable option until an alternative could be found to produce equivalent or better yields.

A reason why CRF is studied as an alternative is due to the simplistic nature of the application and mode of action (Kinoshita et al., 2016). On the other hand, fertigation is required to apply nutrients almost every time you need to irrigate, which can lead to unnecessary salt build-up in the root zone requiring subsequent leaching to remove it (Combrinck, 2005). CRF is a potential viable alternative because it requires low maintenance as the bulk of the fertilizer is mixed into the growth medium at the beginning of the growing season, and you can theoretically only focus on the temperature and irrigation schedule for the crop. This method of fertilization is ideal for farmers who do not want to apply fertilizer continuously through the growing season but rather an initial one off application with a controlling mechanism which reduces leaching and increases nutritional use efficiency.

CEA is a well-established industry in the world and South Africa. There are still opportunities for more research regarding CEA practices and technology in South Africa such as the use of CRF as an alternative to the well-received and established LF fertilisation method.

1.1.2 Aims and objectives

The aim is to provide evidence that CRF can be an alternative fertilisation method other than fertigation for greenhouse tomato production on a commercial scale. If CRF is found to be a potential alternative fertilisation method, then the way in which upcoming farmers can produce commercial grade produce will be changed for the better meaning that their initial level of expertise on fertilization can be relatively lower because the initial expensive fertigation system and the skills required to operate it will not be necessary in the first few growing seasons.

The first objective being trial one will be to determine the yield and marketability percentage of the current industry standard CRF programme for greenhouse tomatoes in South Africa vs the yield and marketability of the current industry standard LF fertilisation method. A secondary objective will be to determine the correct ratio of coco coir to perlite to produce greenhouse tomatoes with CRF or LF (fertigation) fertilisation methods.

The second objective being trial two will be to use the most promising coco coir medium treatment from trial one as the standard growth medium for trial two. Different treatments of CRF will be studied where the nutrient composition is supplemented by adding additional calcium sources. The treatments will be a mix of the CRF and LF fertilizers based on the N% content contribution of each. The rationale of this is to determine the nutritional supplementation which must be made for a pure CRF program if the yields and marketability of the 100% CRF fertilization program is not up to standard in trial one. Hence the objective of the second trial will be to compare the yields and marketability of CRF, when used with a nutritional top up fertilization programme and if it can yield better results than pure 100% CRF fertilization from trial one.

CHAPTER 2

Literature Review

2.1 General Background

Recent studies considered the feasibility of controlled release fertilizers (CRF) as a possible alternative method for greenhouse tomato production (Kinoshita et al., 2016; Xiao, Fan, Ni, Li, Zou, et al., 2017). In one of these studies, the method of CRF application was by adding the CRF prills to a water recirculation tank in a closed soilless growing system (Kinoshita et. al., 2016). Nitrogen (N) savings of 37% was reported with CRF treatments compared to conventional fertigation and EC based treatments (LF). Moreover, CRF produced equivalent fruit yields than the LF (Kinoshita et. al., 2016). Controlled release fertilisers are a mix of nutrients coated with a resin polymer, with the rate of diffusion being directly proportional to the thickness of the coat (Azeem, KuShaari, et al., 2014; Carson, Ozores-Hampton, Morgan, & Sargent, 2014; Trenkel, 1997). In accordance with the principles of Le Chatelier (Fernandez-Prini, 1982), temperature is the foremost factor determining the rate of nutrient release by the CRF prills. Optimum nutrient release occurs at about 25 °C and any temperature above that will lead to excessive release of nutrients and could lead to a build-up of salts in the rootzone, which in turn leads to osmolarity imbalances and sub-optimal growing conditions (Carson, Ozores-Hampton, Morgan, & Sartain, 2014).

Fertigation is the means by which nutrients are supplemented to crops such as tomatoes in to the rhizosphere through the irrigation water (Hagin et al., 2002; Khaleel, 2018; Singh et al., 2018). The larger the scale of production the more important it is to apply the correct quantity of fertilizers to prevent concentration and nutrient imbalances in the feeding water. Usually an automated dosing and irrigation system that regulates the electrical conductivity (EC), pH and application rate and frequency automatically is proposed (Shamshiri et al., 2018). This set-up can be expensive and requires a skilled labourer with expertise in fertigation to manage and monitor the whole system (Shamshiri et al., 2018).

Emerging or inexperienced farmers might take some time to acquire the necessary expertise and almost certainly do not have the capital to purchase such an expensive automated system (Department of Agriculture, 2017; Kruss et al., 2015).

Therefore, it is necessary to investigate an alternative method of fertilization that can be offered particularly to new farmers and potentially even commercial farmers, which can bypass the advanced techniques and skills needed to operate and manage fertigation units.

Two of the most important factors to control during the cultivation for crops grown under controlled climatic conditions are the irrigation schedule (volume and frequency), relative humidity and temperature. Water is one of the main factors required for nutrient translocation in plants. Water is also an integral part in the cooling mechanism of the plant. Temperature is important due to its effect on the rate of chemical reactions (especially in CRF fertilization programmes and on the evapotranspiration process. Relative humidity determines the state of the water vapor deficit gradient and stomatal activity of the leaves and therefore determines in a big part the rate of nutrient translocation in the plant.

Controlled Release Fertilizer (CRF) may be an alternative method of fertilization in greenhouse vegetable production due to the simplistic method of application and environmental control management requirements during the growing season in relation to fertigation (Agro & Zheng, 2014; Azaizia et al., 2017; Kinoshita et al., 2014, 2016). CRF is also considered a sustainable fertilization method in soil-based greenhouse vegetable production due to its lower level of leaching and hence better nutrient use efficiency. CRF in soil based greenhouse tomato production could reduce irrigation water consumption (Yanmei Li et al., 2017) .

The purpose of this literature review is to acquire a better perspective of CRF in relation to the established concepts of fertilizers and fertilization methods such as fertigation. The literature review will also revisit the well-studied concepts of controlled environment agriculture or greenhouse crop production and the factors needed for successful tomato production.

The literature review will be used as reference for designing the necessary trials needed to compare CRF as a potential alternative method of fertilization to the conventional method of fertigation or liquid fertilization in greenhouse crop production.

2.2 Fertilizers and methods of fertilization

2.2.1 Origin of fertilization

Since time immemorial, humans noticed that supplementary addition to soils will allow the plants to yield better (van der Ploeg et al., 1999). Ancient Romans and Greeks as well as Mesopotamians noticed that when the banks of a river were flooded, the silt deposited increased the yield of the subsequent crop that were grown on the banks of the river (Jursa, 2020). Over the centuries there were numerous scientist who conducted trials on how plants acquired and take up nutrients and what the (best/appropriate) source of nutrients for plants are. It was discovered that plants do not get its nutrients only from soil itself as shown in the classical experiment by Van Helmont (1577 – 1644), but rather from nutrients dissolved in water (van der Ploeg et al., 1999). It was subsequently acknowledged that there must be more than one source of nutrients that plants may obtain. In 1804 Theodore de Saussure provided empirical/quantitative results to show that most nutrients do not come from the soil itself but from somewhere else. In this time the belief was rather that all nutrients came from humus (de Saussure, 1804). It was only in 1840 when Justus von Liebig started to shape the modern way of how to think about plant nutrients as a mixture of different compounds in his law of the minimum, where he stated that growth is only equal to that component which is least available (van der Ploeg et al., 1999). Only after trials done at Rothamsted outside London by Lawes and Gilbert, it was concluded that soil fertility can be maintained by artificial fertilizers. The search for better fertilizers, methods of fertilization and the nutrients and growth regulators needed by plants to grow optimally, is still relevant today as the need for increased food production for an ever-growing world population needs to be addressed continuously.

2.2.2 Soil based fertilization

Soil based fertilization is amongst the oldest techniques of fertilization and still the conventional method of fertilization due to the small percentage of agriculture using inert growth media. It is also the most complex because of the unique parameters in soil, which need to be considered when a fertilization program is designed for a specific crop on a specific soil type. The microbiological activity in the soil is one of the few underestimated factors involved in the effectiveness of artificially applied fertilizers because of the effect of microbial activity in soil on parameters such as nitrification, pH and reduction and oxidation of minerals (Baveye et al., 2018). Also, the natural chemical structure of the soil components must be considered such as the Cation Exchange Capacity (CEC), the Sodium Adsorption Rate (SAR), the exchangeable acidity, porosity of the soil, which leads to redox reactions when saturation of the soil profile occurs (Haliru & Japheth, 2019). The proximity of weeds that may use the nutrients before the crop can is also a factor influencing the nutrient use efficiency (Korav et al., 2018). It is also important to notice in grain crops such as maize that lime amelioration is required on acidic soil before each planting to adjust the pH to suitable levels (Yuan Li et al., 2019). The soil texture plays an important part in the rate of leaching of nutrients such as N after application and therefore more N must be applied to compensate for these leaching losses (Ding et al., 2020).

However, this leads to N pollution of water sources, which subsequently leads to unnatural high levels of algae growth and de-oxygenation of water sources as well as de-stabilisation of water ecosystems (Runo et al., 2020). For this reason, partly, controlled and slow release fertilizers were developed to slow down the leaching of N after application (Shaviv, 2005).

The main way to quantitatively determine how much nutrients are needed in soil-based fertilization is by way of soil sample analyses (Cantarella et al., 2006). A representative soil sample will be analysed for the different soil parameters and for the different levels of the nutrients already in the soil. The levels already in the soil will be interpreted against the norms and suggested nutrient level parameters for the certain crop in question.

The soil physical and soil chemical properties of the soil form will be accounted for, and the ameliorations and fertilization program will be adjusted accordingly. Due to cost factors, sampling is normally repeated every three years in South African agricultural practices. If any micro-nutrient deficiency symptoms occur during the growing season, fertilization can be amended with foliar sprays of foliar fertilizers after analysing leaf tissue nutritional levels.

2.2.3 Soilless fertilization

Soilless fertilization has less parameters, which influence the uptake of nutrients by the plant. The main parameters are EC, inert characteristics of the growth medium, temperature and transpiration, total alkalinity and pH (Cantarella et al., 2006; Combrinck, 2005). Microbial activity in soilless fertilization has little to no effect on the uptake of nutrients because nitrification for instance is not necessary for the plant to be able to take up NO_3^-N which is readily available for plant uptake (Alsanius & Wohanka, 2019). Soilless fertilization mainly takes place in the form of fertigation where the fertilizers are dissolved in the irrigation water although conventional side dress, incorporation and top dressing do occur (Alsanius & Wohanka, 2019). The reason for this is that there is little to no CEC in the inert growth medium and therefore it is required to add fertilizers with every pulse to ensure that optimal levels of nutrients are available for plant uptake. Fertigation is applicable to open field and CEA conditions and soilless fertilization forms the basis for hydroponics. Hydroponics is the practice in which plants are grown in a soilless growth medium where the plant is totally reliable on the amount of water and nutrients it gets through precision monitoring of the EC and the water holding capacity (WHC) of the growth medium (Combrinck, 2005). In CEA, the main fertilization technique is open field hydroponics, which includes the use of soilless growth media in conjunction with fertigation or by having the plants directly in contact with the nutrient source without growth medium.

The main way to quantitively determine how much nutrients are needed in soilless fertilization is by method of water sample analysis (Combrinck, 2005). Most of the growth media such as perlite is 100% inert and has no nutritional or charge implication in soilless fertilization. Other soilless media such as coco coir, saw dust and peat does have a charge and nutritional value, which can affect the soilless fertilization over time as the growth medium decomposes as reported by Baiyeri (2006). Water samples are the main cursor for what the nutrient status needs to be. The results obtained from the water sample are used to calculate the amount of nutrients to be added to the irrigation water. The method used to calculate the additions is based on one of two main methodologies which is mainly Steiner or Albrecht's method of calculating the nutritional need of crops grown in soilless growing systems (Asao, 2012; Combrinck, 2005; Hussain et al., 2014). The EC of the water will continuously be monitored throughout the growing season since EC plays a major role in the uptake of nutrients in soilless growing systems (Cliff et al., 2012; Combrinck, 2005; Schwarz et al., 2005)

Following will be a discussion on fertigation and CRF to illuminate our understanding of each fertilization technique to compare relative information of both fertilization techniques and to be able to identify if CRF can potentially be an alternative for fertilization in CEA given its lower input cost factor and limited skill needed to grow crops.

2.3 Controlled Release Fertilizers (CRF)

2.3.1 Definitions

According to the Association of American Plant Food Control Officials (AAPFCO) Controlled-Released Fertilizers (CRF) are any fertilizer that contains a plant nutrient in such a form that the availability thereof is delayed after application. The nutrients remain available longer than the rapidly available nutrient fertilizers such as ammonium nitrate or urea, ammonium phosphate or potassium chloride (Trenkel, 1997, 2010). There are different methods and technologies used to delay the release of the fertilizer. These include controlled water solubility of the material by semi-permeable coatings, occlusion, protein materials, or alternative chemical forms, by slow hydrolysis of water-soluble low molecular weight compounds, or by other unknown means. There are different opinions regarding the differentiation between CRF and slow-release fertilizers. Shaviv (2005) defined CRF as: “Fertilizers in which the factors dominating the rate, pattern and duration of release are well known and controllable during CRF preparation.” With slow-release fertilizers (SRF) the rate, pattern and duration of nutrient release may also be slower, but can’t be controlled as well as with CRF (Trenkel, 1997, 2010). Nitrogen products which are microbial and biologically decomposed are referred to as slow-release fertilizers. Products that are encapsulated or occluded are known as CRF in the trade. P. Lu et al. (2013) suggested a practical difference between CRF and SRF; SRF is fully dependent on environmental factors such as soil and climatic conditions that are difficult to predict to determine the pattern of nutrient release. For CRF the release pattern, quantity and time can be predicted with certain limits. The European Standardization Committees task force on slow-release fertilizers made a conclusion that: “A fertilizer may be described as slow-release if the nutrient or nutrients declared as slow-release meet, under defined conditions – including at a temperature of 25°C – each of the following three criteria; (a) no more than 15% released in 24 hours, (b) no more than 75% released in 28 days, and/or (c) at least about 75% released at the stated release time” (Shaviv, 2005; Trenkel, 1997, 2010).

Handreck et al. (2002) indicated that SRF and CRF fertilizers could be used interchangeably. The growing tendency is for SRF to refer to other managed-release fertilizers and CRF to refer to polymer-coated fertilizers. Therefore, the term polymer-coated fertilizers (PCF) and controlled-release fertilizers (CRF) will be used interchangeably in this literature review. “Prill” refers to an individually coated CRF granule (Trenkel, 2010).

2.3.2 Mode of action and mechanics of CRF

Since the 1960s (Shaviv et al., 2003), agricultural engineers tried to develop fertilizers, which can release nutrients to the plant in the quantity the plant metabolically needs during the different phenological stages, since it is well established that the nutrient demand of plants differ over the growth period (Trinh et al., 2015). According to Adams et al. (2013) up until 2013 there were no PCF that met the ideal of releasing nutrients according to the plant’s nutrient demand since the release rate is predominantly affected by temperature. By creating models to determine the release of nutrients from CRF researchers determined when and how much of the nutrients will be available for the plants during any given time during its growth cycle (Al-Zahrani, 1999; P. Lu et al., 2013; Trinh et al., 2015). By doing so, agricultural engineers can start to manufacture CRF with a controlled nutrient release rate as required by the specific crop during the different growth stages (Adams et al., 2013). It is difficult to determine exactly the release mechanism for secondary and micronutrients. The general term to use in how CRF control nutrient release, is because the nutrients are encapsulated by a physical barrier, which slows down the release of nutrients (Trenkel, 2010). The technology to coat calcium in a CRF is still in development and therefore the majority of CRF on the market lack coated Calcium and must be additionally added.

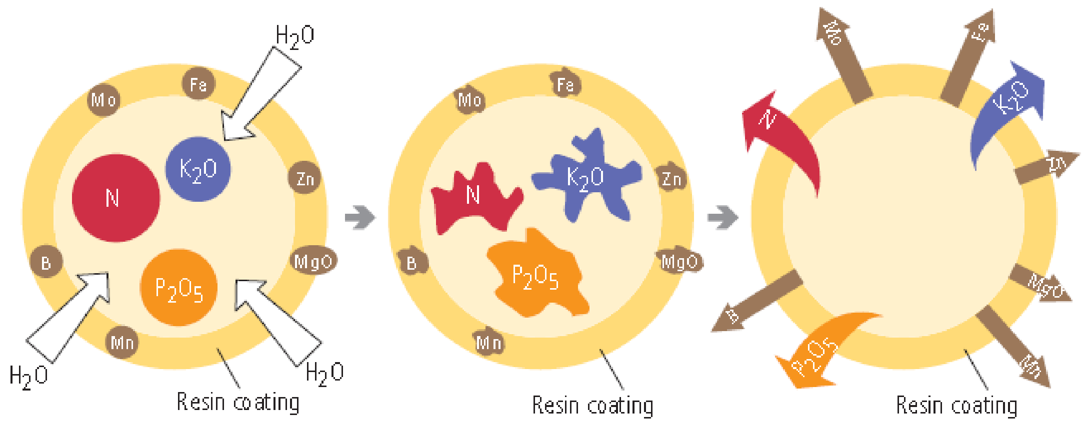

Figure 2.1 Mode of release from a coated controlled-release fertilizer (Adopted from **Hähndel, BASF, 1997 in Trenkel, 2010)**

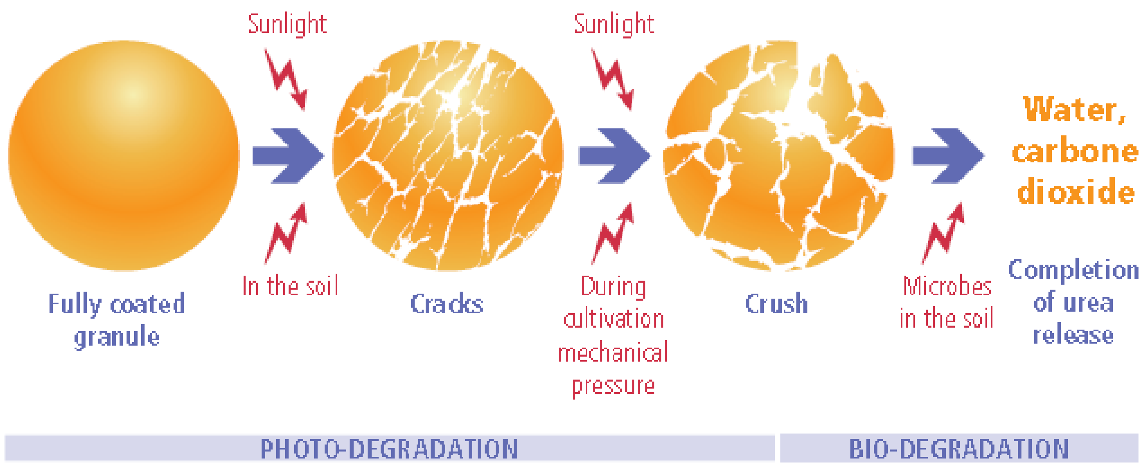

Figure 2.2 Decomposition of Slow-Release Fertilizer (Adapted from Chissoasahi,2007 in Trenkel 2010)

2.3.3 Models used to calculate nutrient release

Several authors accepted that the release of nutrient from an encapsulated granule is mostly due to diffusion such as discussed by Fick's law of diffusion (Shaviv et al., 2003). Shaviv et al. (2003), also refer in their work to three stages regarding the release of nutrients from a single polymer coated granule. The first stage: the initial (lag) stage where no nutrient release is observed. The duration of the lag phase is determined by the time it takes for the void in the prill to be saturated with water and the fertilizer salts to be hydrated, the result is the formation of hydrostatic pressure within the coating. The second stage: the main stage where the nutrient is released at a constant rate. The final stage is where the nutrient release starts to decrease. Shaviv's model assumes that at the time of the nutrient release the coating will be saturated with water. Trenkel,(2010) described Shaviv's model with a practical example using urea. He stated that if the concentration of dissolved urea in the core declines then the rate of urea exiting the core will also decline until no urea is released from the core anymore. Lu & Lee, (1992) applied Fick's Law of diffusion to determine the release of N from latex coated urea (LCU). Fick's Law states that the rate of transfer of a gas through a sheet of tissue or membrane is proportional to the tissue or membrane area and the difference in gas partial pressure between the two sides and inversely proportional to the tissue or membrane thickness. In this case tissue refers to membrane and gas refers to the nutrient solution, whilst pressure equates to the nutrient concentration inside the core. Several reports highlight the eloquence of the model (Lu & Lee, 1992; Shaviv, 2005). Azeem et al. (2014) concluded that the simplest approach to determine the nutrient release rate is with the use of regression modelling. He found that the problem with earlier model studies is that it ignored effects from the geometry and size of the granules, because the size and geometry of each individual granule differs and is not completely spherical. Therefore the other main problem is that the models couldn't account for the initial lag period where there is no release of nutrients from the core.

2.3.4 Factors affecting nutrient release

Adams et al. (2013) found that the effect of water content in the substrate was inconsistent across previous studies in the literature. The authors also found that the difference between nutrient-release rates in water and solid moist substrates is negligible. The conclusion is that the release rates in water can be used to model the nutrient concentrations in moist soil or soilless media, which is bio-available where the desorption or sorption properties can alter the concentration after release. Furthermore, it was demonstrated that the nutrients most affected by temperature is N, K, B, Cu and Zn and the nutrients least affected by temperature is P, Mg and Fe (Adams et al., 2013). Several authors affirmed that the bulk of the nutrients of many PCFs are released early and found that PCF is largely insensitive to the biological activity, pH and substrate type or texture (Adams et al., 2013; Broschat, 2005; Kochba et al., 1990).

These authors also noted that there is scant information on the release characteristics of other micro- and macronutrients other than N, P and K. However, Broschat & Moore (2007) found that the release of Mg, Fe and Mn is less than 50%. In addition, Trenkel (2010) found that the nutrient release through a polymer membrane is not significantly affected by normal soil-based parameters such as pH, salinity, texture, microbial activity, redox-potential or ionic strength of the soil solution. The nutrient release is affected by temperature and moisture permeability of the polymer coating. It was proposed that, to ensure the longevity of nutrient release, the degradation or physical damage to the polymer coating must be kept to a minimum during the nutrient release period (Trenkel, 2010).

2.3.5 Types of CRF granule coating

Controlled release fertilizers that are encapsulated by a physical barrier, slowly degenerate to release nutrients**.** The fertilizer can be encapsulated in two forms namely as granules or tablets (Trenkel, 2010)*.* Figure 2 shows the distinct barrier line between the coating and the nutrients. According to their physiochemical properties CRF are conveniently divided into organic and inorganic CRF. Inorganic CRF have a sub-category of polymer CRF's such as polyethylene (PE) and polyurethane (PU). Polymer coated CRF have the most superior controlled release of nutrients capability (Azeem, Kushaari, et al., 2014)**.** An example of a polyurethane coated fertilizer is Haifa Multicote®**.** Polymer coated fertilizers are further divided into either thermoplastic resins or thermosetting resins (Husby et al., 2019). According to the IUPAC Compendium of Chemical Terminology (2003) (Horie et al., 2004) the definition of thermosetting resin is as follows: "*Prepolymer in a soft solid or viscous state that changes irreversibly into an infusible, insoluble polymer network by curing. Note 1: Curing can be induced by the action of heat or suitable radiation, or both. Note 2: A cured thermosetting polymer is called a thermoset*." Fertilizer companies use the term "resin" and "polymer" interchangeably (Adams et al., 2013). Here, the emphasis is on thermoset PCF.

The rate of nutrient release from a polymercoated product, can – to a reliable extent – be controlled by varying the type and the thickness of the coating, as well as by changing the ratio of different coating materials (Trenkel 2010). It has previously been suggested that the polymer coating material represents approximately 10% to 15% in weight and 50 to 60 μm in thickness of an individual prill (Fujita and Shoji, 1999).

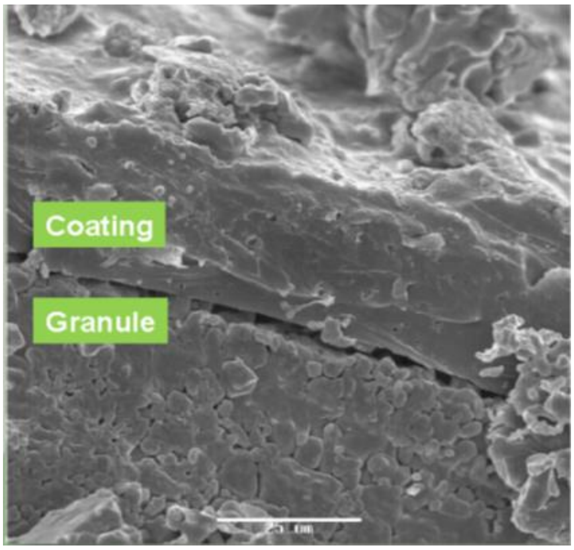

Figure 2.3 Multicote® coated granular fertilizer

2.3.6 Recent studies' results on the application of CRF in CEA.

A study was conducted to determine if the yield of a simplified soilless tomato culture system fertilized with CRF could be compared to the yield of conventional liquid fertilizer or fertigation systems (Kinoshita et al., 2016). It was demonstrated that the CRF system used 37% less nutrients, but with the same fruit yield equivalent as for the fertigation system. However, in this current study, rather than dissolving the CRF in the tank with irrigation water, the CRF was blended into the growth media before transplant.

2.4 Fertigation

2.4.1 Fertigation history and introduction

Fertigation constitutes growing plants where the nutrients are added to the irrigation water source. (Combrinck, 2005; Hagin et al., 2002). Hydroponics dates to the old Aztec civilization and the hanging gardens of Babylon (Reade, 2000). The Chinese also grew rice in hydroponic conditions for centuries. Using natural oxygen and nutrient rich water in ancient hydroponic practices enabled the growing of the plants.

The first man-made hydroponic nutrient solution was water extracted from soil in the 18th century (Jones Jr, 1982). Jean Baptiste Boussingault identified some of the elements essential for plant growth in the middle of the 19th century (Jones Jr, 1982). He was able to identify these elements by growing plants in inert growth media to which he added known amounts of chemical combinations in water solutions.

Von Sachs was the first to develop a standard formula for a nutrient solution to grow plants with success (Jones Jr, 1982). Nutrient solutions were mainly used for plant nutrition research (Jones Jr, 2016). During 1925 the CEA community started to explore hydroponics as an alternative to replace the conventional soil culture methods (Jones Jr, 2016).

After the successful adaption of fertigation and hydroponics in CEA, the technology started to expand to other countries where more research and technology and applications for hydroponics began to take 'root' (Asao, 2012). Development of plastic for containers and piping made the application of hydroponics much easier and more specialized (Combrinck, 2005).

The mixing of fertilizers with irrigation water was limited until the 1950's (Kour, 2018). With the invention of surge pumping systems, the ability to control the application of irrigation water increased and therefore the ability to control the application amount and distribution of fertilizers emerged as a new research field (Hagin et al., 2002).

As was the case in 1925 when the CEA community searched for alternative methods to fertilize crops other than what then the conventional soil culture method, fertigation and hydroponics progressively became the conventional methods of growing crops in CEA (and to some extend in open field agriculture), particularly given the situation revolving around an ever changing financial and food production climate.

2.4.2 Fertigation crop yield comparisons.

One of the main factors which contributed to fertigation in inert media was increased yields in comparison with soil-based fertilization (Asaduzzaman et al., 2015). The other factor is that of the efficiency of fertilizer and water use because the fertilizer is applied directly into the root zone as well as the right small quantity of water per pulse of irrigation, which lead to much less pollution of the environment or water wastage than with conventional soil-based irrigation and fertilization. The major advantage can be seen in a comparison review on the production of tomatoes in open fields and CEA. The fertigated tomatoes yield were higher with more dry matter and improved size, soluble sugars and firmness of the fruit compared to conventional irrigation and fertilization techniques (Kinoshita et al., 2016; Sepat et al., 2013). The increase in yield and amount of fruit can be ascribed to the readily availability of nutrients provided by fertigation.

An alternative to fertigation**,** needs to be able to obtain close to the same levels of fruits and yields to be able to be a viable option for upcoming farmers. It is proposed that CRF could provide such an alternative fertilization technique.

2.4.3 Fertilizers used in fertigation

Fertilizers used in fertigation is usually more complex and more factors need to be considered when mixing and choosing fertilizers for fertigation than for soil-based fertilization. The application of soil-based fertilizers is quite simple in comparison to the complex mixing and application of fertilizers in a fertigation system. The use of water soluble and liquid fertilizers is common due to the fertilizer being able to dissolve in the feeding water with little to no precipitation. Insoluble fertilizers are prone to precipitation, thus forming insoluble salts precipitates, which leads to clogging of the irrigation systems emitters. However, even when the fertilizer is soluble it is important to consider the reactions between all the compounds added to the fertigation tank. The concentrations of calcium (Ca) and magnesium (Mg) in the irrigation water will determine the precipitations of some chemicals such as some phosphate compounds (Cliff et al., 2012; Martinez-Mate et al., 2018). Moreover, the temperature must also be considered because it determines the solubility of fertilizers in water (Combrinck, 2005; Martinez-Mate et al., 2018). It is well known that the fertilizer solutions used for fertigation can be prepared on site, but skill and knowledge by emerging farmers to prepare fertigation solutions is often lacking. Thus, considering the technicality of the preparation and management of fertigation solutions, it remains an ideal to find a simpler alternative method of fertigation for upcoming and small-scale farmers.

2.4.4 Fertigation technology

The effectiveness of a fertigation system depends on the successful combination of irrigation techniques with the correct fertilization technique (Hagin et al., 2002). If the correct fertilizer program is followed but the irrigation technique is wrong, then the yield will be suboptimal. It is also true that when you have a well-managed and effective irrigation technique, and the fertilization technique is wrong, then the yield will also be sub-optimal. This is another basis for the study of CRF as alternative for fertigation because the CRF is dependent on a well-managed irrigation technique. So, by eliminating the fertilization management with CRF throughout the growing season, the only well managed factor remains irrigation, which is supposedly less complex than the management of the fertigation nutrient solution as discussed earlier (Trenkel, 1997).

One of the main irrigation techniques used in CEA fertigation systems is pressurized irrigation, which means some sort of pump is used to supply irrigation water under a controlled amount of pressure and is managed by the flow rate (Subramanaya, 2007). The application method is drip irrigation because in CEA the vegetables such as cucumbers, tomatoes and peppers are grown in containers which only need small amounts of water per irrigation cycle.

Open system fertigation is commonly used in South African commercial vegetable CEA. The main crops grown in these systems are tomatoes, green peppers, and cucumbers. For this the nutrient solution drains to waste after application (Combrinck, 2005). The method by which fertilizer is added to a pressurized irrigation system is by injecting the fertilizers with a differential pressure into the irrigation stream to overcome the internal pressure.

The main components of the fertigation system consist of; (a) fertilizer and irrigation (feeding) water tanks, (b) pump system, and (c) fertilizer injection site. The bigger the set-up the bigger the tanks and usually also more of them. The one tank approach means all the fertilizers are added into one tank (Combrinck, 2005). The multi-tank approach is the most common in commercial set-ups because the control over the chemical reactions can be conducted in a more precise manner. The fertilizers tank is the first important step to manage in the fertigation system as this is the source of the nutrients and feeding water (irrigation water). The first step is to ensure that the feeding water's quality is suitable to add fertilizers and is pathogen free. Then, the source of fertilizer is important as described above in terms of solubility (Othman et al., 2019). It is important to have a tank with pure irrigation water to be able to dilute fertigation solutions when the EC may be too high. Constant agitation of the tanks mechanically or with a returning fluid stream is important to prevent the precipitation of chemicals at the bottom of the tank, which will change the concentration and distribution of chemicals in the feeding water (Combrinck, 2005; Ingram, 2014). With regards to the pump system, the pump is the source that provides the build-up of pressure in the irrigation lines and therefore it is important to choose a pump capacity, which is not too big or too small for the set-up. Finally, with the pump system, the method by which the fertilizer gets injected into the feeding water stream is important as this determines the amount of fertilizer added and if it is uniformly distributed or not. The even distribution of fertilizer injection is dependent on the type of apparatus utilised and the amount of money spent on this technology (Hagin et al., 2002).

The automation of the irrigation schedule and the injection of the right concentration of chemicals is of utmost importance as the wrong irrigation schedule may lead to under irrigation and therefore the under fertilization of the crop, keep in mind that in inert growth media the source of nutrients is solely dependent on when the rhizosphere is moist, and the nutrients are in the irrigated water. If the irrigation is inadequate the roots cannot grow towards a more nutrient rich environment such as found in soil for instance. The WHC of inert growth media is also lower than for soil (Baiyeri, 2006). Therefore, it is important to have the adequate means of monitoring and controlling to prevent the dehydration of the rhizosphere. Furthermore, in soilless CEA the method to add the fertilizer is by means of proportional dosing (Hagin et al., 2002). The fertilizer is mainly added in the middle of an irrigation cycle and not the whole irrigation cycle to ensure the build-up of the pressure before adding the nutrients, and then making sure the nutrients are flushed out before the cycle ends. The method of controlling and monitoring the fertigation cycle becomes more complex with the increase in the production set-up and the need for more expensive automatic technology (Combrinck, 2005; Hagin et al., 2002).

2.4.5 Parameters to consider for a fertigation fertilization programme

Fertigation in soilless CEA differs from fertigation in soil-based agriculture since inert growth media have small to no effect on the chemical composition in the rhizosphere (Baiyeri, 2006). The method to determine the chemical composition of the rhizosphere and therefore the nutrient availability for the plant is through analysing the root zone water (Bryla & Strik, 2015; Chamindu Deepagoda et al., 2013; Toze, 2004). There are several parameters to be considered when calculating the fertilization programme for a fertigation system.

Electric Conductivity is the indication of the concentration of dissolved salts in solutions. The more salts in solution the higher the osmotic pressure in the rootzone, which causes the plant to expend more energy to overcome the osmotic pressure differential to take up water and nutrients. When the salt content of the feeding water is too high, the osmotic pressure after the fertilizer salts (ions) are added may be too big and the potential yield will be lower (Martinez-Mate et al., 2018; Toze, 2004). The build-up of salts in the rhizosphere will increase the EC value of the effluent (water coming out of the rhizosphere after irrigation), which must be monitored every day. When the effluent EC rises the ratio of irrigation water to nutrients must be adjusted to flush the excess salts out of the rhizosphere (Zhai et al., 2015). In addition, acidity and alkalinity is determined by the pH level of the feeding water. It is important to know the pH level of the solution as this will determine in which form the ions will be and whether it is plant available or not (Cliff et al., 2012).

The quality of the feeding water determines the amount of fertilizer which can be added, the less salts the feeding water contains before addition of fertilizers the easier it is to create the fertilization programme (Combrinck, 2005). Micronutrient concentrations on the other hand does not influence the EC of the feeding water because of the small concentrations present in the feeding water. The removal of unwanted ions from feeding water is imperative before fertilizers can be added (Bres, 2009; Toze, 2004). A complex method is needed to determine how much of each fertilizer compound needs to be added to the feeding water (Combrinck, 2005). In South Africa, the basis of the nutrient calculation used is that of Steiner (Combrinck, 2005). This reflects the complexity of using a fertigation system. If the technical support and skills necessary is not on-hand to manage a fertigation programme, the risk of failure and wasting a lot of high input cost capital is inevitable (Toze, 2004).

2.5 Controlled Environment Agriculture (CEA)

2.5.1 Production Techniques

Controlled environment agriculture is more than just the outer structure, inside the outer structure is where the controlled environment production system come into its own. The two main production methods are soil-based production and soilless production, soil-based production refers to the growing of crops directly into the soil underneath the structure. This is the same method which is mainly used in open field production. The main advantage of soil-based production is that the input cost is lower than for soilless production because no additional grow bags or growth media are necessary (Engindeniz & Gül, 2009). However, some of the disadvantages of soil-based production under cover may relate to the capital needed to construct an outer semi-permanent structure. Other disadvantages of soil-based production in a controlled environment is that of soil borne pathogens and nematodes (Yücel et al., 2007). It is also more complex to calculate the plant nutrient requirements because the soil factors such as Cation Exchange Capacity (CEC), exchangeable acidity and salinity of the soil must be considered before the nutrient fertilization recommendation can be provided (Rurinda et al., 2020)**.** The soil types also differ largely in soil physical and soil chemical characteristics which lead to variation in yields (Shani et al., 2007)**.**

Soil based production is mainly limited to soils that are suitable for crop production which means the soil is a less controllable factor in CEA. Controlling the soilless cultures properties in CEA allows for the utilisation of the full potential of the true meaning of the term CEA (Laio et al., 2006)**.** One of the soil-based controlled environment agriculture areas in South Africa is in Mooketsi, Limpopo. In this area the climate and soil are among the best in South Africa for crop production with mainly uniform soil characteristics and moderate to sub-tropical climate. In this area, the need for high technologically advanced systems to control climate and production is not necessary. The use of CEA in this area are mainly limited to the use of net houses to only keep pests out and to a lesser extend to control the environment. The conclusion is that low-end technology is enough for CEA in areas with a favourable climate and soil for crop production.

CEA comes to its full potential in areas where the natural soil and climate is unfavourable for crop production. Then, more specialised technology is needed to change the climate and growing conditions to make it more favourable for crop production. The use of soilless production in this case is the most studied and used method of crop production in CEA today (Combrinck, 2005; Hussain et al., 2014). The main advantages of soilless based agriculture are that the potential susceptibility for soil borne pathogens is very low, and that the water effluent and feeding water can be sterilized by using UV or other sterilization options. (Schnitzler, 2004). All the problems associated with various soil characteristics are solved using inert and homogenous growth media. Therefore, the same treatment will mainly have the same result, which creates more uniform management practices. Soilless production has also been successfully established in unfavourable growing environments such as the arctic and desert (Jensen, 2002). Growth media may vary greatly because it is not used as a source of nutrition, but rather as an anchorage for the plant and a buffer to prevent the roots from drying out (Sabatino, 2020). One of the main concerns about soilless production, is the inert characteristics of the growth media subsequently requiring careful consideration to what the plant must be supplemented with in order to provide the plant with the right amount and form of nutrition (Bugbee, 2004; Combrinck, 2005)

The main parameters that influence plant growth is usually more challenging to manipulate in the open field. Trees planted as windbreaks can be used to subdue the force of wind and decrease to some effect thigmomorphogenesis (Cleugh et al., 1998). Shallow soils can be ridged to increase root depth and aeration (Antwerpen et al., 1991; Myburgh & Moolman, 1991). Mulches can be used to decrease evaporation and conserve soil water content (Sharma & Bhardwaj, 2017). Row direction and planting density can help reduce sunburn on fruit crops (Piskolczi et al., 2004).

Planting fruit trees above the frost line in valleys can reduce freeze/frost damage, yet these parameters are difficult to control completely. Most of these adaptions was qualitatively measurable due to the unpredictability of the natural factors. The one aspect that typically sets CEA apart is the quantitative control of most of the aspects of the growing process (Challa & van Straten, 1991; Ingram, 2014). This means that every parameter which affects the growth of the plant, must be adjustable to provide the plant with the optimal level for any given parameter. This provides higher yields per hectare for CEA versus open field agricultural because each limitation is optimised (Sepat et al., 2013). In the following section each of the main plant growth parameters will be discussed in the term of how it is controlled in a CEA environment versus open field agricultural environment.

2.5.2 Variables to be controlled in CEA.

2.5.2.1 Soil

The heterogeneity was soil types results in different management practices needed to obtain uniform results over a production area. The ability to grow in inert substrates as growth media makes it possible to grow in areas where soils are infertile, rocky or sandy areas such as deserts or the arctic and follow the same management practice in a greenhouse (Putra & Yuliando, 2015).

2.5.2.2 Water quantity

Water quantity refers to both the amount and frequency of irrigation water that a particular crop is supplemented with. In open field agriculture, overhead, micro- or drip irrigation systems are used. More than the crops need is applied with these systems because water retention by the soil and losses by evaporation and runoff occur (J. L. Hatfield et al., 2001). For dry land production of grains, the crops are solely dependent on rainwater and morning dew. In CEA the irrigation water is stored in tanks and with a closed irrigation system the water is circulated and therefore much less water is used than in conventional irrigation systems (Putra & Yuliando, 2015). This method of irrigation allows production of crops even in areas with limited water supplies because water is used more efficiently.

2.5.2.3 Water quality

For rainfed and primitive open field agriculture the quality of the water is dependent on the quality of the water source in terms of the concentration of salts, pH, electric conductivity (EC) and pathogen levels. For artificial irrigation systems either in open field agriculture or CEA, the water can be treated and desalinised to control the abovementioned parameters for optimum growth (Runia, 1995). In closed system CEA, the control is that much better when the water is being recycled (Schnitzler, 2004; Van OS, 1999)**.** Thus, the quality of the feeding water is important, since supplementary nutrients could progressively increase the build-up of salts causing imbalances in osmosis for root uptake of nutrients and water as well as pathogens. The EC of the water needs careful consideration in CEA as opposed to other methods of plant production (Ahn & Son, 2019; Combrinck, 2005).

2.5.2.4 Aerial – and root zone temperatures – (Roots and Atmosphere):

Natural temperature extremes in the winter and summer is difficult to combat in open field production although there are some extreme measures such as making fires or using big wind turbines (Ribeiro et al., 2006) in the winter to reduce frost damage and using misters in the summer to cool down crop canopies (Shih, 2002). Temperature control for CEA is much easier. For instance, using a wet wall and extraction fan or using shade net or open vents during hot periods can reduce the temperature inside the CEA structure (Savage, 2014). Floor heating or heater fans or solar energy can be used during cold periods to increase the temperature inside the CEA structure (Esen & Yuksel, 2013). The control of temperature was one of the first successfully controlled growth parameters as discussed earlier. The reason why temperature is of such importance is because lower temperatures correlate with slower chemical reactions according to the principle of Le Chatelier (Jerry L. Hatfield & Prueger, 2015; Kirsta, 2006; Went, 1953). To this end, the lower the temperature, the slower the plant's physiological processes and plant growth will be suboptimal.

2.5.2.5 Light – (Photoperiod, Photosynthetic Active Radiation, Photon Flux):

Daylight decreases and increases with the seasons due to the tilted earth's orbit around the sun. The length of daylight has a big effect on daylight sensitive plants, due to the amount of daylight is correlated to a certain season. In the winter months the daylight time is shorter than in the summer, affecting daylight sensitive plants such as certain strawberries (SØnsteby & Heide, 2007). When growing under CEA conditions daylength can easily be manipulated by blackening out the structure when shorter day periods are needed for example in the cut flower industry to induce flowering (Blacquière et al., 2002; Mor & Halevy, 1980). By extending daylight by means of artificial lighting the plants photosynthesise longer during out of season periods (Palmer & van Iersel, 2020; Sipos et al., 2020). When the irradiation is too high in the summer, shade nets or lime can be used to cover the structure to reflect excessive irradiance and therefore reduce sunburn of some sensitive fruiting crops (Puglisi et al., 2021).

2.5.2.6 Relative Humidity (RH)

The lower the RH in field crops, the more evaporation and evapotranspiration will occur, which in turn could lead to significant levels of water loss (Hand, 1988). Under CEA conditions the RH can be manipulated due to the closed environment (Körner & Challa, 2003). The RH can be increased with misters and decreased by opening of the vents (Labidi et al., 2017).

2.5.2.7 Plant Nutrition

The natural source of nutrients in soils is mainly from the vegetation grown on the soil, which eventually decomposes and from the natural mother material in the soil genesis process (van der Ploeg et al., 1999). In soilless CEA the plant nutrition is mainly from inorganic and organic chemical compounds added to the substrate either by hand or by fertigation (Dasgan & Bozkoylu, 2007). The plant nutrition parameter is the main subject of this literature review and the different methods of providing the plant with nutrients will be discussed in depth as well as the role of nutrients in plant metabolism. Moreover, how nutrition integrates with various other parameters important to optimise plant growth and development will be discussed. This is particularly important since some of the abovementioned parameters might be more complicated to control than others because of complex interactions both at a metabolic and molecular level (McCully, 1999). Other important factors to consider include the cost of electricity and the maintenance there-off, the equipment as well as the costs for the technology to control these factors (Engindeniz & Gül, 2009). With time the technology has polarised around lower end technology, which is less expensive mainly because it is less automated and more labour intensive, and higher end technology that is much more automated and less laborious, yet more expensive. Therefore, compromises are normally made regarding the best technology for each parameter which is the least expensive with the most effective quantitative control of the growing parameters.

2.5.3 Low input-cost controlled environment agriculture.

Most of the higher end technologies are credited to developed countries such as the Netherlands and the United States of America (Ernesto Tavoletti et al., 2008; Suprem et al., 2013)**.** In countries such as South Africa the rural infrastructures are usually compromised, which affect functionality. The number of graduate professionals in CEA in South Africa is lower than for the developed countries (Wood, 1997). By implication, when capital is invested into higher end technologies in South Africa, the skills to fully operate that technology are often lacking. For example, nutrient film technique (NFT) hydroponic farming is dependent on the flow of water at a constant speed to ensure that roots do not dry out and when there is an electric outage the pumps cannot function and provide water to the systems which in turn leads to crop damages. When lightning hits a pump on the Highveld of Gauteng South Africa on Christmas eve the water will stop to run, and the roots will systematically become dry. The farmer notices it 2 hours later, he tries to contact a pump specialist to come and fix the pump, unfortunately there is only five pump specialists for hydroponics in Gauteng and all of them are at the coast for the holidays. Now he gets a normal pump specialist and many hours later the pump starts to run again. The point is that the skills to maintain CEA is few and far apart in South Africa. There is a farm in Zebediela, Limpopo which specialises in certain grape scions. When I visited the farm I noticed that the expensive fertigation room is now a glorified water storage system. I asked the farmer and he said that the fertigation program led to chemical scorching of the roots of the propagules, and they lost a lot of money. They also lost their faith in the technology although the same fertigation set-up has been proven to be the most effective for big scale commercial CEA in South Africa**.** What interested me was that they have converted back to manual irrigation and using controlled release fertilizer (CRF). They are content with their low end technology set up over their high end technology.

It is envisaged that technological advances in CEA will keep on increasing yields (Shamshiri et al., 2018). However, sometimes a low input, cost-effective technology may be more appropriate in developing countries such as South Africa to help the upcoming farmers who enter the market to eventually facilitate their transition to the higher end technologies more seamlessly.

2.6 The tomato (Solanum Lycopersicon L.)

2.6.1 Short History on Origin

The ancestral tomato found its origin in the Andean mountains of South America as well as its deserts and coastal plains (Menda et al., 2014). It is known that the wild species of tomatoes has adapted to their different habitats gradually over time (Nakazato et al., 2008). The tomato was introduced into Europe in the 16th century (Bergougnoux, 2014) and is the number one ranking vegetable in the world in terms of production as it accounts for 14% of all vegetables produced (Bauchet & Causse, 2012). It is widely acknowledged that the tomato is a model species for research and therefore it will be used as the study crop in the review of the use of CRF in the production of vegetables in CEA (Dayan et al., 1993)**.** It is therefore important to understand the general physiology and characteristics of the tomato for later interpretation of the results.

2.6.2 Cultivars

Breeding efforts of tomato species are driven by finding new suites of genes which give newer varieties resistance to biotic and abiotic stresses (Hoisington et al., 1999)). These resistance genes are mainly sourced from ancestral wild tomato species (Richards & Rose, 2019). There are five main groups of tomato cultivars in South Africa namely: determinate salad, determinate saladette, indeterminate salad and an indeterminate novel variety. Determinate means the tomato plant has a limit in the production of fruit after a certain period (Monamodi et al., 2013). In contrast, indeterminate tomato plants continue producing fruit indefinitely as long as the crops growth can be sustained (Maboko & Du Plooy, 2018). The cultivar used for this study is 'Heidi' form Sakata. 'Heidi' is an indeterminate F1 Hybrid. It has characteristically good fruit quality and uniform fruit size as well as good disease resistance. It also has a good shelf life because of its thick peel. 'Heidi' has a strong vigour and therefore is less susceptible to common leaf diseases under normal high pathogen risk environmental conditions. However, 'Heidi' is very sensitive to over application of Nitrogen (N) fertilizers (www.sakata.co.za).

2.6.3 Phenological Stages

It is important to understand the phenological stages of a crop, because each stage has certain nutrient requirements (San martín-hernández et al., 2021).The main phenological stages for tomato are; early growth or plant establishment (between 25-30 days), where root formation and optimal cell differentiation is important to establish the basis for the vegetative growth phase. The vegetative state (20-25 days)(Hobson & Grierson, 1993), is the stage where optimal photosynthesis needs to be reached to maintain the subsequent reproductive stage. Therefore, it is important to produce as much leaf area as possible for optimal photosynthate production. For the flowering stage (20-30 days), it is important to have optimal flower differentiation because the flowers lead to the formation of fruit. The vegetative growth rate needs to be reduced to improve flower formation and fruit formation (Kazemi, 2014). During fruit formation (20-30 days), all the main nutrients such as calcium needs to be readily available to ensure optimal fruit development. The last stage is fruit maturity (15-20 days), that requires measured irrigation to prevent bursting of the fruit (Peet, 2018).

The nutrient requirement for each stage varies greatly due to the different physiological and metabolic activities (Terabayashi et al., 1991). It is therefore important to supply the plant with the correct amount and ration of nutrients in each stage for optimal quality and yields. The fertilization technique determines the total management of nutrients available for the plant throughout all the stages. The mode of action of CRF will be discussed in detail to see how it is able to provide each phenological stage with the right quantity of fertilizers.

2.6.4 Fertilization Techniques

As for most other crops, tomatoes are commercially grown in non-indigenous areas. This means that the natural requirements for the crop to grow optimally is not always present in its new growing habitat and amelioration, including fertilization, must take place to provide the optimal growing conditions. Fertilization is the process in which additional plant nutrients are added to the soil or growth medium to provide the plant with more nutrients to be able to grow more optimal than it would in the conditions it was. The need for the right amount and ratio of nutrients in each phenological stage of the plant’s growth is more important than just adding plant nutrients to the soil or growth medium. Fertilization is one of the main components in agriculture in terms of revenue to highlight the importance in modern agriculture (Alley & Vanlauwe, 2009). In CEA, fertilization is one of the most important parameters to monitor because of the inert qualities of the main growing media, which means that all the nutrients a plant needs must be added to the growing medium (Olympios, 1999). To have a better appreciation for the role of fertilization in agriculture one must observe the history thereof.

2.7 Concluding remarks

An alternative low input cost fertilization technique is needed for emerging and new farmers to be able to produce good quality crops with a relatively good yield. This review highlights that controlled release fertilizers could be a viable and more simplistic method of fertilization in CEA given the skills involved to manage a commercial fertigation system as well as all the factors involved in managing a cropping unit in a controlled environment. In the case of rural development, the lack of skills and post market services and funding does not justify the expensive fertigation fertilization programmes but the need to produce quality crops still exist. Therefore, the use of CRF is a potential alternative as fertilization technique.

CHAPTER 3

3.1 Material and Methods – Trial 1

3.1.1 Plant Material

F1 Hybrid tomato seed, cultivar 'Heidi' received from Sakata were used for the trial. 'Heidi' is an indeterminate salad tomato, chosen due to its big and fleshy tomatoes which can be consumed in salads or eaten raw. 'Heidi' were also chosen due to its potential to have resistance to: Verticillium Wilt race, Fusarium Wilt races 1 and 2, Tomato Mosaic Virus (TMV), Tomato Spotted Wilt and root knot nematodes. Due to its strong vigour 'Heidi' is also less susceptible to common leaf diseases under circumstances normally conducive to disease development. The seed were germinated in seedling trays, filled with vermiculite at Welgevallen Experimental Farm of the University of Stellenbosch. At 20 to 30 cm shoot length the seedlings were transplanted into 10-litre black plastic growing bags.

3.1.2 Treatments

The trial was conducted during September 2016 – November 2016 in a greenhouse covered with Perspex (hard plastic). The planting rows were North-West to South-East orientated. The grow period coincided with the summer growing period for commercially grown tomatoes in the Western Cape, South Africa. The follow up trial 2 will use the same nutrient compositions from trial 1 but with the best performing growth medium as standard and then the different ratios of LF:CRF based on the Nitrogen % contribution (Table 3.1) as well as additional calcium sulphate or calcium nitrate sources were added irrespective of the ratio, due to the lack of calcium in the controlled release fertilizer composition.

Different combinations of perlite and coco coir (medium-to-coarse) were used in conjunction with either a standard fertigation (liquid fertilizer) fertilization programme (Table 3.4) or an industry standard CRF fertilization programme (Table 3.1; 3.2). The CRF used was Multicote MCA (8) Hydro from Haifa. The nutrients were not adjusted as the aim of the trial was to determine the yield potential as is for the industry standard programme for LF and the industry recommendation for CRF.

Table 3.1: The comparison tables below are for 90 grams of Controlled Release Fertilizer (CRF) for the CRF treatments per plant for the whole season. It must be noted that liquid fertilizer (LF) represents the equivalent of the grams per only 1 litre applied to each plant. This quantity is just to get a comparison of the amount of nutrients applied for Controlled Release Fertilizer (CRF) and Liquid Fertilizer (LF) respectively in each treatment.

Fertilization Method	Nutrients (g)											
	N	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Mo	Zn
CRF applied (90g)	0,012	0,004	0,014	0,001	0,001	0,004	0,021	0,030	0,271	0,039	0,007	0,042
LF (1L)	0,148	0,036	0,155	0,143	0,043	1,730	0,031	0,005	0,001	0,001	0,001	0,003

Table 3.2: Nutrient comparison between the Controlled Release Fertilizer (CRF) applied (90g per bag blended with the growth medium before transplant) and the Liquid Fertilizer (LF) (with fertigation cycles every week based on the g per Litre and for comparison derived to grams per kg)

Fertilization method	Nutrients (g/kg)											
	N	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Mo	Zn
CRF	0,133	0,045	0,153	0,006	0,009	0,048	0,235	0,335	3,015	0,436	0,076	0,469
CRF applied (90g)	0,012	0,004	0,014	0,001	0,001	0,004	0,021	0,030	0,271	0,039	0,007	0,042
LF	0,148	0,036	0,155	0,143	0,043	1,730	0,031	0,005	0,001	0,001	0,001	0,003

Table 3.3: Nutrient composition for the controlled release fertilizer: Prescription blend from Haifa, Multicote MCA (8) Hydro.

N	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Mo	Zn
133 g/kg	45 g/kg	153 g/kg	6 g/kg	9 g/kg	48 g/kg	235 mg/kg	335 mg/kg	3015 mg/kg	436 mg/kg	67 mg/kg	469 mg/kg

Table 3.4: Nutrient composition for tank A and tank B in the fertigation (liquid fertilizer) fertilization fraction: Welgevallen Standard Nutrient Solution (EC of Solution = ca. 2mS/cm)

Nutrient	Application g / 1000 ℓ	200 x concentration g / 900 ℓ
Tank A		
Macronutrients		
Potassium nitrate (KNO_3)	100.00	18000
Potassium chloride (KCl)	75.00	13500
Mono potassium phosphate (KH_2PO_4)	136.00	24480
Magnesium sulphate ($MgSO_4$)	440.00	79200
Micronutrients		
Manganese sulphate ($MnSO_4$)	2.23	401.40
Zink sulphate ($ZnSO_4$)	1.47	264.60
Solubor (Boron) Boric Acid, H_3BO_3. Borax Pentahydrate, $Na_2B_4O_7 \cdot 5H2O$. Sodium Pentaborate, $Na2B_{10}O_{16} \cdot 10H_2O$	1.51	271.80
Copper sulphate ($CuSO_4$)	0.20	36.00
Ammonium heptamolybdate $(NH_4)_6Mo_7O_{24}$	0.09	16.20
Tank B		
Macronutrients		
Calcium nitrate ($CaNO_3$)	850	153000.00
Potassium nitrate (KNO_3)	100	18000.00
Micronutrients		
Libfer (Fe-EDTA) 13%	6.54	1177.20

Table 3.5: Treatment description for Liquid Fertilizer (LF) and Controlled Release Fertilizer (CRF). The six treatment combinations were replicated three times and arranged in a split plot design. Five plots per treatment, three were used for measurements.

Treatment	**% Perlite**	**% Coco Coir**	**Fertilization Programme**
1	100	0	LF
2	100	0	CRF
3	20	80	LF
4	20	80	CRF
5	40	60	LF
6	40	60	CRF

The 90 g CRF was blended into the growth media before transplant. No additional plant nutrients were added throughout the growing season for the CRF treatments. The only additions were the irrigation water without any nutrient additives. The standard LF fertigation was supplemented with the irrigation water and managed to have a 30% over application of water to prevent salt build-up in the rhizosphere or growth media (Combrinck, 2005; Zhai et al., 2015). The amount and frequency of irrigation for both the LF and the CRF were managed by the farm technician. A standard pesticide programme was followed.

3.1.3 Pre-Harvest Measured Parameters

The pH of the effluent, ambient temperature (degrees Celsius) and relative humidity (%) and electrical conductivity (EC) ($mS.cm^{-1}$) of the effluent as well as the volume of applied irrigation water (millilitres) per cycle were all monitored daily over the course of the experiment. The EC were measured daily for one plant per repetition by measuring the leachate.

3.1.4 Fruit and Vegetative growth Measured

The plants were grown for three months during which three harvests were made to compare the fruit size and yield per treatment. Only three of the five plants per experimental unit were harvested for data collection. The vegetative growth was divided into the stem length and the leaf length, including all side growth. The side growth of the bottom 30-40 cm of each plant was pruned during the growing season and not included in the final measurements. The stem length, stem fresh mass and the leaf fresh mass were measured at harvest. The stem and leaves were dried for four to six days at a temperature of 60 ^{0}C. The dry mass of leaves and stems were subsequently recorded.

3.2 Material and Methods – Trial 2

3.2.1 Plant Material

F1 Hybrid tomato seed, cultivar ‘Heidi’ purchased from Sakata were used for these trials. ‘Heidi’ is an indeterminate salad tomato. Seeds were germinated in standard nursery seedling trays filled with vermiculite at Welgevallen, experimental farm of the University of Stellenbosch. The seedlings were transplanted 20-30 days after germination to 10-litre black plastic growing bags when they reached between 20 cm and 30 cm in shoot length.

3.2.2 Treatments

The trial was conducted during February 2017 and May 2017 in a greenhouse covered with industry standard cladding plastic at Welgevallen. The growth period coincided with the summer-winter growing period for commercial grown tomatoes in South Africa. This investigation focused on the vegetative growth and yield of a ratio of CRF and LF in addition with a calcium fertilizer supplement in the form of calcium-sulphate ($CaSO_4$) solely or in combination with calcium-nitrate [$Ca(NO_3)_2$] (Table 3.8) Plants were cultivated in the same growth medium of 20% perlite to 80% coco-peat. The CRF treatment used was Multicote MCA (8) Hydro from Haifa. The ration between CRF and LF for each treatment was based on the nitrogen (N) percentage of each. The calcium amendments were made once a month by applying 30 grams to the surface of the growth medium of each of the calcium sources. This took place over 3 months. Thus, a minimum of 90 grams of each calcium source were added over the duration of the trial.

The histograms below (figure 3.1 – 3.3) are for 90 grams of CRF for the whole season and the fraction there of in the part where LF is also used. It must be note that LF represent the equivalent of the grams per only 1 litre applied to each plant. Hence every week the plant received more than 1 litre of LF which will increase the total amount of nutrients significantly. This quantity is just to get a comparison of the amount of nutrients applied for CRF and LF respectively in each treatment.

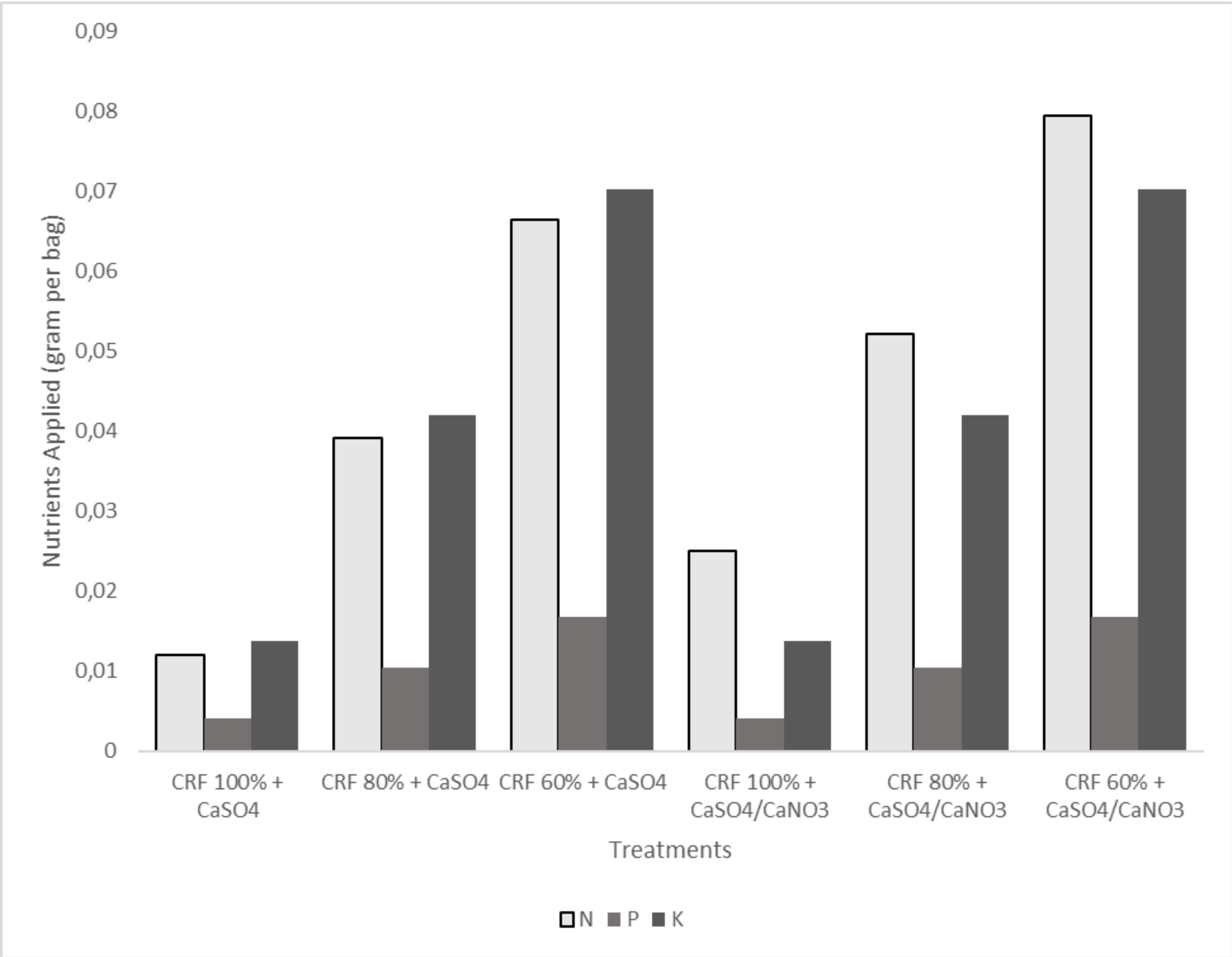

Figure 3.1: Comparison between the macronutrients received for each treatment for one application of the Controlled Release Fertilizer (CRF) and the relative amount of nutrients received from 1 litre of liquid fertilizer based on the ration of the contribution of the N%.

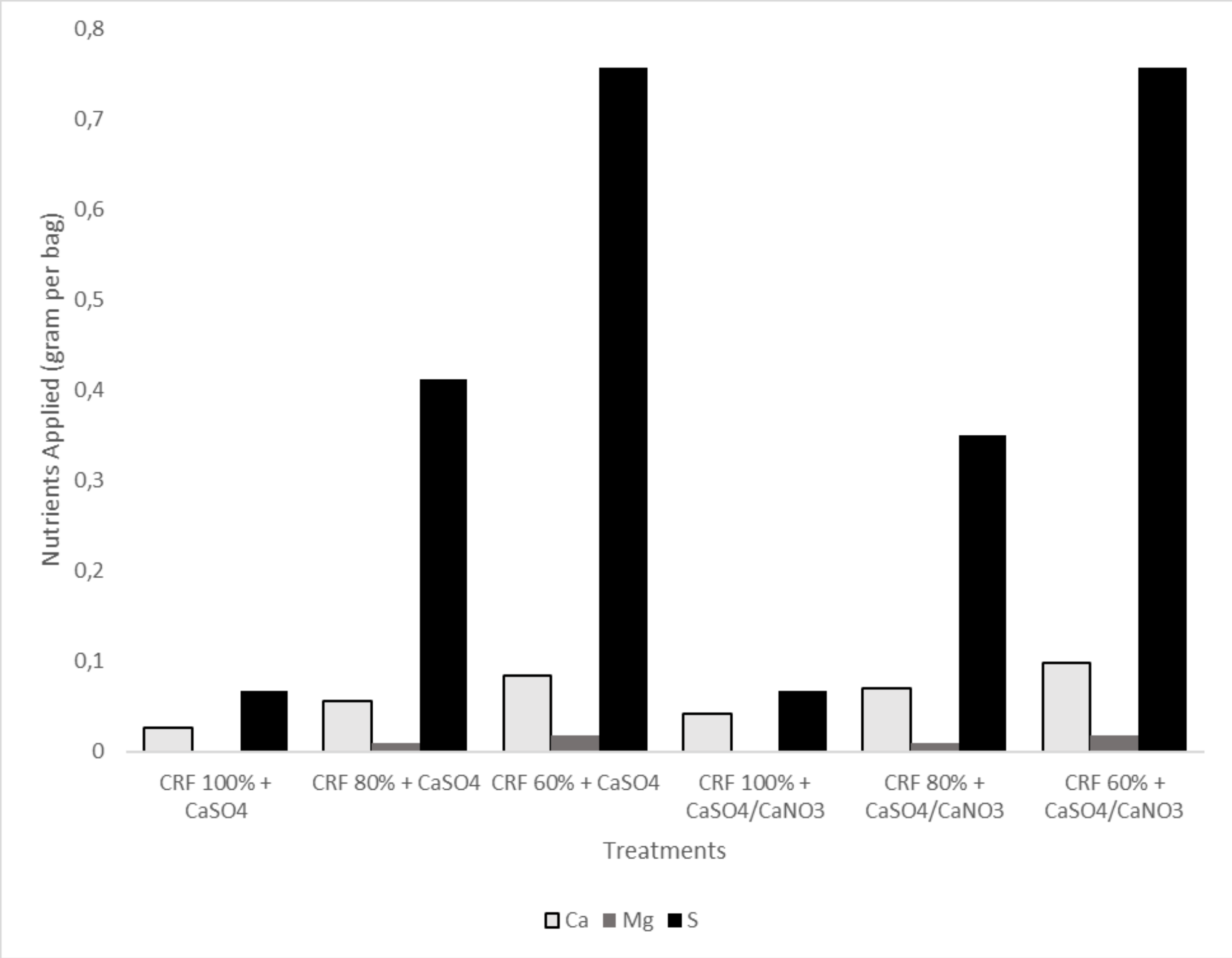

Figure 3.2: Comparison between the macronutrients received for each treatment for one application of the Controlled Release Fertilizer (CRF) and the relative amount of nutrients received from 1 litre of liquid fertilizer based on the ration of the contribution of the N%.

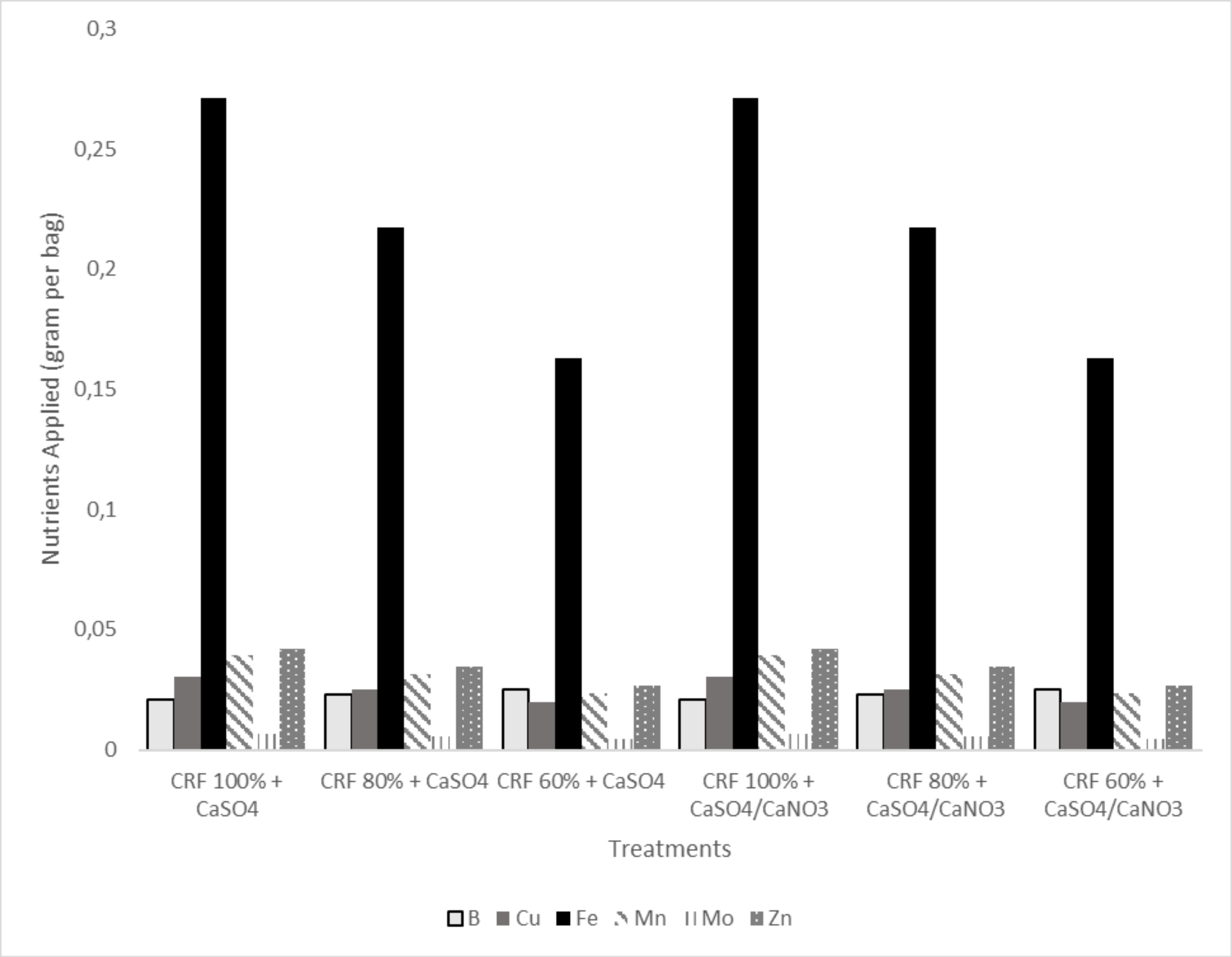

Figure 3.3: Comparison between the micronutrients received for each treatment for one application of the Controlled Release Fertilizer (CRF) and the relative amount of nutrients received from 1 liter of liquid fertilizer based on the ratio of the contribution of the N%.

Table 3.6: Nutrient composition for tank A and tank B in the fertigation (liquid fertilizer) fertilization fraction: Welgevallen Standard Nutrient Solution (EC of Solution = ca. 2mS/cm)

Nutrient	Application g / 1000 ℓ	200 x concentration g / 900 ℓ
Tank A		
Macronutrients		
Potassium nitrate (KNO_3)	100.00	18000
Potassium chloride (KCl)	75.00	13500
Mono potassium phosphate (KH_2PO_4)	136.00	24480
Magnesium sulphate ($MgSO_4$)	440.00	79200
Micronutrients		
Manganese sulphate ($MnSO_4$)	2.23	401.40
Zink sulphate ($ZnSO_4$)	1.47	264.60
Solubor (Boron) Boric Acid, H_3BO_3. Borax Pentahydrate, $Na_2B_4O_7 \cdot 5H2O$. Sodium Pentaborate, $Na2B_{10}O_{16} \cdot 10H_2O$	1.51	271.80
Copper sulphate ($CuSO_4$)	0.20	36.00
Ammonium heptamolybdate $(NH_4)_6Mo_7O_{24}$	0.09	16.20
Tank B		
Macronutrients		
Calcium nitrate ($CaNO_3$)	850	153000.00
Potassium nitrate (KNO_3)	100	18000.00
Micronutrients		
Libfer (Fe-EDTA) 13%	6.54	1177.20

Table 3.7: Nutrient composition for the controlled release fertilizer: Prescription blend from Haifa, Multicote MCA (8) Hydro.

N	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Mo	Zn
133 g/kg	45 g/kg	153 g/kg	6 g/kg	9 g/kg	48 g/kg	235 mg/kg	335 mg/kg	3015 mg/kg	436 mg/kg	67 mg/kg	469 mg/kg

Table 3.8: Treatment description for liquid fertilizer (LF) and Controlled Release Fertilizer (CRF) All of the six treatment combinations were laid out in a randomized block design (RBD) and were replicated five times.

Treatment	% CRF	% LF	Calcium addition
1	100	0	Calcium Sulphate
2	80	20	Calcium Sulphate
3	60	40	Calcium Sulphate
4	100	0	Calcium Nitrate + Calcium Sulphate
5	80	20	Calcium Nitrate + Calcium Sulphate
6	60	40	Calcium Nitrate + Calcium Sulphate

3.2.3 Pre-Harvest Measured Parameters

Prior to harvesting, data was continuously captured for pH of the effluent, atmospheric/ambient temperature, and the EC of the effluent as well as the percentage of applied irrigation water, which percolated from the planting bag. These parameters were later utilised to interpret the harvest quality parameters. Ambient temperature was measured with a data logger, installed midway between the roof and the floor. One data logger was used per block (replication).

3.2.4 Fruit and Vegetative Measured Parameters with Harvest

Plants were grown for three months, while three harvest intervals were completed during this period to compare the fruit size and yield per treatment. Only three of the plants per experimental unit were harvested. The vegetative growth was divided into the stem length and the leaf length, which included all side growth. The bottom 30 cm leaves and branches of each plant were removed during the growing season to prevent diseases and to promote vertical growth of the stem. The stem length, stem fresh mass and the leaf fresh mass were measured at harvest. The stem and leaves were dried for four to six days at a temperature of 60 °C. The dry mass of leaves and stems were subsequently measured.

3.3 Statistical Analysis

To investigate the changes in measurements over time, 3 parameter growth curves and linear straight regression lines were fitted separately for the different treatments using the “drc” package in R. The formula for the 3-parameter logistic growth curve is:

y=(upper*lower*Exp(rate*time))/(upper+lower*(Exp(rate*time)-1))

To compare where more than one repeat was measured per row, mixed model ANOVA were conducted with fertilizer type, treatment as fixed effects and the rows as random effect. For post hoc testing, Fisher Least Significant Difference (LSD) testing was used. In cases where there was just one repeat per row, standard 2-way ANOVAs were done. All the collected data were organized for analysis using Microsoft Excel and subjected to Analysis of Variance (ANOVA) using Statistica (ver. 13.5). Significant means were separated using the post hoc Tukey test ($p \leq 0.05$).

CHAPTER 4

Results

For both trials no nutrient analysis of the effluent water, nor the fertigation water could be collected which would have given a better understanding of the results obtained. Foliar nutrient analysis throughout the growing season would also have given a better indication of the nutrient content of the leaves during critical phenological stages, Due to unforeseen reasons this could also not been analysed.

For the first trial there was no significant difference in the fresh vegetative weight between the CRF treatments with different growth media treatments (figure 4.4). There was a significantly lower fresh vegetative weight for all the CRF treatments compared to the LF treatments (figure 4.4). It is interesting to note that there was significant more fruit for the LF treatments compared to the CRF treatments (figure 4.6) The marketable fruit component (figure 4.5) varied between all the treatments with the LF treatments yielding more fruit compared to the CRF treatments (figure 4.7).

The weekly mean ambient temperature increased from ca. 20 degrees Celsius in the first growing week to ca. 25 degrees Celsius in the last growing week. The mean relative humidity stayed between 60 and 70% for the duration of the growing period (figure 4.1) It is interesting to note that the effect of the temperature on the LF and CRF treatments were different. The CRF treatments had a spike at the beginning of the growing period while the LF treatments had an increase in EC in the middle of the growing period (figure 4.2).

The pH tended to be the same for all the treatments, although there was a difference in the EC of the LF treatments from the CRF treatments throughout the growing season (figure 4.3).

For the second trial the comparison was for the addition of calcium sulphate or a combination of calcium sulphate and calcium nitrate to a blend of CRF and LF based on the nitrogen % contribution of the CRF. The focus of the results was to observe the response in growth and yield to the different treatments and to compare the EC and pH level of the leachate of the different treatments throughout the growing season.

The treatments with a portion of LF had more vegetative growth than the treatments with 100% CRF (figure 4.10). This is also the case for the marketability of the fruit where the treatments with 100% CRF had less marketable fruit. There was also more trusses and number of fruits on the treatments with a portion of LF (figure 4.11).

It is interesting to note that the LF portion treatments without additional calcium nitrate had no significant differences in vegetative growth than those treatments who did not have additional calcium nitrate (figure 4.11).

The daily maximum temperature over the growing period was between 16°C and 31°C. The temperature decreased steadily form transplant up until harvest in accordance with the shifting season (figure 4.9).

The pH and EC levels fluctuated between the treatments throughout the growing season with some interesting responses of the EC and pH levels (figure 4.8):

The pH level for the all the treatments with additional calcium nitrate were between 6.6 and 6.9 (figure 4.8).

The pH level for the treatments with no additional calcium nitrate followed the same trend except for the 80% CRF treatment which had a lower pH level throughout the growing season (figure 4.8).

The EC level fluctuates for all the treatments with no trend able to be established. All the treatments had an increase of EC levels throughout the growing season excluding the 100 CRF without additional calcium nitrate. The treatment with 60% CRF and additional calcium nitrate had a reduction in EC levels throughout the growing period (figure 4.8).

4.1 Trial 1

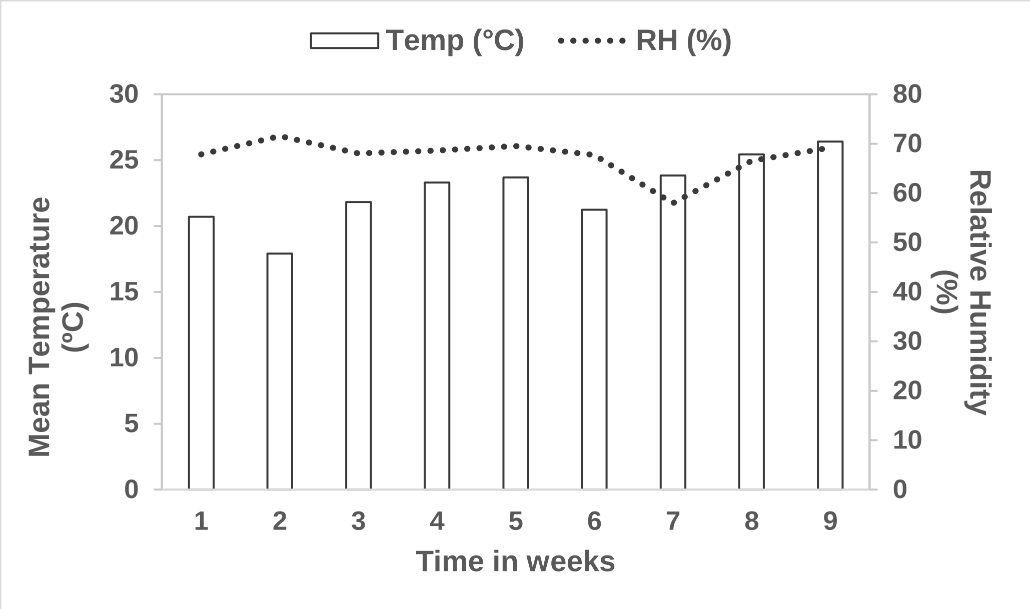

Figure 4.1: Weekly mean ambient temperatures (in °C) and relative humidity (%) in the greenhouse for the duration of the trial.

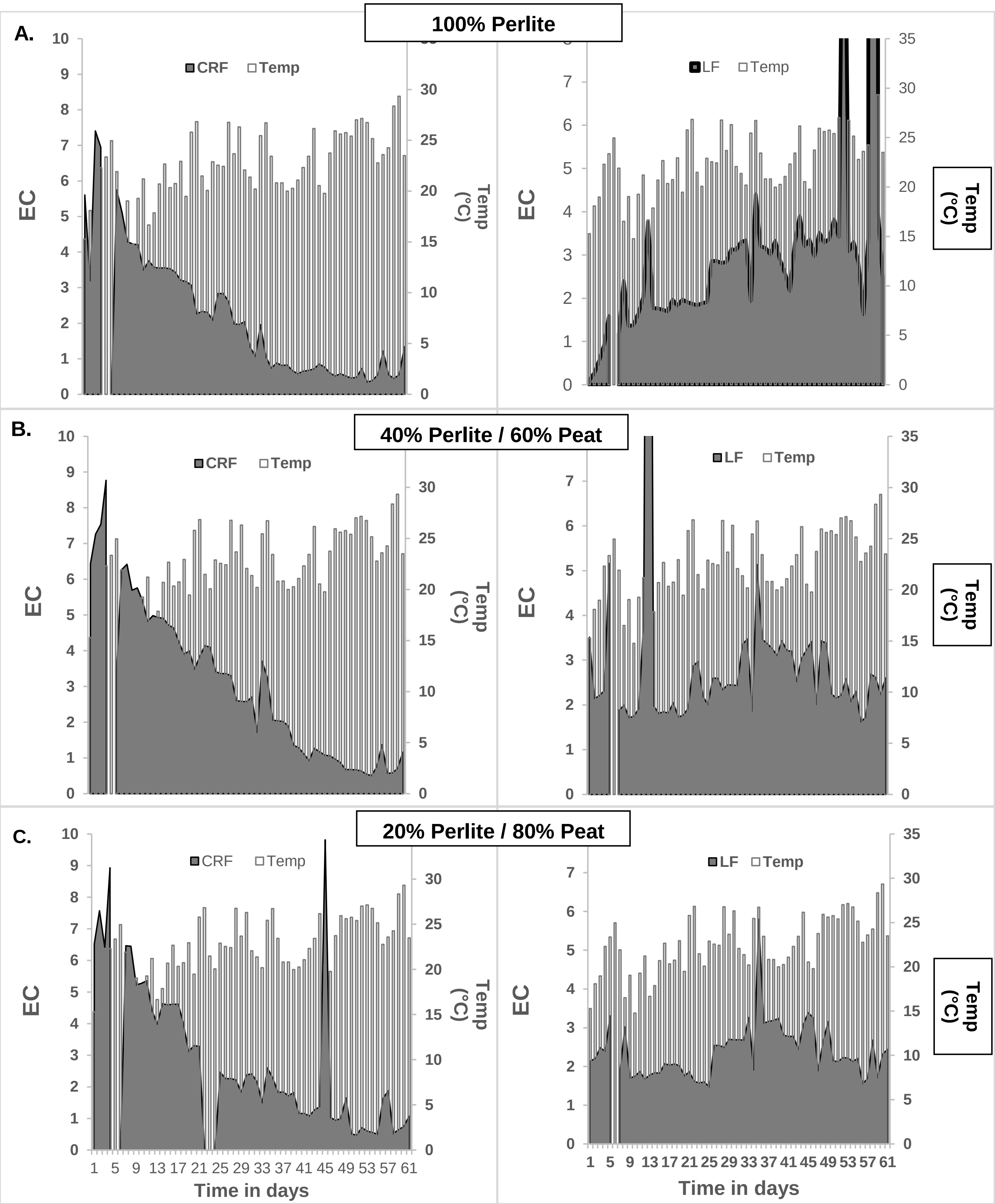

Figure 4.2. Average ambient temperature comparison with effluent EC (mS.cm^{-1}) during a two-month growing period (September 2016 – November 2016) for plants treated with Controlled Released Fertilizers (CRF; left panel – a, b, c) and plants treated with Liquid Fertilizers (LF; right panel – a, b, c) in growth media (a – 100% perlite) or in different mixing ratios with peat and perlite; that is, 40% perlite:60% peat (b) and 20% perlite:80% peat (c)

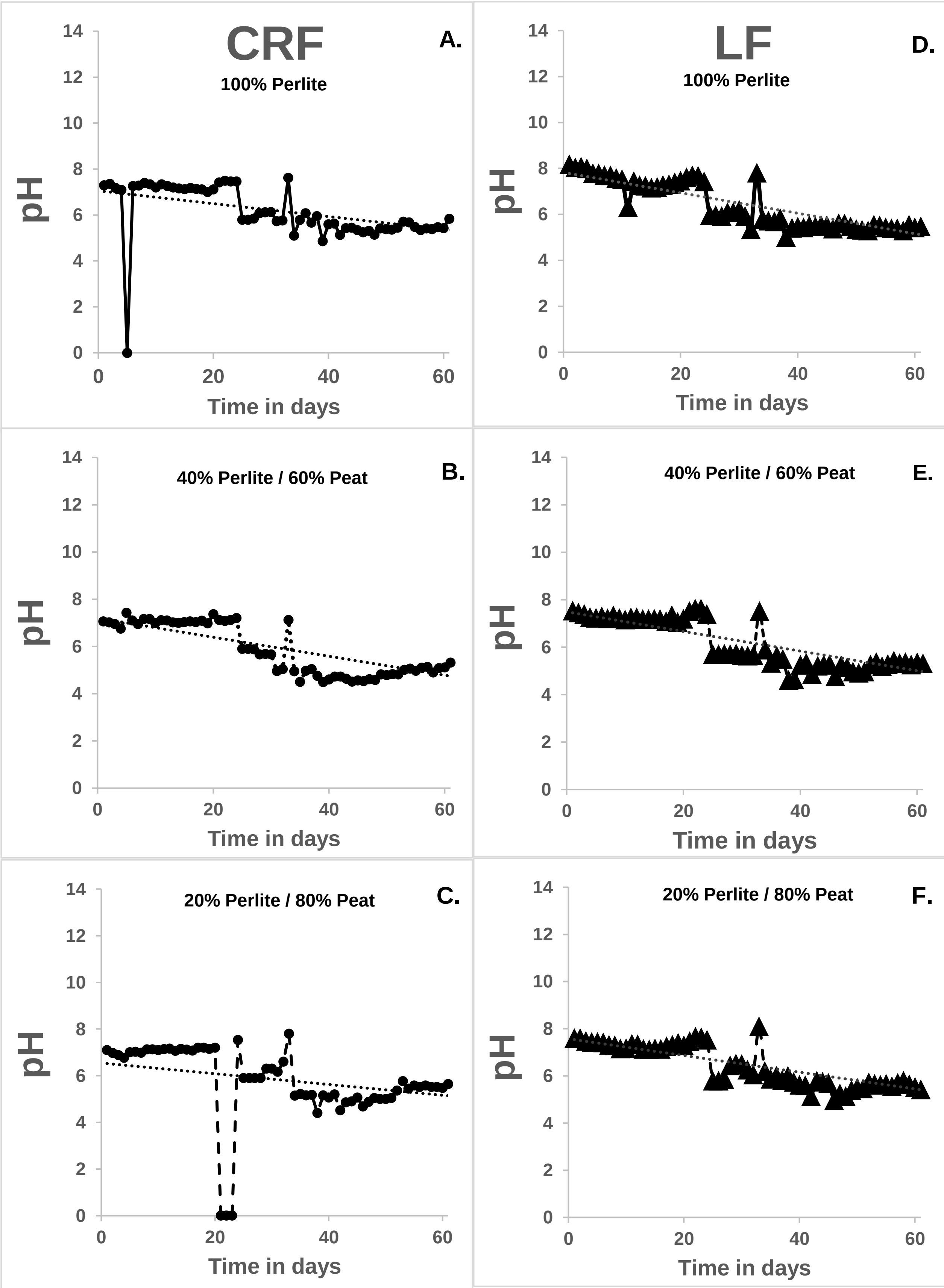

Figure 4.3 The pH level (of leachate) for plants grown for a two-month period and treated with Controlled Released Fertilizers (CRF – a, b, c) and plants treated with liquid fertilizers (LF – d, e, f) in growth media (a, d – 100% perlite) or in different mixing ratios with peat and perlite; that is, 40% perlite:60% peat (b, e) and 20% perlite:80% peat (c, f).

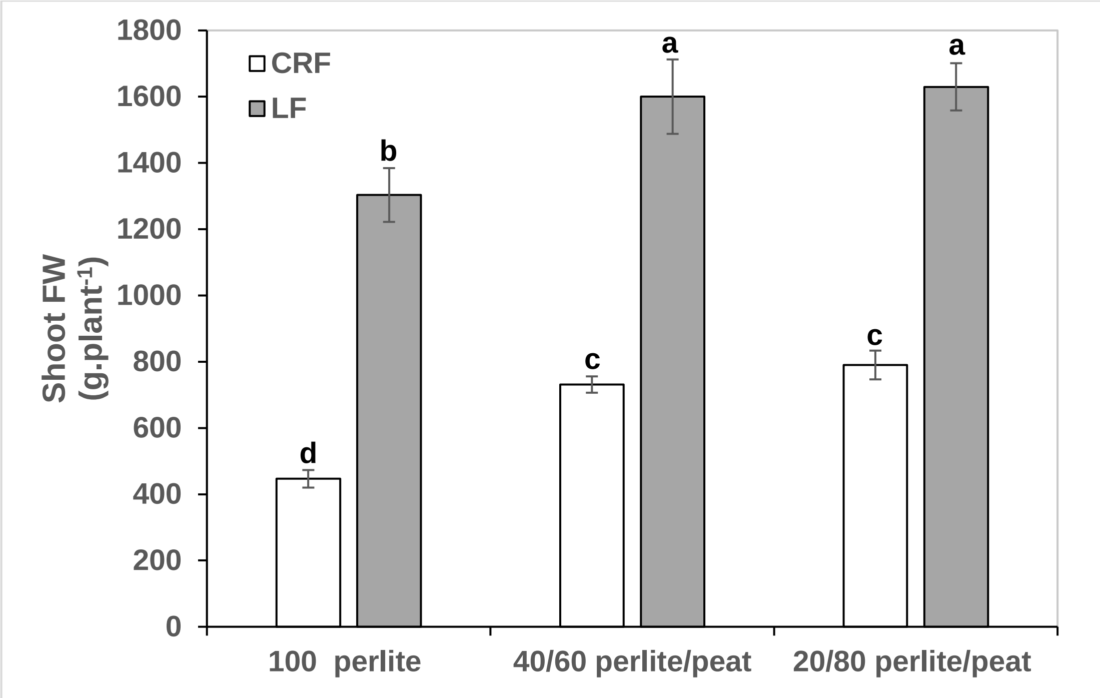

Figure 4.4 The shoot fresh weight (grams per plant) of tomato plants grown for two months and supplemented with Controlled Release Fertilizer (CRF) or Liquid Fertilizer (LF) cultivated in growing media of 100% perlite or mixed in different ratios with peat; that is, 40% perlite: 60% peat and 20% perlite: 80% peat. Values are the means of three replications (n=3). Means with the same letter are not significantly different ($p \leq 0.05$).

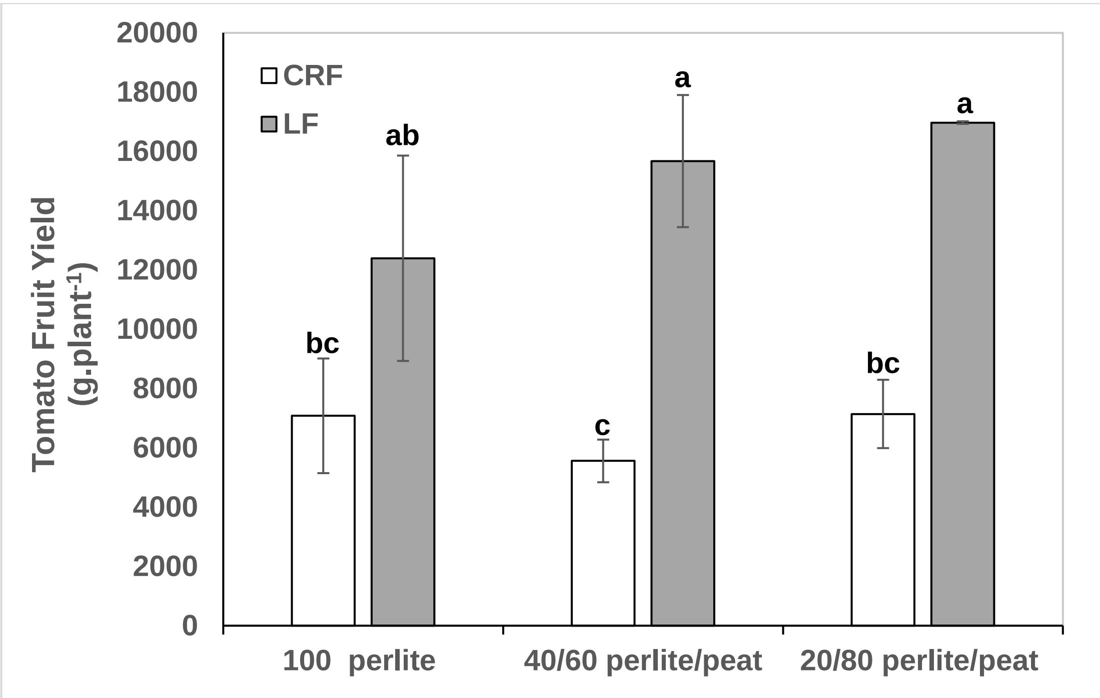

Figure 4.5 The fruit yield (grams per plant) of tomato plants grown for two months and supplemented with Controlled Release Fertilizer (CRF) or Liquid fertilizer (LF) cultivated in growing media of 100% perlite or mixed in different ratios with peat; that is, 40% perlite: 60% peat and 20% perlite: 80% peat. Values are the means of three replications (n=3). Means with the same letter are not significantly different ($p \leq 0.05$).

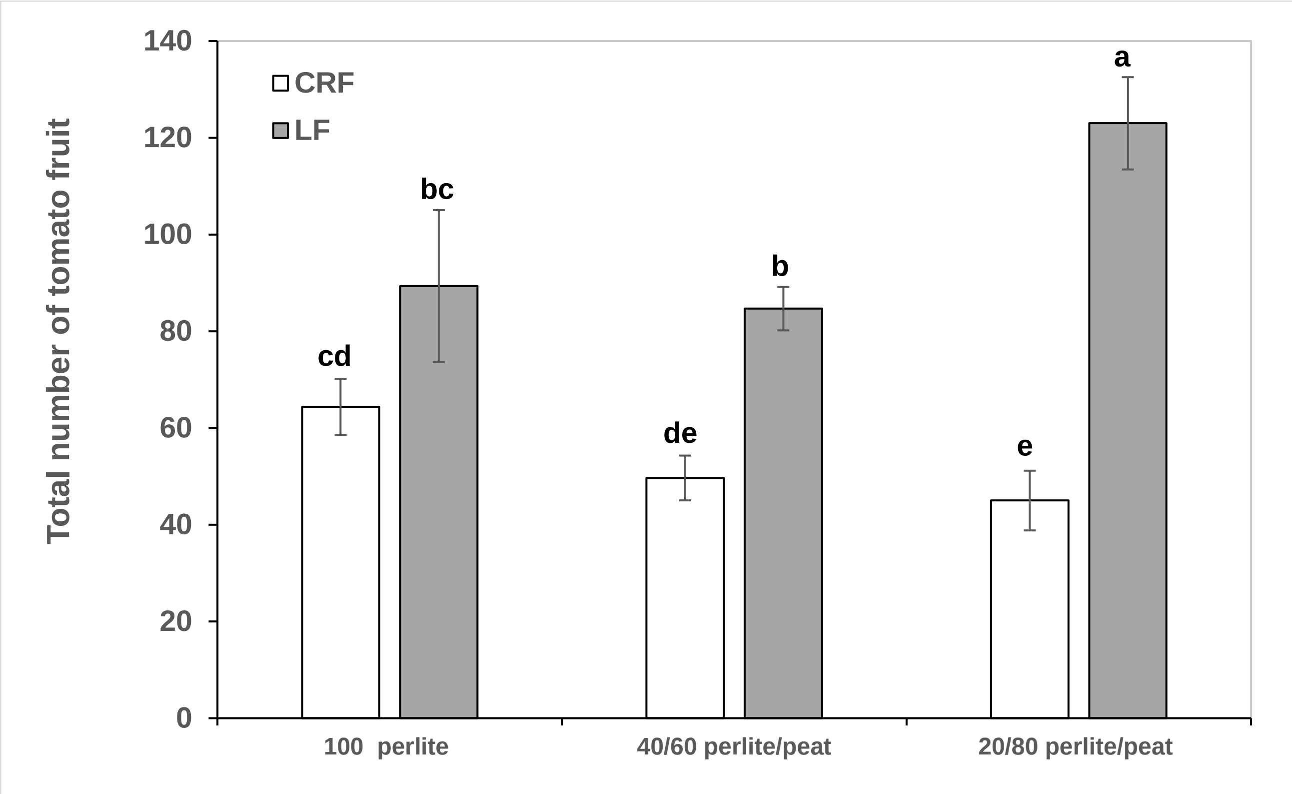

Figure 4.6 The total number of fruits of tomato plants grown for two months and supplemented with Controlled Release Fertilizer (CRF) or Liquid Fertilizer (LF) cultivated in growing media of 100% perlite or mixed in different ratios with peat; that is, 40% perlite: 60% peat and 20% perlite: 80% peat. Values are the means of three replications (n=3). Means with the same letter are not significantly different (Tukey's HSD; $p \leq 0.05$).

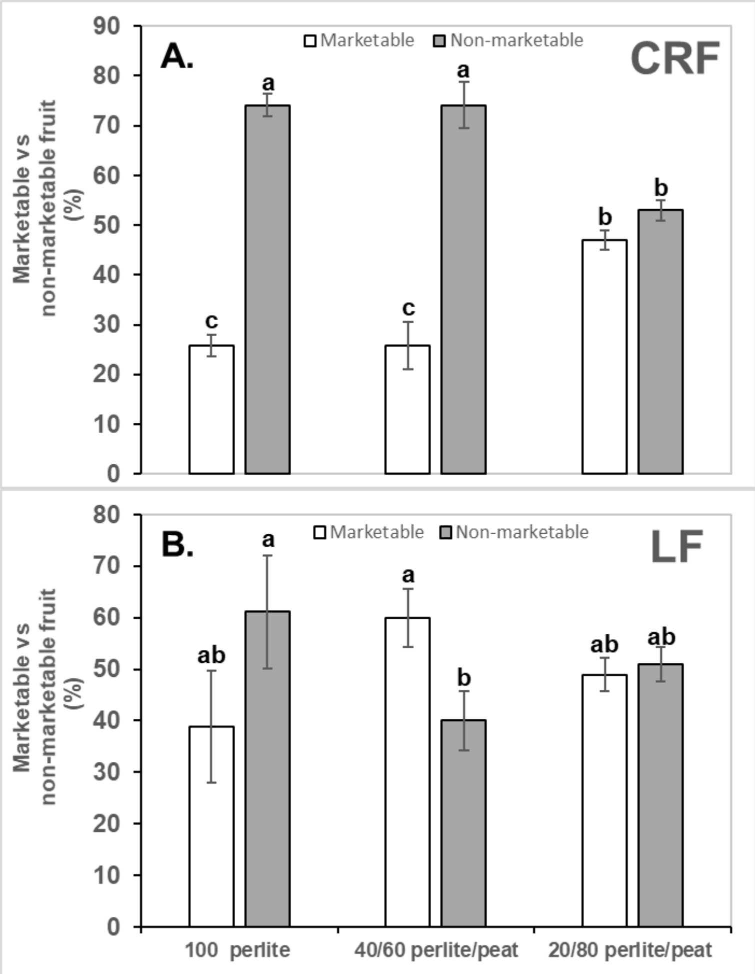

Figure 4.7 Marketable vs non-marketable fruit (%) for tomato plants grown for two months and supplemented with (a) Controlled Release Fertilizer (CRF) or (b) Liquid Fertilizer (LF) cultivated in growing media of 100% perlite or mixed in different ratios with peat; that is, 40% perlite: 60% peat and 20% perlite: 80% peat. Values are the means of three replications (n=3). Means with the same letter are not significantly different (Tukey's HSD; p ≤ 0.05).

4.2 Trial 2

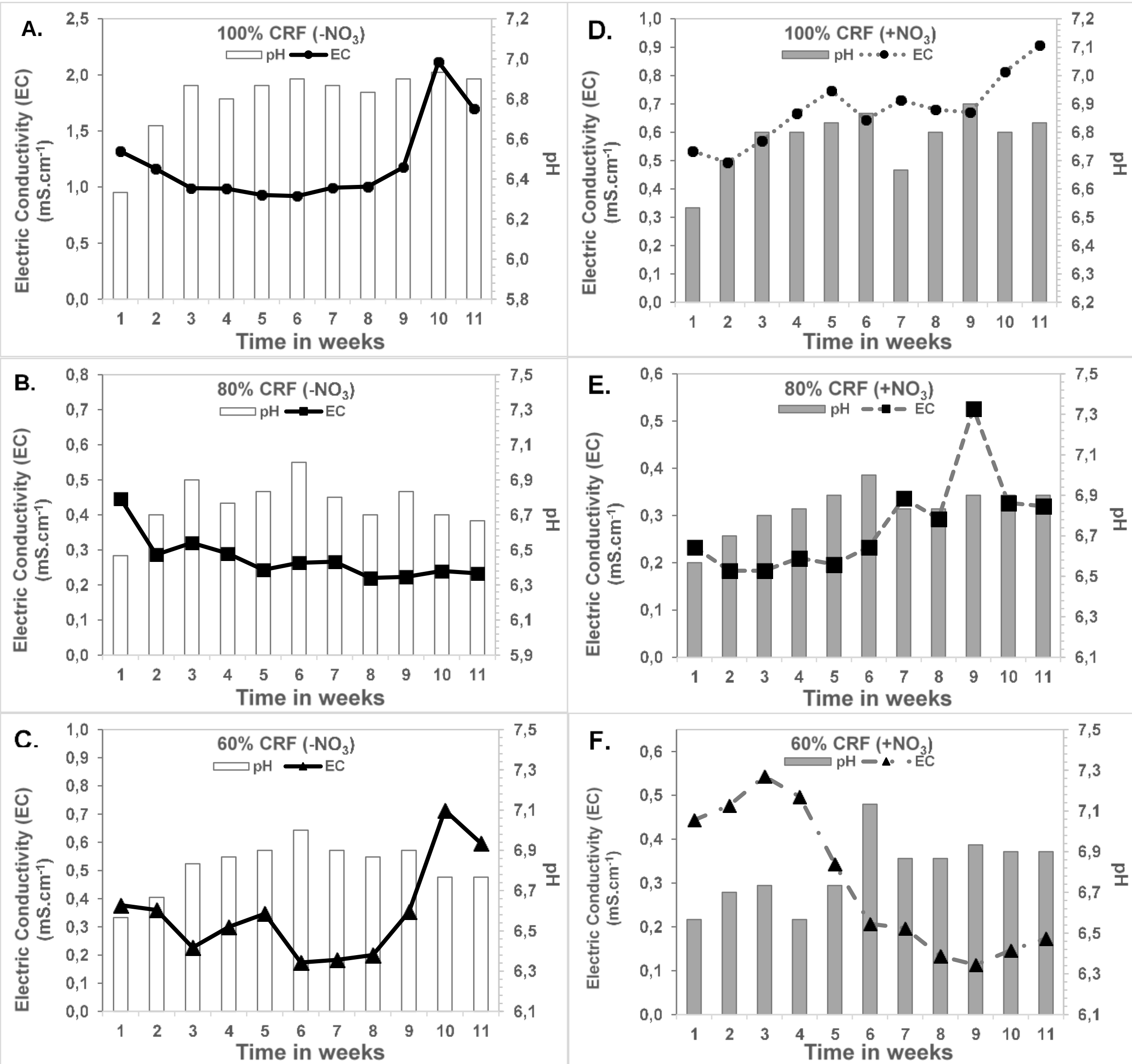

Figure 4.8 The EC (mS.cm^{-1}; line) and pH (a-f; bars) during an 11-week growing period (Feb 2017 – May 2017) of effluent for tomato plants fertigated with Controlled Release Fertilizer (CRF) at three different ratios; i.e., 100% (a,d), 80% (b,e) and 60% (c,f) with (open bars) or without $Ca(NO_3)_2$ (filled bars), respectively. Plants were cultivated in growing media of 20% perlite: 80% peat.

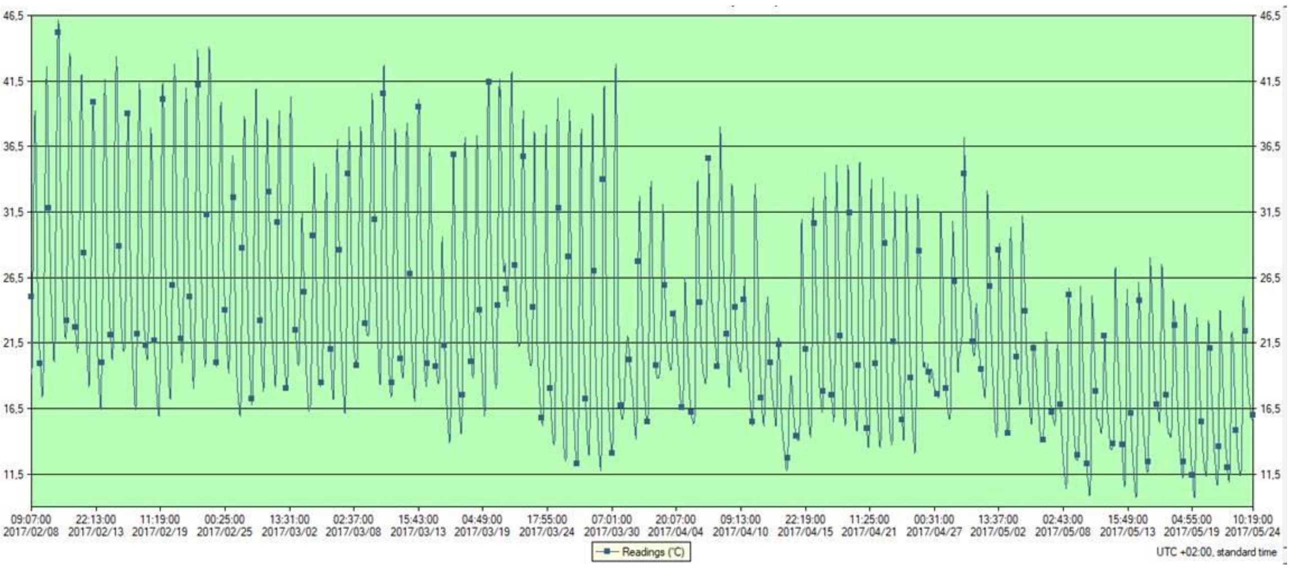

Figure 4.9 Daily mean, minimum and maximum temperatures (degrees Celsius) in the greenhouse from February 2017 to May 2017.

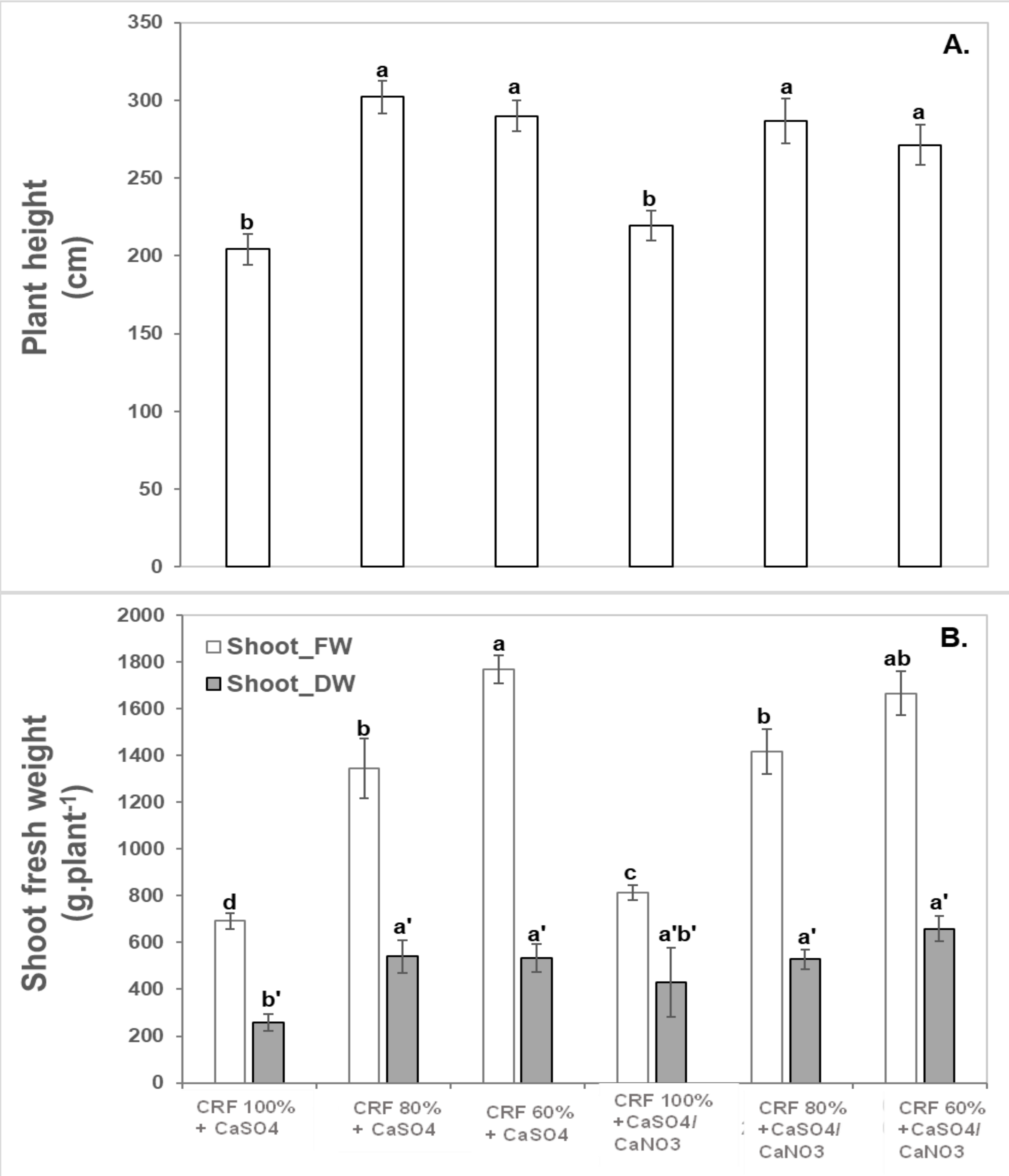

Figure 4.10 (a) The plant height (cm) and (b) shoot fresh weight (open bars) and dry weights (filled bars) (gram per plant) of tomato plants grown for 11 weeks fertigated with Controlled Release Fertilizer (CRF) at three different ratios (i.e., 60%, 80% and 100%) with or without $Ca(NO_3)_2$. Plants were cultivated in growing media comprised of 20% perlite: 80% peat. Values are the means of three replications (n=3). Means with the same letter (open bars) or letter with an apostrophe (filled bars; e.g., a') are for shoot FW and shoot DW, respectively, and where letters are not the same there are no significant differences between treatments (Tukey's HSD; $p \leq 0.05$).

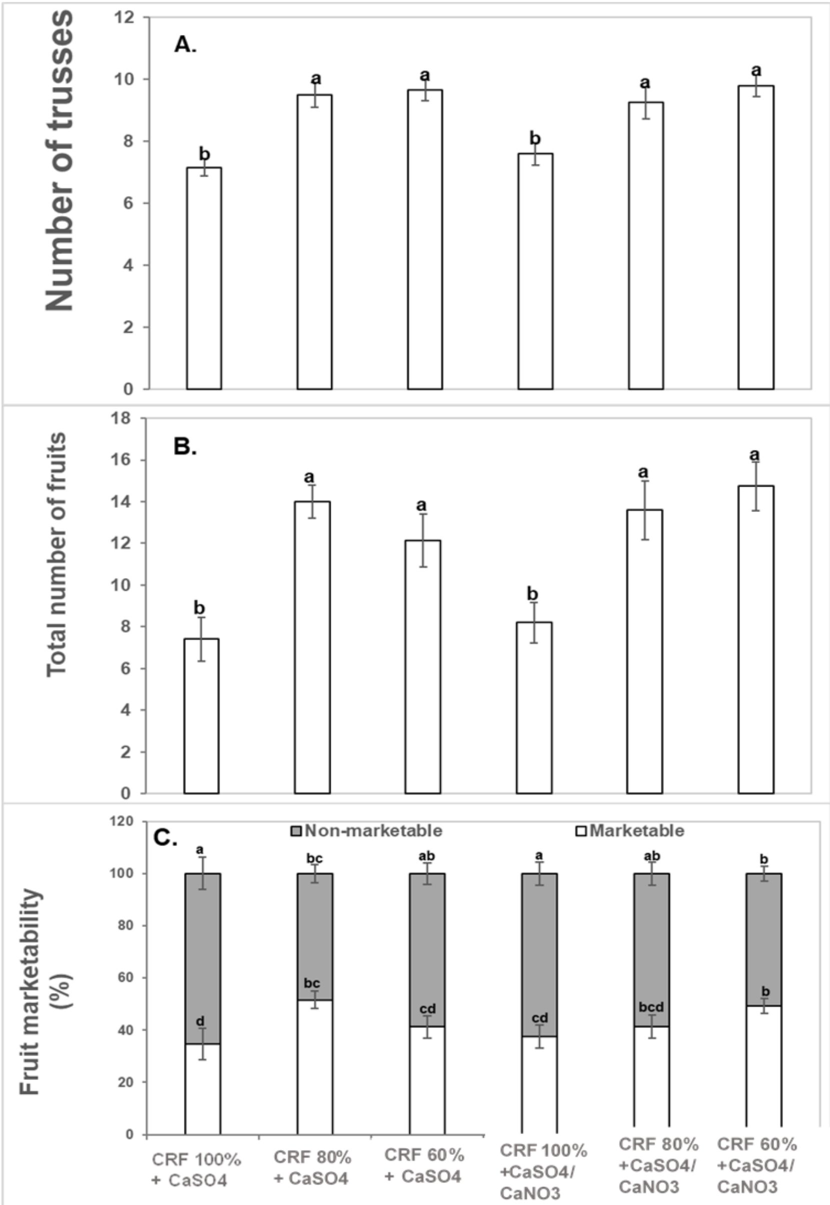

Figure 4.11 (a) The number of trusses, (b) the total number of fruits, and (c) the marketable (open bars) vs non-marketable fruits (filled bars) (%) of tomato plants grown for 11 weeks fertigated with Controlled Release Fertiliser (CRF) at three different ratios (i.e., 60%, 80% and 100%) with or without $Ca(NO_3)_2$. Plants were cultivated in growing media of 20% perlite: 80% peat. Values are the means of three replications (n=3). Means with the same letter are not significantly different (Tukey's HSD; $p \leq 0.05$).

CHAPTER 5

Discussion

The findings of this study suggests that a 100% CRF fertilization method as it was prepared and applied in the manner of this study had significant less marketable fruit and lower yields than a program with LF as part of the fertilization programme. CRF is therefore a less suitable management tool for productivity of tunnel-grown tomatoes.

The results of this study differ from the results of a study conducted by Kinoshita et al. (2014). They used a different experimental design whereby the CRF were added to the irrigation water tank directly and not mixed in with the growth medium as was the case with the current study. The results obtained in that study indicated that the use of CRF for greenhouse tomato production resulted in less nutrients used without the reduction of yield compared to a conventional LF fertigation method.

For both trials, according to figures 3.1 – 3.3 and table 3.2, the bigger the CRF fraction the less nutrients overall were received by those treatments compared to the LF fraction treatments. Lack of nutrients is a major limiting factor in growth and yield responses of crops as was the results in the current study.

Given the results in trial one, the CRF tended to release the nutrients earlier as intended leading in a spike in the EC levels which in turn resulted in even less nutrients during the important phenological growth stages (figure 4.2) In trial two, the mean temperature was lower in the beginning of the growing season resulting in less of an EC level spike due to a slower release rate of nutrients (figure 4.8). CRF have a high release rate once the temperature is above 25 degrees Celsius ((Adams et al., 2013; Broschat, 2005; Kochba et al., 1990).

It was interesting to note that once the CRF had a fraction of LF added to the treatment, the yield increased and the marketability of the fruit as well. This can be described due to the increase in nutrients received by the treatments.

The EC level in the trial of Kinoshita et al (2014) where more stable due to the thermodynamic properties of water (Kumar et al, 2008). It is therefore a better experimental design for a more controlled release of nutrients from CRF for experimental studies.

Limitations of this study included the lack of chemical nutrient analysis throughout the growing seasons and therefore a lack of evidence in the interpretation of the results. Also, the experimental design should have included the measurement of irrigation water to understand whether there were sufficient water applied during the growing seasons. Leaf area indexing as well as photosynthetic active radiation measurements would have provided an insight into the understanding of the rate of photosynthesis during the growing seasons.

CHAPTER 6

General Conclusion

6.1 Synopsis

The purpose of the study was to compare the yields of greenhouse cultivated tomato crops in soilless culture between an industry standard Liquid Fertilizer (LF) fertilization program and an industry standard Controlled Release Fertilizer (CRF) fertilization program. This was done to assess whether only using CRF pre-mixed into the growth medium to produce commercial tomatoes and then only control the irrigation application volume and temperature might be a viable alternative to the more commonly used and relatively complex LF. The secondary aim was to assess the role of the growing medium, i.e., the ratio of perlite: coco peat in the growth medium, on the fruit yield.

Given the results (Yanmei Li et al., 2017) regarding the use of CRF in soil-based greenhouse tomato production we can see that the effect of CRF is greatly improved when applied in an environment where the temperature and growth media properties are favourable for the slow release of the nutrients and it can greatly benefit the system in cases where crops are planted in soil.

Kinoshita et al., (2016) conducted a trial by using CRF in a water reservoir instead of mixing it in with the growth media. They concluded that the closed CRF application system used less nutrients than the normal liquid fertilizer system with the same results in yield. Their closed system prevented nutrient losses since nutrients were re-circulated. By using a drain-to-waste system, in our study, the nutrients released by CRF were lost, making it less attractive for local use. Therefore, the results obtained in our study indicate the sensitivity of CRF in a system where it was mixed into the growth medium. The response to temperature changes was much more dramatic since the buffer capacity of the growth medium in the bags were much less than the buffer capacity for CRF in soil-based systems. Also, the fact that the buffer capacity to temperature in the water reservoir was much higher which resulted in a more evenly released CRF nutrient curve, which could be better correlated with the intended formulated release curve calculated by the developer of the CRF.

The pronounced difference in the mass of the marketable fruit yield for the LF treatments and the CRF treatments may be ascribed to the significant lower vegetative dry mass of the CRF fertilization treatments due to the premature release of nutrients from the CRF treatments, because of high initial temperatures, which led to a high concentration in the rhizosphere and almost no nutrients near the end of the growth season when fruit development was important. If the size of the fruit and total dry vegetative mass could be increased, then the feasibility to grow commercial greenhouse tomatoes with only CRF might be possible. Finally, it should be cautioned that by using the industry standard CRF without any supplemental nutrient source, may hinder its usability as a viable alternative to produce CEA vegetables commercially. It should be noted that the overall nutrients received by the LF treatments were higher than the CRF treatment could be provided by the CRF formulation and recommendation for the trial.

6.2 Shortcomings and recommendations

A better understanding of the crop responses would have been obtained if a continues leachate water extract analysis throughout the growing season for each treatment could have been obtain. Unfortunately, the trials had financial limitations on continues water analysis for comparisons and interpretation.

Also, a second replication of each trial would have given better statistical evidence to the findings in this study.

Water and nutrient use efficiency comparison in relation to production costs for each fertilisation method would have added more significant meaning of the study to the commercial farming industry.

6.3 Future prospects

Water and nutrient use efficiency were not the focus of this study but is worth investigating in future studies on CRF in greenhouse crop production in South Africa.

A study on the nutrient levels throughout the growing season in the plant bags correlated with the nutrient levels in the leaves at the important physiological stages is recommended to see the plant nutritional response to the nutrients release throughout the season.

A study on the true release curves of CRF throughout the growing season in reaction to the climatic conditions is also recommended.

A study on the behaviour of CRF placed directly into a feeding water source and monitoring the release rate will be beneficial for the soilless crop production industry in South Africa.

CHAPTER 7

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