The use of a starch-based superabsorbent polymer to support and optimise potato production in the sandy soils of the Sandveld production region in South Africa.

by

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Thesis presented in partial fulfilment of the requirements for the degree

Master of Agricultural Sciences

at

Stellenbosch University

Department of Agronomy, Faculty of AgriSciences

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March 2023

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Abstract

Trends in agriculture are rapidly shifting towards more sustainable approaches. This is no different for the ecologically sensitive Sandveld region, where agricultural activities put pressure on the indigenous biodiversity and available resources. Potato production in the Sandveld region is highly reliant on groundwater resources for irrigation purposes, due to the low annual precipitation coupled with very high evaporative demands, especially in summer months. Additionally, potato crops are sensitive to water stress and the crop's poorly developed rooting system is inefficient in extracting the already low plant available water in sandy soils. The aim of this study was to evaluate the potential of the biodegradable superabsorbent polymer, Zeba™, to support and improve potato production systems in semi-arid, drought prone areas. This study was approached by means of a field trial as well as a supplementary pot trial. In the field trial, four rates of Zeba™, were applied in-furrow at planting, and compared to a control. Soil water content measurements showed that the soil layers from the treatments contained more moisture than the control. Generally, increased potato tuber yield ($P<0.05$) was observed with increasing rates of Zeba™, except for the highest treatment rate, which had a similar yield as the control ($P>0.05$). The application of Zeba™ did not adversely affect the tuber quality. The increased tuber yields resulted in improved resource-use efficiencies. The water-use efficiencies, as well as nutrient-use efficiencies were either higher, or equivalent, to values reported for previous research in the area. Three application rates, similarly as three of the rates in the field trial but adjusted for a 15 cm pot, were compared to a control in a pot trial. The water holding capacity of the soil and polymer system was assessed one day, and three days after a weekly irrigation event. The trial was run over a twelve week period. The results showed that both the treatment rate and the time intervals had a significant influence on the water holding capacity of the soil. Similar to the findings of the field trial, the water holding capacity increased with an increase in product applied. The use of the superabsorbent polymer had a more pronounced effect on the water holding capacity as the soil dried out after the irrigation event, due to its superior ability to retain water compared to the large pores of sandy soils. In comparison to the control, the use of this product retained more water on the third day after irrigation than on the first day after irrigation. Although a decrease in water holding capacity was observed as the trial progressed, there was no clear indication that it was due to a reduction in the polymer's absorption ability from degradation. The decrease observed is ascribed to the increase in temperature, which led to a higher evaporation rate. Zeba™ successfully improved potato production in the Sandveld by increasing the water holding capacity of the sandy soils, leading to an increase in fresh tuber yield and improved resource use efficiencies. A treatment rate of 10 kg ha^{-1} of Zeba™ is recommended as optimal to support and optimise potato production in the Sandveld region. This product could also be used to sustain production in other semi-arid regions and drought prone areas, with similar soil textures, when water stress limits production.

Opsomming

Tendense in landbou is vinnig besig om na meer volhoubare benaderings te verskuif. Vir die ekologies sensitiewe Sandveldstreek, waar landbou-aktiwiteite tans druk op die inheemse biodiversiteit en die natuurlike hulpbronne plaas, is dit geensins anders nie. Aartappelproduksie in hierdie streek is baie afhanklik van grondwaterbronne vir besproeiingsdoeleindes. Dit is as gevolg van ‘n baie lae jaarlikse reënval en hoë verdamping, veral in die somermaande. Aartappels is ook uiters sensitief vir waterstres en hul vlak wortelstelsel is oneffektief in die opname van die reeds lae beskikbare grondwater in die sandgrond. Die doel van hierdie studie was om die potensiaal van die bioafbreekbare superabsorberende polimeer, Zeba™, te evalueer en om te bepaal of dit aartappelproduksie in droë streke kan ondersteun en optimaliseer. Hierdie studie is deur middel van 'n veldproef, sowel as 'n aanvullende potproef, uitgevoer. In die veldproef is vier Zeba™ behandelings met ‘n kontrole vergelyk. Grondwaterinhoudmetings het bepaal dat die grond waar die Zeba™, toegedien is, meer water as die kontrole bevat het. In die meeste van die Zeba™ behandelings was ‘n verhoging in opbrengs waargeneem ($p < 0.05$), behalwe vir die hoogste toedieningspeil wat ‘n soortgelyke opbrengs ($p > 0.05$) as die kontrole gehad het. Die toediening van Zeba™ het ook nie die kwaliteit van die aartappelknolle negatief beïnvloed nie. Die verhoging in opbrengste het die hulpbronverbruiksdoeltreffendheid verbeter. Die waterverbruiksdoeltreffendheid, asook die doeltreffendheid van die verbruik van voedingstowwe was óf hoër, óf soortgelyk aan die bevindinge van vorige studies in die area. Drie toedieningskoerse, soortgelyk aan dié van die veldproef, maar aangepas vir ‘n 15 cm pot, is met ‘n kontrole in die potproef vergelyk. Die waterhouvermoë van die grond en polimeersisteem was een dag, sowel as drie dae na besproeiings plaasgevind het, geassesseer. Die resultate het getoon dat beide die toedieningskoers en die tydsintervalle 'n beduidende invloed ($p < 0.05$) op die waterhouvermoë van die sandgrond gehad het. Soortgelyk aan die bevindinge van die veldproef, het die waterhouvermoë van die sandgrond met die toediening van Zeba™ verbeter. Die superabsorberende polimeer het veral ‘n beduidende effek op die waterhouvermoë gehad namate die grond uitgedroog het. Dit is omrede die polimeer ‘n beter vermoë het om die water te hou, as die groot porieë van sandgrond. Alhoewel 'n afname in waterhouvermoë waargeneem is namate die proef gevorder het, was daar geen duidelike aanduiding dat dit as gevolg was van ‘n afname in die polimeer se absorpsievermoë, wat ontstaan het as gevolg van die afbreek van die produk nie. Die afname wat waargeneem is word toegeskryf aan die toename in temperatuur, wat gelei het tot 'n hoër verdampingstempo. Zeba™ was suksesvol in die optimalisering van aartappelproduksie in die Sandveld, deurdat dit die waterhouvermoë van die sandgrond verbeter het wat tot verhoogde opbrengste en ‘n verbetering in hulpbrongebruiksdoeltreffendheid gelei het. ‘n Toedieningspeil van 10 kg Zeba™ ha^{-1} word voorgestel as die optimale peil om aartappelproduksie in die Sandveldstreek te ondersteun en optimaliseer. Hierdie produk kan moontlik ook gebruik word in ander droë streke waar gronde met soortgelyke teksture aangetref word en waar produksie beperk word deur waterstres.

Acknowledgements

First and foremost, I want to express my gratitude to my supervisors. This project and thesis would not have been possible or up to standard without their assistance and guidance, and it was a privilege working alongside them. I want to thank Prof Pieter Swanepoel for his leadership, his encouragement, and for always going out of his way to help and support me. I consider myself lucky to have had you as a mentor - you taught me more than I could have envisioned. I want to thank Prof Martin Steyn for his continued support, especially during the field trial, and for sharing his expert knowledge about potato production and the potato industry. I want to also thank Dr Freddie Denner for all his guidance during the field trial, his expertise and the knowledge he shared, especially regarding information about Zeba™ and superabsorbent polymer trials.

I want to express my gratitude towards UPL Ltd (Mount Edgecombe, South Africa) for the funding of the field trial and for providing me with the Zeba™ used in my pot trial. This project would not have been possible without your support. I would also like to thank Potatoes South Africa, not only for their funding, but also for their support and for granting me amazing opportunities over the course of these two years.

Further, I am grateful to everyone at the Agronomy Department, Stellenbosch University, for sharing your knowledge, ideas, and skills. Thank you to all my fellow students for the help during field trial visits, and for your continuous support and encouragement throughout the course of my studies.

Finally, I want to thank all my friends and family for their encouragement over the past two years. I appreciate every cup of coffee, word of encouragement, suggestions and all the support you provided me during tough times. I want to especially express my gratitude to my parents. You provided me the freedom to create my own path in life, knowing that you will always support me along the way. Thank you for all your love and guidance over the years - without you I would not have been exposed to many opportunities or be where I am today.

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List of Abbreviations

ANOVA	Analysis of variance
B	Boron
Ca	Calcium
Cu	Copper
CWR	Crop water requirement
DAP	Days after planting
DM	Dry matter
EPN	Entomopathogenic nematode
ETc	Crop Evapotranspiration
ETo	Reference Evapotranspiration
Fe	Iron
IWUE	Irrigation water use efficiency
K	Potassium
KUE	Potassium use efficiency
Mg	Magnesium
Mn	Manganese
Mo	Molybdenum
N	Nitrogen
Na	Sodium
NUE	Nitrogen use efficiency
P	Phosphorous
PAW	Plant available water
PUE	Phosphorous use efficiency
S	Sulphur
SAP/s	Superabsorbent polymer/s
SG	Specific gravity
VWC	Volumetric water content
WUE	Water use efficiency
Zn	Zinc

Chapter 1: Introduction

1.1 Background and locality

Globally, potatoes (*Solanum tuberosum*) are the fourth most important crop when based on production, trailing behind rice, wheat, and maize. However, when based on human consumption, potatoes are deemed the third most important crop (Zhang *et al.* 2017. International Potato Centre, 2021). Potatoes are one of the most planted, and consumed vegetable crops globally and has a long history of importance in the human diet (Zhang *et al.* 2017).

Potatoes are crops that can adapt to many environments, climates, and altitudes. The adaptability of the potato crop therefore makes it a suitable crop to produce worldwide (Birch *et al.* 2012, Devaux *et al.* 2020). Globally, potatoes are produced in more than 100 countries (International Potato Center, 2021). In South Africa alone, potatoes are produced across 16 different production regions, all having different climatic and environmental conditions (Potatoes South Africa 2021b,c).

One of South Africa's potato production regions, the Sandveld region, comprises of the narrow strip between the Swartland and the West Coast, in the Western Cape province of South Africa (Potatoes SA 2021a). The Sandveld has a typical Mediterranean climate, with hot and dry summers and moderate to cold winters with most of the rainfall occurring in the winter months (May to August). The Sandveld has a low annual precipitation, with a long term average of 300 – 400 mm in Aurora, the study region. The Sandveld also has high evaporative demands that are far greater than the rainfall (Department of Environmental Affairs and Development Planning 2017). Due to the low, and unreliable rainfall, dryland potato production is not economically feasible and full irrigation is necessary to sustain production in this area (Haverkort *et al.* 2013; Steyn *et al.* 2016).

The Sandveld is characterized by very sandy soils, which naturally have a low water retention due to the large pore sizes between the sand particles. This results in a high risk for the leaching of water and nutrients from the crop root zone. Potato crops further have a poorly developed rooting system and water is therefore not extracted effectively from the plant available water (PAW), which is already low in sandy soils. Potato crops are also very sensitive to drought stress, and even a short period of stress will affect the tuber yield and quality (Steyn *et al*. 2012a,b). The lack of water in critical growth stages can result in physiological disorders as well as an increased susceptibility to disease. It is due to these reasons that water is the most limiting factor for potato production in South Africa (Steyn *et al.* 2012b), and especially the Sandveld region.

The low rainfall, high evaporation, and low water retention capabilities of the soils in the Sandveld, result in a high reliance on groundwater resources for irrigation purposes. The inability of the soil to retain a large volume of water leads to it moving past the shallow rooting zone of the potato crops. This ultimately causes the leaching beyond the crop root zone of water, fertiliser, and other agricultural chemicals, which are all associated with high input costs. Losses of these chemicals are also known to have negative effects on groundwater quality.

The effects of climate change might have an unfavourable effect on future potato production in the Sandveld, as projections point to the increase of temperatures, the reduction of groundwater recharge, and the reduction of rainfall in critical months. Water stress in the Sandveld production areas are likely to increase in future years (Archer *et al.* 2009). However, in the Sandveld it is not only the reduction of groundwater levels but also the decline in quality thereof that is the most urgent threats to sustainable production (Franke *et al.* 2011; De Wit and Crookes 2013). Agricultural activities, especially the leaching of chemical agricultural products significantly contribute to the deterioration of groundwater quality, not only locally, but also on a global scale. Furthermore, the Sandveld is also an ecological sensitive area, and the indigenous biodiversity is critically endangered by current agricultural activities (Department of Environmnetal Affairs and Development Planning 2017). Farming is the most important land use and economic activity in the region, and it is therefore important that agricultural land- and resource use, and biodiversity conservation are prioritised in conjunction with each other (Department of Environmnetal Affairs and Development Planning 2017).

The use of superabsorbent biopolymers (SAPs) is proposed to combat the above-mentioned soil problems by increasing the water holding capacity of the sandy soils. Superabsorbent polymers, also commonly referred to as hydrogels in literature, can retain great amounts of water, absorbing and releasing water several times throughout the growing season. The use of SAPs in agriculture have globally risen in popularity in recent years, and are being used to combat production limitations, most notable relating to water and nutrient retention constraints (El-Asmar *et al.* 2017; Behera and Mahanwar 2020; Chang *et al.* 2021).

Zeba™ is an example of such a SAP and has been reported to have the potential to reduce the occurrence and frequency of drought stress by increasing the plant available water in the rooting zone of crops (Hüttermann *et al.* 1999; Narjary *et al.* 2012; Montesano *et al.* 2015). The improved water holding capacity achieved by the addition of Zeba™ to the cropping system, might also reduce leaching and therefore decrease the loss of water and nutrients from the soil (Singh *et al.* 2021). These reductions have the potential to ultimately lead to improved water- and nutrient use efficiencies. Improving resource use efficiencies is very important for the economic, social, and environmental sustainability of potato production globally (Steyn *et al.* 2016).

Zeba™, being starch-based, is classified as a biodegradable polymer. It, therefore, has the added benefit that it is an environmentally friendly option for increasing water retention in the agricultural sector (Skrzypczak *et al.* 2020). The positive effects achieved from the addition of an SAP to the soil will not be limited to influencing the water status of the soil. Multiple studies have shown how SAPs influence the growth, yield, and quality of crops (Waly *et al.* 2016; Salavati *et al.* 2018; Jahan and Nassiri Mahallati 2020). This increased crop productivity can be ascribed to the polymer creating a reservoir for water and nutrients in the soil.

1.2 Aim and objectives

Not much research has been done on the use of superabsorbent polymers to support and optimise potato production. The aim of this trial is to evaluate the potential of the biodegradable superabsorbent polymer, Zeba™, to improve potato production systems in semi-arid, drought prone areas. This aim was approached through two objectives.

Objective one was to assess, by means of a field trial, the effects that the use of the superabsorbent polymer, Zeba™, has on the soil water content of sandy soils, the production parameters of processing potatoes, and the potential of the product to improve resource use efficiencies.

Objective two was to assess, by means of a pot trial, the duration for which the product, Zeba™ can provide improvements in absorption potential to the pot system, before degrading to the point where it can no longer retain water.

The knowledge gained will be examined and used to recommend the use of this product in the Sandveld and other similar production systems.

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Chapter 2: Literature Review

2.1. Water requirements and effects of water stress on potatoes

Water is the second most limiting factor to agricultural production, after land (Ullah *et al.* 2019). An imbalance between the available water and water demand leads to water scarcity. This is currently regarded as one of the most urgent threats globally, and on average, around 70% of freshwater resources are used for agricultural production (Sidhu *et al.* 2021).

Crop water requirement (CWR) is defined as the quantity of water required to meet the evapotranspiration (ETc) demand of a disease-free crop growing under ideal conditions (Pereira and Alves 2005). Crop evapotranspiration (ETc) is the evapotranspiration, expressed as mm day^{-1}, of a crop as affected by its growing stage, the environmental factors, as well as crop management, to maximise the crop yield (Pereira and Alves 2005). The CWR is calculated as the total ETc over the crop's full growing season (Pereira and Alves 2005).

For irrigated crops, the CWR is supplemented by irrigation water requirement (IWR), which represents the fraction of the CWR that is not met through rainfall (Pereira and Alves 2005). The amount of irrigation required is therefore affected by the soil, climate, and crop characteristics and management. The soil properties, affect the amount of water that can be held by the soil profile, therefore determining the water available to the plant. The climate, crop characteristics, and crop management determines the ETc (Niederwieser and Barnard 2018). The water, and irrigation, requirement for potato crops (*Solanum tuberosum*) will therefore vary widely between regions, growing seasons, and different management practices.

Potatoes are shallow rooted crops that is very sensitive to drought stress due to their inefficient uptake of soil water (Djaman *et al.* 2021). The crop needs frequent irrigation to avoid tuber and yield reductions (Lutaladio *et al.* 2009). Even very short periods of only moderate water stress can have detrimental effects on the growth of the crop. In most soils, water stress of potato crops will commence when 35-40% of the plant available water have been depleted, as reported by Steyn and Du Plessis (2012), and a depletion of more than 50% plant available water should be avoided (Singh 1969). Water stress especially has a significant effect on the yield and yield parameters during the tuber initiation and bulking stages (Onder *et al.* 2005; Djaman *et al.* 2021). A study conducted by Wagg *et al.* (2021) however, shows that the vegetative growth stage (period between emergence and tuber initiation) and tuber initiation stages were the most sensitive to water stress. Stress at the tuber initiation stage not only affects the growth of the foliage and plant but also reduces the number of stolons, which in turn results in fewer tubers, ultimately impacting the yield (Obidiegwu *et al.* 2015). Stress at the tuber bulking stage limits plant and tuber development, reduces the size of the tubers due to a reduced photosynthesis rate, may cause malformed tubers and increases leaf senescence (Obidiegwu *et al.* 2015; Aliche *et al.* 2018).

2.2. Water use efficiency of potato production

Improving water use efficiencies (WUE) or improving the productivity of agricultural water use is a crucial response to the increase in global water scarcities. This is especially of importance where water shortages are already a production limitation (Waraich *et al.* 2011; Falkenmark 2013; Sharma *et al.* 2015), such as in the Sandveld production region. The effects of climate change, along with the increased need for food, fuel, fibre and feed, raises the urgency with which the WUE need to improve, as well as the urgency to understand the factors affecting it (Hatfield 2015; Sharma *et al.* 2015).

Various definitions of WUE have been used, dependent on the discipline and reason for use. Concepts of efficiency are a measure of the outputs compared to the inputs (Hillel 2003). Agronomists define WUE as the economic yield produced per quantity of water applied, or alternatively per the amount of evapotranspiration measured (Ullah *et al.* 2019).

Although the potato is one of the highest yielding crops per hectare, and is a very effective water user, yielding more tonnes of produce per mm of water used than other major crops (Vos and Haverkort 2007; Lutaladio *et al.* 2009; Liu *et al.* 2021; Zhai *et al.* 2021), inefficiencies still exist. Tang *et al.* (2021) found that the amounts of water and nutrients applied for potato production in Northern China, were higher than the amounts necessary to maximise WUE, and reducing these inputs can increase incomes by 9.6%. In Argentina, a study showed that the large water footprint (323.99 $m^3\ t^{-1}$) and the misuse of groundwater led to a lack of sustainable potato production. This had a negative effect on the hydrological system, and increasing water- and nutrient efficiencies was proposed to combat this problem (Rodriguez *et al.* 2015).

In South Africa, differences in WUE were not only observed among the different potato production regions, but variability also exists between the farms within the same region. The similarity in production conditions within regions, indicates that opportunities exist for individual farmers to improve their efficiencies (Steyn *et al.* 2016).

More efficient use of resources is not only more environmentally friendly, but also leads to various social and economic benefits. The most notable benefit on farm level probably being the reduction in cultivation costs and a decrease in energy used for water withdrawals and -applications (Sharma *et al.* 2015). Increased efficiencies will stabilize crop production over a broad range of climates and improve agricultural abilities to provide the necessary food with the available water (Hatfield 2015; Sharma *et al.* 2015).

Improving water use efficiencies in potato systems

From an agronomists' perspective, WUE can be improved by either improving the irrigation system and management practices, the agronomic management practices, and the soil management practices (Ullah *et al.* 2019). These management practices include the improvement of the efficiency of irrigation systems, and irrigation management (Waraich *et al.* 2011; Knight *et al.* 2012), the modification of soil surfaces and crop residue management (Hatfield 2015), and improving the water holding capacity of the soil.

The method of irrigation influences the WUE of potato production (Djaman *et al.* 2021). Onder *et al.* (2005) found that WUE improved when surface drip irrigation was used compared to subsurface drip in Turkey. Alternate furrow irrigation improved WUE by 49% compared to conventional furrow in Ethiopia, without significantly affecting the tuber yield and quality (Kassaye *et al.* 2020). An improvement in WUE under drip irrigation compared to furrow irrigation was also observed by Ati *et al.* (2012) in Iraq. Furthermore, in Ethiopia, alternate deficit irrigation (water applied to alternate furrows) which applied only 75% of the ETc produced similar results to a 100% ETc irrigation level. This study concluded that alternate furrow irrigation at a 25% irrigation deficit improved WUE and economic benefit without reducing yield and quality (Kassaye *et al.* 2020).

Although drip irrigation methods also showed a reduction in usage of water compared to sprinkle irrigation in Northern China, the large-scale adaption of this irrigation method is challenging. This is due to the high costs associated with instalment and maintenance, as well as the current lack of knowledge and experienced regarding the operation thereof in the region. Similar adaption problems may exist in other parts of the world as well (Blom-Zandstra and Michielsen 2020).

The irrigation interval can also affect the WUE, as seen by Karim *et al.* (2019), where the highest WUE obtained was from a 5 day irrigation interval, whilst the highest irrigation water use efficiency (IWUE) obtained was from a 10 day irrigation interval. Irrigation intervals, however, is affected by the soil and the capacity thereof to retain water. Soils with higher soil water holding capacities, and management practices reducing ETc, should therefore be able to support the respective crop with less frequent irrigation events. The irrigation scheduling should be optimised to ensure an irrigation frequency that balances the soil moisture and oxygen conditions, and that maintains a high enough soil matric potential to avoid stress on the crop, thereby increasing crop growth and maximising yield (Zhang *et al.* 2019).

Fertigation, via drip irrigation, improved WUE in Mongolia by 1.4 - 2.0 times without yield reductions, when compared to conventional furrow irrigation methods (Jia *et al.* 2018). The nutrient status of the soil affects the WUE, as the amount of nutrients and water in the soil-plant environment are highly dependent on each other. Better plant nutrient maximises the plant’s ability to utilize the available water (Waraich *et al.* 2011; Ullah *et al.* 2019).

2.3. Relationship between soil water content, nutrient uptake, WUE and NUE

The availability of water and soil nutrients, and therefore irrigation and fertilization, is very important for potato production, especially in arid and semi-arid regions (Badr *et al.* 2012). Water taken up by plant roots is a vital process for plant growth and the transport of essential nutrients in the soil-plant system (Wu *et al.* 1999). Soil water deficits affect the availability of various nutrients in the soil solution, therefore affecting the nutrient uptake of plants, as well as the effectiveness by which it does so (Ierna *et al.* 2011; Ullah *et al.* 2019).

Plants often suffer from nutrient deficiencies and a reduction in photosynthetic assimilation rate under water stress. This affects normal growth and limits yields in agricultural systems (Ullah *et al.* 2019). Several studies have shown that potato yields and yield components are affected by not only irrigation and fertiliser levels, but also the interaction thereof (Ierna *et al.* 2011; Badr *et al.* 2012; Zhang *et al.* 2018; Zhou *et al.* 2018; Milroy *et al.* 2019; Wang *et al.* 2020; Tang *et al.* 2021).

Tuber yields are generally more sensitive to irrigation changes than fertilisation rates. Yields increase with an increase in irrigation rates (Ierna *et al.* 2011; Badr *et al.* 2012; Xing *et al.* 2022). Wang *et al.* (2020) found contradicting results where tuber weights, and yields, increased until irrigation amounts of 80% of the ETc, but it then decreased at the full irrigation level. This is likely due to the different evaporation losses resulting from different irrigation techniques across the different studies. Yields further increased with an increase of fertilisation under full irrigation (100% ETc) (Badr *et al.* 2012). However, under deficit irrigation at 80% and 60% ETc, Xing *et al.* (2022) found that the yields first increased, but then decreased with an increase in nitrogen fertiliser. Potato plants grown under deficit irrigation had lower nitrogen uptake, probably due to the lack of available nitrogen in the soil solution. Maximum nitrogen uptake occurred at full irrigation, and increasing the N rate from 160 to 340 kg/ha resulted in a 45.5% yield increase (Badr *et al.* 2012). The same trend in uptake was seen by Zhang *et al.* (2022) for potassium fertiliser, and increasing the soil water content increased the effect of K on the plant. This is due to the increased uptake of K at higher soil moisture levels. The limitations of nutrient uptake under deficit irrigation levels therefore also reduces fertiliser use efficiencies (Wang *et al.* 2021a).

In practice, it is very difficult to maximise yields, quality- and efficiency parameters at the same time. For example, Badr *et al.* (2012) reported that nitrogen use efficiency (NUE) was the highest in full irrigation and the lowest for the lowermost irrigation level, whereas water use efficiency increased with a decrease in irrigation amount. The optimal production parameters will therefore be different for different production goals (Tang *et al.* 2021). These interactions are very complex, and an irrigation and fertilisation level should be determined that provides the most optimal results regarding the tuber yield, quality, and resource use efficiencies whilst still economically viable.

2.4. Groundwater contamination

The use of groundwater has risen over the past half-decade, contributing to increased food production, and improved livelihoods for many communities across different climatic conditions and areas globally (Giordano and Villholth 2007). However, groundwater contamination is a concern globally, and approaches are needed to mitigate different groundwater problems (Li *et al.* 2021).

A study conducted by Sánchez Pérez *et al.* (2003) showed that amount of nitrate leached from cultivated fields are five times more than those of uncultivated fields under the same conditions. This can be explained by the usage of fertilisers in the cultivated fields. Elevated nitrate concentrations in surface- and groundwater has often been linked to extensive potato production (Liang *et al.* 2019). In Mongolia, the nitrate level in the groundwater near potato production is higher than the threshold for drinking water (20 ppm) in China (Jia *et al.* 2018). Sánchez Pérez *et al.* (2003) conducted a study that showed that 87% of the nitrate applied leached and ended up in groundwater in Spain. Significant nutrient leaching under potato production have also been documented across various other regions and cropping systems (Davenport *et al.* 2005; Oppeltová *et al.* 2021; Wang *et al.* 2021b).

In their review of 30 African countries, Xu and Usher (2006) found that agricultural chemicals are among the major sources of groundwater pollution on the continent. The inorganic compounds of nitrogen are of particular concern, and they have listed it as the most important environmental pollutant. Once groundwater is polluted, it is very difficult, if not near impossible, to rectify.

The method of irrigation affects the amount of nutrients lost in a system, due to the differences in soil water content and soil water movement resulting from the different methods. This was seen in the study by Yu *et al.* (2022), that showed that furrow irrigation, compared to drip irrigation, increased nitrogen losses, including leached nitrogen. Many times, nutrients leached can be reduced by a reduction in percolation (Bohman *et al.* 2020). This has also been shown by Wallis *et al.* (2011), whom showed that additional applied irrigation water had a very big influence on the amount of nutrients leached beyond the rooting zone, and can increase the nutrient load on the underground water source.

The low water holding capacity, high permeability and shallow water table of the sandy soils in the Sandveld poses a high risk of groundwater pollution (Knight *et al.* 2012; Steyn *et al.* 2016). This statement is supported by the results of a study conducted by Levallois *et al.* (1998), which showed that intensive potato production on sandy soils, in Québec City, Canada, have the potential to have serious impacts on the groundwater quality. Strategies to improve soil water holding capacity, and reduce drainage and leaching, will therefore be beneficial for production on sandy soils.

2.5. Superabsorbent polymers in agriculture

Definition and classification of superabsorbent polymers

A superabsorbent polymer (SAP) consists of cross-linked polymeric chains, capable of absorbing and retaining great amounts of an aqueous solution whilst maintaining their structure. The functional groups on the backbone of the polymeric chains are of hydrophilic nature and are therefore responsible for the polymer's ability to absorb water (Ahmed 2015; Chang *et al.* 2021). SAPs are also commonly called hydrogels, due to their gel-like appearance when saturated with water.

Superabsorbent polymers can be classified according to various characteristics. These include their source and degradability, structures, responsiveness to external stimuli, size, and function (Chen 2020). The most basic classification of SAPs is their source – being from natural or synthetic origin.

Natural SAPs are either polysaccharide based (such as starch, alginate, agarose, cellulose, chitosan, dextran, etc.), or polypeptide based (such as gelatine and collagen) (Behera and Mahanwar 2020; Chen 2020). These natural sources are abundant and highly biocompatible and easily biodegradable, making them environmentally friendly. Synthetic polymers, which don't degrade as rapidly as natural polymers, are petrochemical based and are synthesised using, *inter alia*, polyacrylic acid and its derivatives, polyvinyl alcohol, and polyethylene glycol (Behera and Mahanwar 2020; Chen 2020).

Properties and uses of superabsorbent polymers

SAPs have an extensive amount of uses, across a broad range of disciplines (Ismail *et al.* 2013; Behera and Mahanwar 2020). For the current study, the application in agriculture will be the focus.

Various studies showed that the application of SAPs increased the water content and water holding capacity of soils (Koupai *et al.* 2008; Yu *et al.* 2017; Hou *et al.* 2018; Thombare *et al.* 2018; Smagin *et al.* 2019). A reduction in the water leached pass the rooting zone was also observed due to this increase of water holding capacity of the soil. The reduction in leached nutrients and water results in an increased availability thereof to the plant, thereby having a positive effect on resource use efficiencies (Egrinya Eneji *et al.* 2013). The benefits that these properties offer, coupled with the importance of water in an agricultural environment, has resulted in an increased interest in SAPs.

Increased water content and/or production parameters associated with SAPs applied were especially significant for soils with a lower clay content, and a naturally low water holding capacity. Koupai et al. (2008) further noted that the application of SAPs extended the period of the soil to reach permanent wilting point by increasing the available plant water, and possibly also due to the reduction of evapotranspiration (Johnson 1984; Yu *et al.* 2017; Hou *et al.* 2018). The repeated absorption of water alters the drying stages of a soil (Adjuik *et al.* 2022). This results in the reduction of saturated hydraulic conductivity and diffusivity in soils amended with SAPs, thereby retaining the water in the application layer for a longer period (Bhardwaj *et al.* 2007; Dabhi *et al.* 2013; Adjuik *et al.* 2022).

SAPs have the ability to decrease the bulk density, and increase the porosity of sandy loam soils Hou *et al.* (2018) and Thombare *et al.* (2018), although this is not always the case (Xu *et al.* 2015). The polymer can therefore be used as a soil conditioner, rectifying soils with these problems.

Biodegradable starch-based biopolymers can be used to encapsulate fertiliser, creating a slow-release nutrient source or fertiliser, which improves the effectiveness of the fertiliser (Qiao *et al.* 2016; Pushpamalar *et al.* 2018; Sarkar *et al.* 2021). Similarly, these polymers can also be used for the controlled release of pesticides by minimising their volatilisation, degradation, and leaching, thereby ensuring their target is reached successfully. This can significantly reduce environmental pollution associated with the use of pesticides (Ismail *et al.* 2014).

Despite not pertaining to potatoes, the use of these polymers is also beneficial for crop establishments, as it can have a positive effect on the germination of seeds, and can increase seedling survival (El-Asmar *et al.* 2017; Abrisham *et al.* 2018; Ai *et al.* 2021).

Production limitations of superabsorbent polymers

The uses of SAPs discussed above, clearly shows how these polymers can benefit agricultural production systems, not only to increase the water holding capacity, and related processes of soils, but also as a fertiliser management tool and a soil conditioner. There are, however, production limitations.

The amount of SAP applied have a strong influence on the ability thereof to improve soil properties. The correct dose is therefore important to maximise the benefits (Yang *et al.* 2020). The amount of polymer applied in experimental studies, differs widely in the literature. The inability to predict a standard rate is due to the variation between different soil types and texture and the effect it has on the soil-polymer interaction. The optimal dose of SAP therefore needs to be determined according to the soil texture, the water availability, the frequency of the water application, the method of polymer application, and the abilities of the polymer (Ostrand *et al.* 2020). The current lack of large, field scale experiments and long-term trials on the effects of superabsorbent polymers on crop production, contributes to the absence of knowledge in this regard.

Synthetic polymers have better mechanical strength than natural polymers, which results in better durability. This often makes the synthetic polymers the more popular choice for use (Behera and Mahanwar 2020). These synthetic polymers are also easy to produce, and can easily be modified to exhibit certain properties, but they have poor biocompatibility and biodegradation compared to their natural alternatives (Behera and Mahanwar 2020; Chen 2020). The lack of biodegradability of synthetic polymers is a serious concern as it may become an environmental contaminant by building up in the soil (Thombare *et al.* 2018). Synthetic polymers are often petrochemically-based, making their production environmentally unfriendly due to the use of non-renewable resources (Gamage *et al.* 2022).

Starch-based water retention polymers have a strong affinity for water and has great degradation abilities, which make them environmentally friendly. However, compared to other water retention polymers, they are weak in water absorbance, they have a lower mechanical stability, and a lower tolerance to saline solutions. Larger volumes of these natural polymers are therefore needed to improve production (Chang *et al.* 2021). Bai *et al.* (2013) found that the absorption potential decreased under repeated cycles of drying and wetting, such as is found in cropping systems. This suggests that the polymer might lose its efficiency as the season progresses.

It is also widely seen in literature that almost all the SAPs have a lower absorbency when exposed to a saline solutions, compared to distilled water (Johnson 1984; Bai *et al.* 2013; Banedjschafie and Durner 2015). It is expected that the SAPs will have a decreased efficiency due to the quality of irrigation water, particularly when fertigation is used. Dissolved salts in irrigation return flows are the main anthropogenic source causing salinity in the Western Cape (DEA & DP_*et al.* 2011). This reduced efficiency will further be exacerbated in systems where heavy doses of fertiliser is relied on to sustain production, as is the case for potato production in the Sandveld region.

The starch-based superabsorbent biopolymer Zeba™

Zeba™ [starch-g-poly (2-propenamide-co-propenoic acid) potassium salt] is an ionic starch graft copolymer (Frazier 2006). It is manufactured using corn-starch and is a SAP that saturates with, and retains water (Leinauer *et al.* 2010). This polymer is non-toxic, biodegradable and has a neutral pH due to its natural composition.

Zeba™ has been used as a seed coating to promote germination and survival of turfgrass species (Leinauer *et al.* 2010; Serena *et al.* 2012). These studies indicated that the seed coating could potentially improve establishment, at both recommended and reduced seeding rates, and can support establishment in less favourable growing conditions. Zeba™ has also been used as part of a potting mix to increase seedling survival, and plant growth of coconuts (*Cocos nucifera* L.) grown in a nursery (Gayashini Kelum Perera 2017). The study concluded that Zeba could be used to obtain optimal moisture levels for coconut seedlings and be used to promote maximum growth. Zeba™ application also promoted seedling emergence of cotton (Gossypium hirsutum L.) (Papastylianou and Kousta 2020).

Zeba™ has also been used as an adjuvant in entomopathogenic nematode (EPN) formulations to control various pest insects on several crops (de Waal *et al.* 2013; Van Niekerk and Malan 2014; Platt *et al.* 2018). The SAP is added to the EPN formulation as a water retention agent, which creates a water film that delays dehydration and increases the EPN’s survival on the leaf surface (Van Niekerk and Malan 2014).

Nissi *et al.* (2021) stated that the application of Zeba™ to the soil had a favourable influence on sweet oranges (*Citrus sinensis* L.) due to the water retention ability of the polymer, and the use thereof will be useful for plant survival in drought prone areas. Similarly, Rasanjali *et al.* (2019) indicated that the use of Zeba™ can reduce water stress conditions of black pepper (*Piper nigrum* L.), and can be used as part of standard greenhouse management.

The majority of the published papers focussed on the synthesis, properties, and potential of the corn-starch-based SAP, rather than the application thereof (Zhang *et al.* 2006; Liu *et al.* 2017; Xiao *et al.* 2017; Qamruzzaman *et al.* 2022). There are limited published studies on the effect of Zeba™ on the growth and yield of major crops. There are, however, some published studies on the effects of other corn-starch, or starch-based SAPs. Improved plant growth and yield parameters of tomato crops, grown in pots and amended with a corn-starch SAP, have been documented (Kathi *et al.* 2021). Nnadi and Brave (2011) tested the use of starch-based SAP as a water retention agent and concluded that the SAP successfully supported plant growth during water stress conditions and can be used as an environmentally alternative to petroleum-based SAPs.

It is often difficult to directly relate pot trials to field application. There are a lack of field trials studying the potential of natural SAP, and more of these studies will be beneficial in determining the capability of these products to improve or support crop production.

2.6. Synthesis

Water is a major limiting factor to agricultural production and is becoming increasingly scarce locally and globally. Water is an integral component in crop production and plants require large amounts thereof. Water is needed for photosynthesis, respiration, cellular processes, and nutrient uptake, all important for plant growth. Improving water and nutrient management and the efficient use of these resources in any crop production is extremely important, especially to ensure the sustainability of the specific sector.

Potatoes are very sensitive to water stress due to the crop's shallow rooting depth. Potato production is limited by the availability of water and even short periods of drought stress can lead to severe yield and quality reductions. Potatoes in the Sandveld area are typically produced under centre-pivot irrigation. The low rainfall, low water holding capacity of the soils, and the nutrient poor sandy soils, result in the need for high volume groundwater abstraction and irrigation, and the application of large amounts of fertilisers to sustain production (Archer *et al.* 2009).

Further, the low water holding capacity of the sandy soils in the Sandveld is of concern due to the high possibility of resource losses associated with it. The loss of water and nutrients lead to reduced efficiencies in these systems. The Sandveld is an ecologically sensitive area, and the impact of these losses on the environment threatens the indigenous biodiversity. Strategies to combat these issues are important to ensure sustainable potato production in the Sandveld.

Superabsorbent polymers have been shown to improve water and nutrient retention in sandy soils. These polymers can have significant positive effects on the growth of crops, especially in drought prone areas and areas with sandy soils. These effects can more often than not, be attributed to the increased water holding capacity of the soils amended with the SAP, which then also allows for more soluble nutrients to be held in the soil profile. Superabsorbent polymers could also reduce the amount of leaching through the soil profile, although this has not extensively been studied in field trials.

There is currently limited research on the use of superabsorbent polymers in Africa/Sub-Saharan Africa. Furthermore, there is limited literature, specifically on the effect of the SAP Zeba™ on crop production, especially for important vegetable crops. The rate of biodegradation, and the period of positive influence of Zeba™ on production is currently unknown. This study aimed to answer some of the gaps in knowledge on the physiological responses of potato to Zeba™, the reaction of Zeba™ in soil, and to use the information gained to recommend the use of Zeba™ for potato production in the Sandveld, and other areas with similar production limitations.

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Chapter 3: The use of a starch-based superabsorbent polymer to optimise potato production in the Sandveld production region of South Africa

3.1. Introduction

The Sandveld region, situated in the Western Cape Province, is an important potato production region in South Africa. The Sandveld produces 13% of South Africa's total potato crop and 14% of the processing potatoes (Brink *et al.* 2018). Potato production, followed by rooibos tea production, are the two main economic activities in this area. Farming in the Sandveld takes place in an ecologically fragile area with a remarkable variety of flora and critically endangered species, which are threatened by habitat loss due to cultivation (Niederwieser and Barnard 2018). Agricultural production in conjunction with biodiversity conservation should therefore be prioritised to ensure economic, social, and environmental sustainability of this area.

The Sandveld area experiences very little rain (ca. 220 - 320 mm per annum), and the evaporative demand vastly exceeds the precipitation. The low rainfall, coupled with nutrient-poor, deep sandy soils with low water retention capacities, result in the need for high volume groundwater abstraction and the application of fertilisers, in order to sustain crop production (Archer *et al.* 2009).

One of the challenges that the farmers in this region are facing, is to ensure that the sandy soil reservoir can supply enough water for the crop's demand without losing too much water and nutrients to leaching (Niederwieser and Barnard 2018). Potato crops have a poorly developed rooting system that can only extract a small portion of the already low plant-available water in sandy soils. The crop is also sensitive to drought stress - even a short period of stress will reduce crop yield and quality (Steyn and Du Plessis 2012; Aliche *et al.* 2018; Djaman *et al.* 2021). Therefore, frequent irrigation is common. The loss of water beyond the root zone, and consequently also the loss of soluble nutrients, reduces the efficiency of production and poses a risk to the environment through groundwater pollution.

The superabsorbent biopolymer (SAP), Zeba™, is a starch-based granular soil amendment that can absorb and retain a large amount of water (Vizitiu *et al.* 2014). Hypothetically, this product has the potential to increase the water holding capacity of sandy soils and could therefore reduce leaching losses. The increased water holding capacity of the soils might improve the uptake of water and nutrients by plants, and thereby improve potato production efficiency and yields. There is a lack of field-scale experiments to assess the effect of SAPs, including Zeba™, on crop production.

According to literature, the texture of the soil has a big influence on the potential of polymers to improve growth conditions. The improvement of plant available water content, for soils amended with the maximum SAP concentration of the trial versus the control, varied from 3.3 to 1.2 times for coarse to fine textured soils, respectively (Saha *et al.* 2020a). Similarly, Abedi-Koupai *et al.* (2008) found a 3.2 times increase in available soil water content for sandy loam soils, compared to the 2.2 times increase for loamy soils and the 1.8 times increase for clay soils. This observation is due to the small pore space of fine textured soils, which does not allow the polymer to swell to its maximum capacity, thereby limiting maximum absorption (Saha *et al.* 2020a).

Due to the variation in results found between different soil textures, it is difficult to predict a standard application rate which can be applied broadly over a range of cropping systems (Ostrand *et al.* 2020). It is important to determine optimal application rates of Zeba™ for sandy soils in the Sandveld region, as this will ensure the best results following SAP amendment. This field experiment aimed to assess the effect of Zeba™ on the growth, yield and quality of potatoes in the Sandveld region.

3.2. Methods and Materials

3.2.1 Site description

A field experiment was conducted in the Sandveld region, in the Western Cape province of South Africa, on a farm near the town Aurora (32°38’03.1”S 18°28’22.3”E) (Figure 3.1). This area has a typical Mediterranean climate, with hot and dry summer, and mild, wet winters (Archer *et al.* 2009). The average annual precipitation in the area ranges between 224 and 312 mm, with annual evaporative demands between 1200 to 1600 mm (Potatoes South Africa 2019). The weather data from the nearby weather station, Rietfontein, was also evaluated.

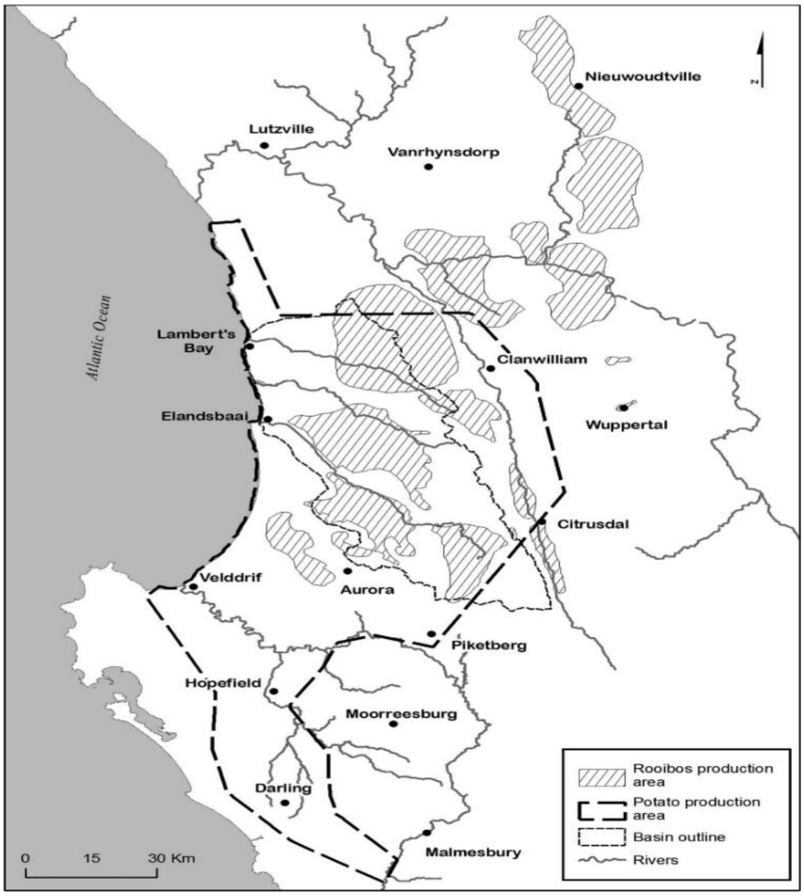

Figure 3.1 Production areas for the main agricultural activities in the Sandveld (Archer et al. 2009).

3.2.2 Experimental design and treatments

The field experiment was laid out in a randomised complete block design (RCBD) with four Zeba™ (UPL, Mount Edgecombe, South Africa) treatment rates. Each treatment was replicated six times, i.e., 30 experimental units. The four Zeba™ treatment rates were T0 = control, T1 = 5, T2 = 7.5, T3 = 10 and T4 = 15 kg ha^{-1} of product. Each treatment plot consisted of four potato rows, which was 0.75 m apart, and 24 m in length. This resulted in a plot area of 72 m^2 (0.75 m x 4 rows x 24 m). The processing potato cultivar FL2108 was used as it is a common cultivar produced in the region. This cultivar typically has a growth season length of 120 days.

The trial was planted on the 30 September 2020. Zeba™ was applied in the planting furrows using a specialised battery-operated applicator that was mounted onto a four-row potato planter (Figure 3.2). The designated Zeba™ rate was applied to two of the four rows, resulting in the adjacent rows remaining untreated, and acting as the control.

Figure 3.2 The planter with the applicator, indicated by the orange block (left), and the Zeba™ being applied in the planting furrow along with the tubers (right).

3.2.3 Trial management

The trial was irrigated and planted under a centre-pivot irrigation system. Irrigation was applied daily, except in the instances when enough rainfall was received, due to the high evaporative demand, coupled with the low water holding capacity of the sandy soil. Figure 3.3 shows the distribution of daily irrigation (Equation 3.1 and 3.2) and rainfall received. The total evapotranspiration over the growth period was calculated from canopy cover and measured weather data.

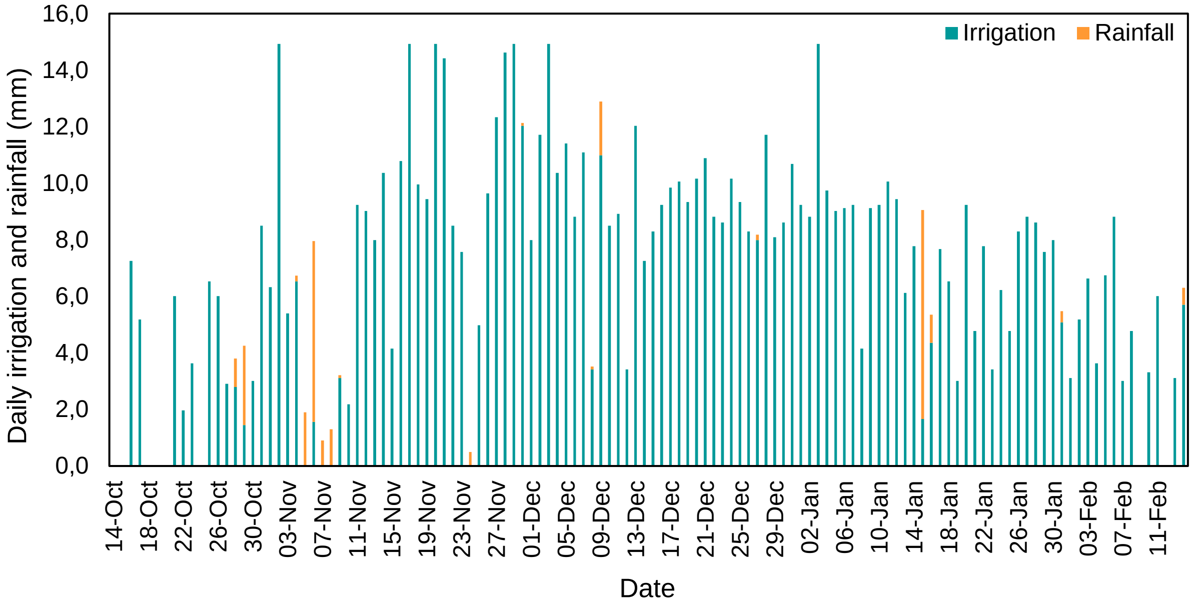

Figure 3.3 The distribution of daily irrigation and rainfall during the growing season.

The trial was managed according to best practices for fertilisation and pest control for potato production in the region. Table 3.1 shows the total amount of macronutrients supplied during the growing season. The nutrients applied prior to planting, the nutrients applied during crop growth (after emergence), as well as the nutrients imported through the irrigation water, are included. Table 3.2 shows the total amount of micronutrients applied prior to planting as well as the micronutrients applied during the crop growth (after emergence). The nutrients applied during the crop growing season was applied through fertigation.

Table 3.1 Total amount of macronutrients applied (kg ha^{-1}) through fertiliser applied pre-plant and during the crop growth, as well as nutrients imported from the irrigation water applied.

Macronutrient	**N**	**P**	**K**	**S**	**Ca**	**Mg**
Fertiliser applied pre-plant	58	156	174	705	932	0
Fertiliser applied during crop growth	260	62	362	0	57	18
Nutrients imported from irrigation water	20	2	9	30	24	99
Total nutrients applied (fertiliser)	318	218	535	705	989	18
Total nutrients applied (fertiliser + irrigation)	338	220	545	735	1013	117

Table 3.2 Total amount of micronutrients applied (g ha^{-1}) during the growing season through fertilisers applied pre-plant and during crop growth.

Micronutrient	**B**	**Cu**	**Fe**	**Mn**	**Mo**	**Zn**
Fertiliser applied pre-plant	104	15	32	62	8	86
Fertiliser applied during crop growth	260	38	80	155	20	215
Total nutrients applied	364	53	112	217	28	301

3.2.4 Equipment installation

The equipment used for monitoring was installed on 13 and 14 October 2020. The disturbance where the equipment was installed, was kept to a minimum, and the areas were restored as best as possible afterwards.

Irrigation monitoring

A flow meter was installed on the primary pipeline entering the pivot system, which continuously logged irrigation volumes. The flow meters could detect when the irrigation was turned on and off and logged the duration of the irrigation event. The running time was calculated from a pressure greater than 80 kPa. This also detected the flow rate, which showed the volume of water that was flowing through the pivot. This information could then be used to provide precise readings of the volume irrigated per irrigation event using Equations 3.1 and 3.2.

$$IWA\ (m^3/ha) = \frac{t\ \times Q}{A}$$

Equation 3.1

$$IWA\ (mm) = \frac{IWA\ (m^3/ha)}{10}$$

Equation 3.2

Where:

IWA refers to the irrigation water applied

T is the time the pivot was running (h)

Q is the flow rate ($m^3\ h^{-1}$)

A is the area under the centre pivot (ha)

Measurement of soil water content and soil water movement

Sensors (Decagon 10HS capacitance sensors with Campbell CR300 dataloggers) were installed to determine the water content of the soil. The 10HS sensors measure the dielectric constant of the soil to determine the volumetric water content (VWC).

A hole, slightly deeper than 50 cm, was dug. The sides of the hole were shaved off to expose the undisturbed soil. One set of the Decagon probes consists of five sensors, which were installed along the sides of the planting ridge at depths of 10, 20, 30, 40 and 50 cm, respectively. The sensors were inserted until the entire sensing portion was implanted into the undisturbed soil. The sensors were placed so that they do not align directly below each other (Figure 3.4). After the sensors were installed, the hole was carefully filled with the soil. The loose wires from the sensors, attached to the datalogger, were tied together, and tied to a wooden pole along with the datalogger. Because of limited available budget, only one replication of the sensors was installed in treatments T0, T2 and T4.

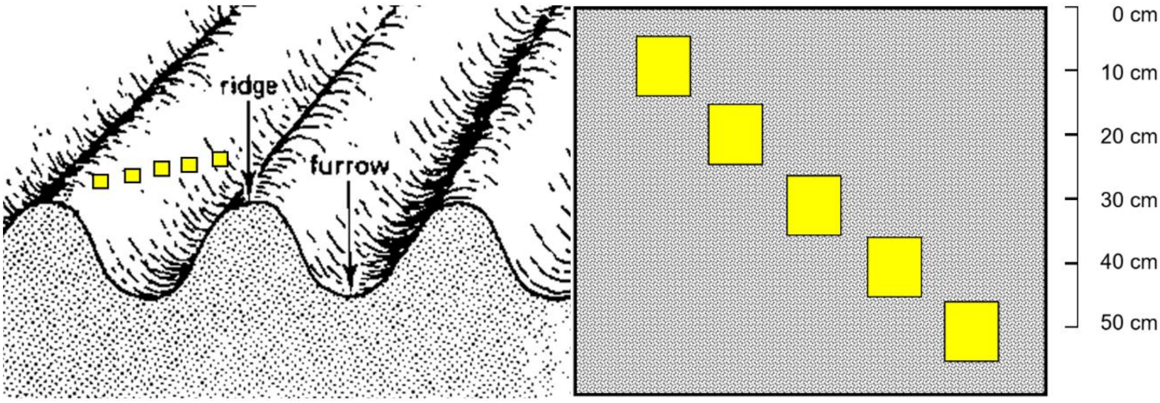

Figure 3.4 A front (left) and sectional view (right) of the placement of the Decagon capacitance sensors in the soil profile.

3.2.5 Pre-harvest sampling and analyses

Water data collected

Irrigation water samples were collected three times during the growing season, on 19 November 2020, the 21 December 2020, and the 27 January 2021. The water was collected from the tap at the pivot centre and kept cool in a refrigerator until it was sent for chemical analysis. The nutrients present was then used to determine the total macronutrients that was imported from the irrigation water, according to Equation 3.3.

$$N_I = \frac{I \times P}{100}$$

Equation 3.3

Where:

N_I refers to the total nutrients applied through irrigation water (kg ha^{-1})

I refers to the total amount of irrigation applied (mm)

P refers to the elemental concentration in the irrigation sample (mg l^{-1})

Data from all the dataloggers installed were downloaded during fortnightly visits to the trial site. The datalogger batteries were tested with each visit, and replaced when the voltage reading was below 12.5 V.

Seasonal growth analysis

Leaf samples were collected twice during the growing period, 80 days after planting (DAP), and then again at the end of the growing season (120 DAP). The youngest mature leaf (third leaf from the top) was collected. Twenty leaves were sampled from each treatment, and across three replicates per treatment. The leaves were kept cool after sampling and as soon as possible thereafter oven dried at 60 °C, whereafter they were stored in paper bags until chemical analyses to determine the nutrient contents.

3.2.6 Post-harvest sampling and analyses

Tuber yield determination

Six replicates of 10-m strips per plot were harvested on 2 March 2021. Each plot was harvested separately. The tubers were sorted and graded directly after harvest to determine the total tuber yield, marketable tuber yield and the tuber size distribution per treatment.

After weighing and sorting, 20 medium sized tubers were randomly selected from each treatment and replicate, labelled accordingly, and kept in brown paper bags for further analyses.

Chip frying colour

Ten of the twenty medium sized tubers that were selected at harvest were used for determining the chip frying colour, according to the standard Simba frying method. The tubers were first rinsed to remove all surface dirt, and then peeled and cut into 2 mm thick slices. The slices were then rinsed with water and patted dry with paper towels. From each sample, ±300 g of randomly selected tuber slices, were used. The palm oil was heated to a temperature of 177 °C before the chip slices were immersed in the oil for frying. During the first minute, the crisps were continuously shaken to prevent them from sticking together. Thereafter, a sieve was placed over the crisps to keep them submerged in the oil, and they were fried for another two minutes (total frying time of three minutes). The crisps were then removed from the oil and placed aside to cool down. Once cooled down, each sample was placed into a clear plastic bag, labelled, and kept for frying colour analysis. The chip colours were then determined using a calibrated Hunter Lab optical colorimeter.

Specific gravity determination

The remaining 10 medium sized tubers sampled from each treatment plot were used to determine the tuber specific gravity (SG). Before the analyses commenced, the potatoes were washed with water to remove the surface dirt. The potatoes were then weighed in air and then in water (Figure 3.5).

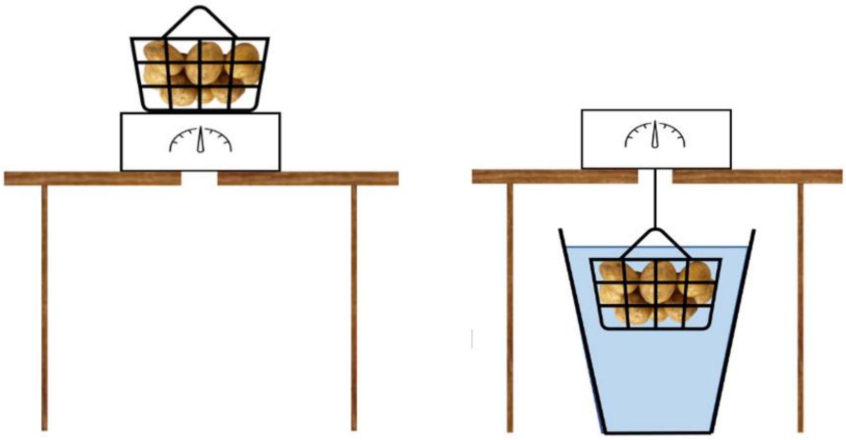

Figure 3.5 Weighing of the tubers in air (left) and in water (right) in order to determine the specific gravity of the tubers.

A scale, equipped with a below balance attachment, and accurate to 0.1 g, was used to weigh the tubers. The scale was placed on the table so that it was level and sturdy. A plastic container filled with room temperature water, was placed under the table. A steel mesh basket, attached to the scale by steel wire protruding through a hole in the table surface, was used for the measurements to avoid the absorption of water by the equipment.

The SG was calculated using the mass in air - mass in water method, according to Equation 3.4 (Kleinkopf *et al*. 1987):

$$Specific\ gravity\ (SG) = \frac{Mass\ in\ air}{(Mass\ in\ air) - (Mass\ in\ water)}$$

Equation 3.4

Tuber dry matter and chemical composition determination

The same 10 tubers used for the SG analysis, were then rinsed with distilled water, and left to dry. The tubers were cut in half, along the length of the tuber. The ten halves from each treatment and replicate were then placed into clean paper bags and weighed immediately to determine the wet mass. After the tubers were weighed, they were cut into smaller pieces of roughly 2 x 2 cm and placed into new paper bags. The tuber samples were then placed in an oven and allowed to dry at 60 °C for 72 – 96 hours, until a constant dry mass was achieved. The paper bags were spread out whilst in the ovens and shaken daily to facilitate faster drying and to avoid rotting of the tuber pieces. The tuber pieces were then removed from the oven and weighed to determine the dry mass.

The percentage dry matter (% DM) was calculated according to Equation 3.5:

$$Tuber\ dry\ matter\ content\ \% = \frac{dry\ mass\ (g)}{wet\ mass\ (g)} \times 100\%$$

Equation 3.5

The dried tuber samples were then stored in a cool place and later sent to a laboratory for chemical analysis to determine the chemical composition of the tubers.

Resource use efficiencies

Water use efficiency (WUE) was calculated for this trial. This is used to indicate the effectiveness of the system to produce biomass with the water applied through irrigation (I) and/or rainfall (r). WUE is generally reported as the crop yield divided by the water used, or by evapotranspiration (ET), according to Equation 3.6 (Ullah *et al.* 2019).

$$WUE_{(I,\ I+r,\ ET)} = \frac{Yield\ (kg)}{I,\ I+r,\ ET\ (mm)}$$

Equation 3.6

Nutrient use efficiency, similarly, can be determined by the ratio of the product produced per unit of nutrient input. Nutrient use efficiency in field trials is often calculated as the yield obtained divided by the amount of nutrient applied, according to Equation 3.7 (Ullah *et al.* 2019).

$$Nutrient\ use\ efficiency = \frac{Yield\ (kg\ ha^{-1})}{Nutrient\ applied\ through\ fertilizer\ and\ water\ (kg\ ha^{-1})}$$

Equation 3.7

3.2.7 Statistical analyses

Statistical analysis was performed with R studio, version 1.4.1106. Descriptive statistics was performed as well as an analysis of variance (ANOVA). Multiple comparison tests by means of least significant difference was performed. Normality was tested for by the Shapiro-Wilk test, and homoscedasticity by means of the Bartlett Test. A 0.05 level of significance was used for all statistical tests.

3.3. Results

3.3.1 Weather station data

The weather data from the local weather station, Rietfontein, is summarised in Table 3.3. The average maximum air temperature over the trial period is 30.0 °C, and the minimum 13.0 °C. The average maximum relative humidity was 85.3 %, and the minimum 26.4 %. The average daily evapotranspiration (ETo) was 6.5 mm and the total rainfall 28.8 mm.

Table 3.3 Monthly averages of weather parameters obtained from the on-site weather station, Rietfontein, for the trial period (October 2020 – March 2021).

	October	**November**	**December**	**January**	**February**
Maximum air temperature (°C)	26.6	27.7	30.4	32.7	32.7
Minimum air temperature (°C)	9.6	11.9	13.8	15.3	14.5
Maximum relative humidity (%)	87.2	85.5	86.3	84	83.7
Minimum relative humidity (%)	27	29.4	27.3	26	22.4
Daily ETo (mm)	5.4	5.9	6.9	7.5	7.0
Total rainfall (mm)	6.4	11.4	2.2	8.8	0.0

3.3.2 Soil water content

The water contents for the 0 – 300 mm (Figure 3.6a) and the 300 – 600 mm (Figure 3.6b) soil layers are shown for the control (T0), and for T2 and T4 treatments, respectively. It is evident from these figures that the soil water content increased with the addition of Zeba™ to the soil. The most water was held in the soil that was amended with the highest rate of Zeba™ (T4), and this is observed in both soil layers. More water was held in the top 300 mm layer than in the 300 – 600 mm soil layer. The differences in soil water content, however, between the control and treatments were more pronounced in the deeper layer, and an even clearer positive influence of the addition of Zeba™ is observed.

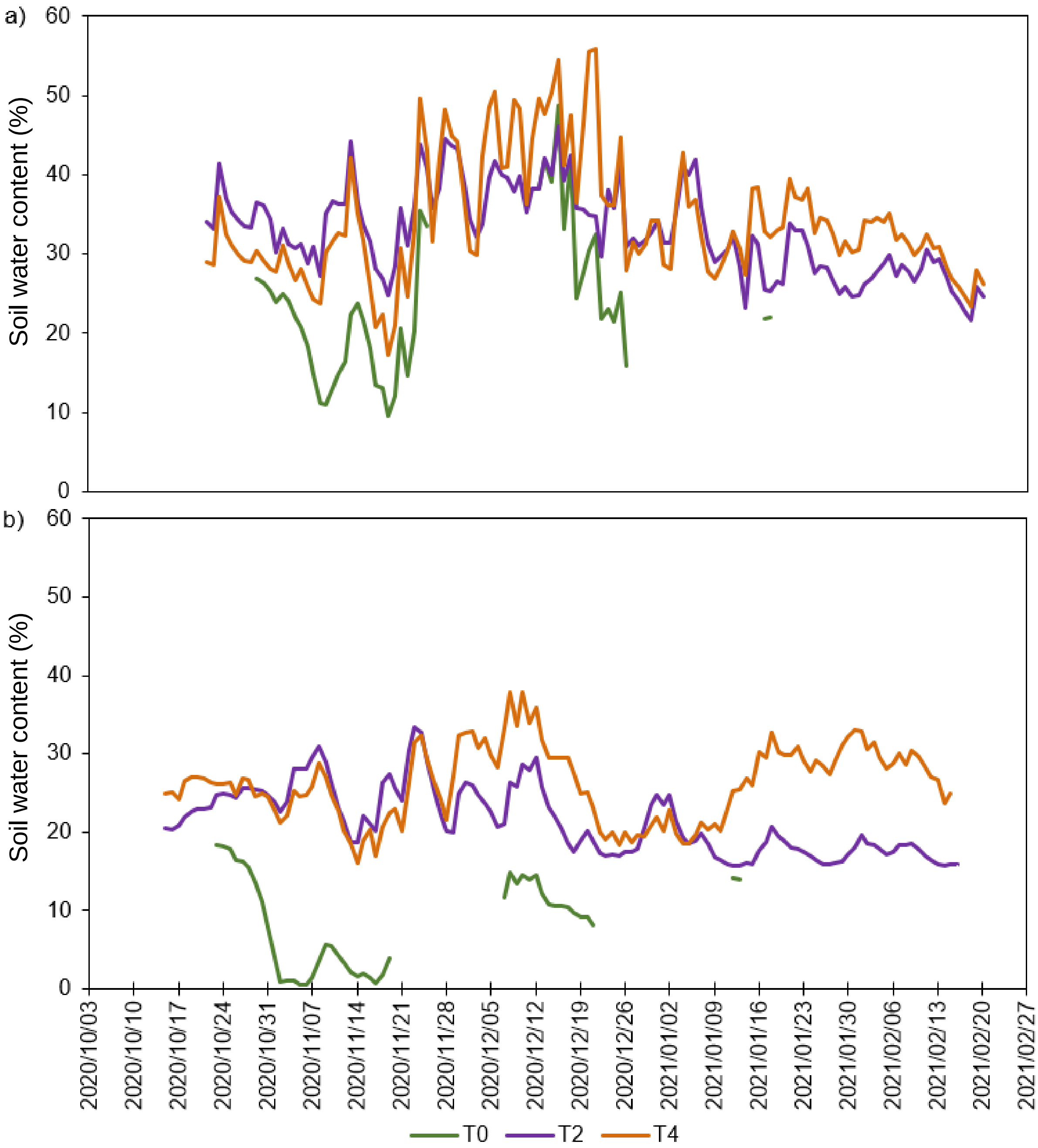

Figure 3.6 Soil water content for the 0 - 300 mm soil layer (a) and for the 300 - 600 mm soil layer (b), for treatments T0, T2 and T4 during the field trial period.

3.3.3 Leaf and tuber nutrient concentrations

<u>Leaf nutrient content</u>

Statistical analyses of the leaf nutrients showed that there was only a significant ($p < 0.05$) treatment effect for calcium (Ca), and only for the 120 days after planting (DAP) leaf sampling (Table 3.4). The mean and differences between the treatments are indicated in Figure 3.7.

Table 3.4 Analysis of variance (ANOVA) table for the Ca (%) in the leaves 120 DAP.

Source of variation	**Sum of squares**	**Degrees of freedom**	**F-value**	**p-value**
Blocks	0.040	1	2.819	0.127
Treatments	0.291	4	5.159	0.019
Residuals	0.127	9		

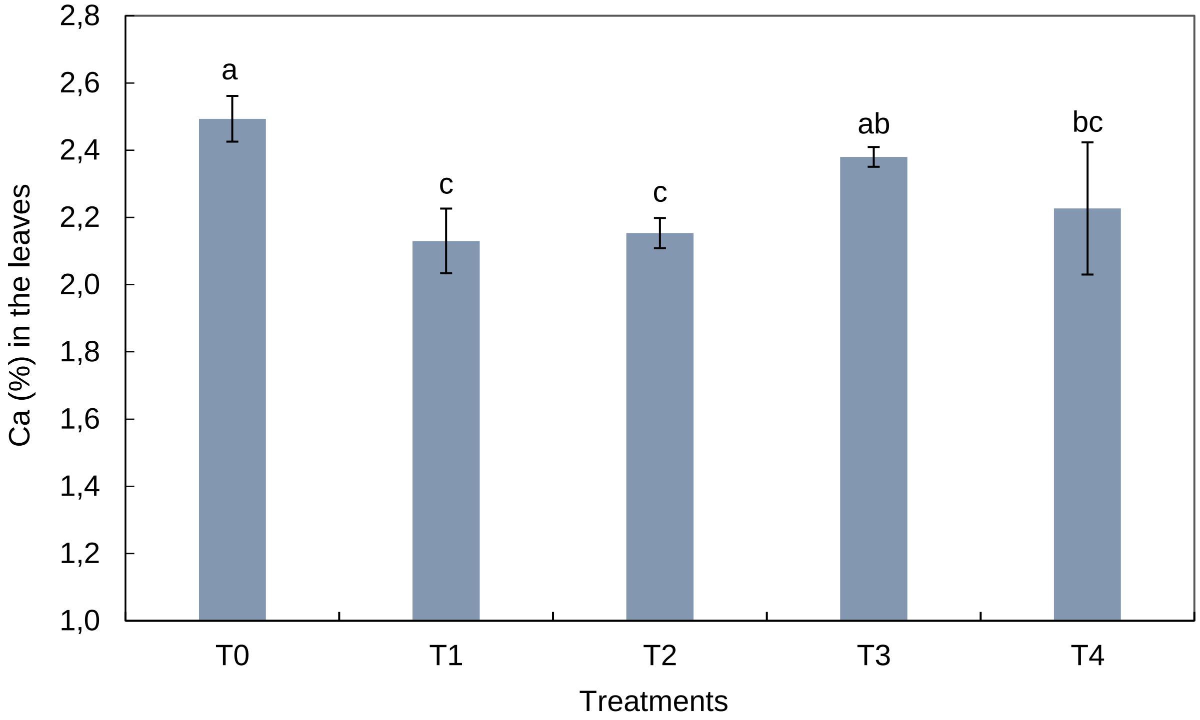

Figure 3.7 Mean calcium content (dry mass basis; DM%), with standard error bars, and the different letters indicative of the significant differences (P<0.05) observed between treatments.

The highest ($p < 0.05$) concentration of Ca was found in the control, and the lowest concentration was in treatment T1 and T2. Treatment T0 differed ($p < 0.05$) from T1, T2 and T4. Treatments T1 and T2 did not differ ($p > 0.05$) from each other and were also not different ($p > 0.05$) from T4.

The chemical composition, indicated by the grand mean, for the remainder of the nutrients are shown for the 80 and 120 DAP samplings in Tables 3.5 and 3.6, respectively. No significant differences ($p > 0.05$) were observed between the treatments, for both sampling days. For more information, see Supplementary Table S-1 and S-2 in the supplementary material supplied.

Table 3.5 Descriptive statistics of the nutrient content (dry mass basis; DM%) of potato leaves sampled 80 days after planting.

Nutrient	F statistic	P-value	Grand mean	Standard deviation
N (%)	1.394	0.311	5.08	0.56
P (%)	1.459	0.292	0.40	0.04
K (%)	1.199	0.375	3.17	0.60
Ca (%)	1.118	0.409	2.48	0.41
Mg (%)	1.024	0.445	1.06	0.17
S (%)	1.468	0.290	0.29	0.02
Na (mg kg^{-1})	2.660	0.103	2542.80	1522
Fe (mg kg^{-1})	0.359	0.832	113.27	17.54
Mn (mg kg^{-1})	3.152	0.070	152.40	35.61
Cu (mg kg^{-1})	1.909	0.193	4.27	0.46
Zn (mg kg^{-1})	1.001	0.455	14.40	1.60
Mo (mg kg^{-1})	0.862	0.522	1.59	0.26
B (mg kg^{-1})	1.749	0.223	59.00	6.13

Table 3.6 Descriptive statistics of the nutrient content (dry mass basis; DM%) of potato leaves sampled 120 days after planting.

Nutrient	F statistic	P-value	Grand mean	Standard deviation
N (%)	1.717	0.230	3.58	0.57
P (%)	2.631	0.105	0.27	0.05
K (%)	0.960	0.474	2.88	0.42
Mg (%)	0.512	0.729	1.03	0.10
S (%)	1.353	0.323	0.24	0.02
Na (mg kg^{-1})	1.170	0.386	6827.47	1705
Fe (mg kg^{-1})	2.246	0.144	123.93	13.08
Mn (mg kg^{-1})	3.504	0.055	89.27	22.88
Cu (mg kg^{-1})	0.605	0.670	8.47	2.97
Zn (mg kg^{-1})	1.105	0.411	12.80	2.60
Mo (mg kg^{-1})	2.079	0.166	1.52	0.26
B (mg kg^{-1})	0.403	0.802	61.53	5.66

Tuber nutrient content

Of all nutrients analysed, only the copper (Cu) concentration in the tubers showed significant differences ($p < 0.05$) between the treatments (Table 3.7).

Table 3.7 Analysis of variance (ANOVA) table for the Cu (DM%) in the tubers.

Source of variation	Sum of squares	Degrees of freedom	F-value	p value
Blocks	0.031	1	0.133	0.718
Treatments	3.000	4	3.194	0.031
Residuals	5.635	24		

The Cu content in the tubers is indicated in Figure 3.8. The highest Cu percentage was observed for the control, with the percentage decreasing as the Zeba™ concentration increased. A negative relationship therefore existed between Zeba™ rate and Cu percentage in the tubers.

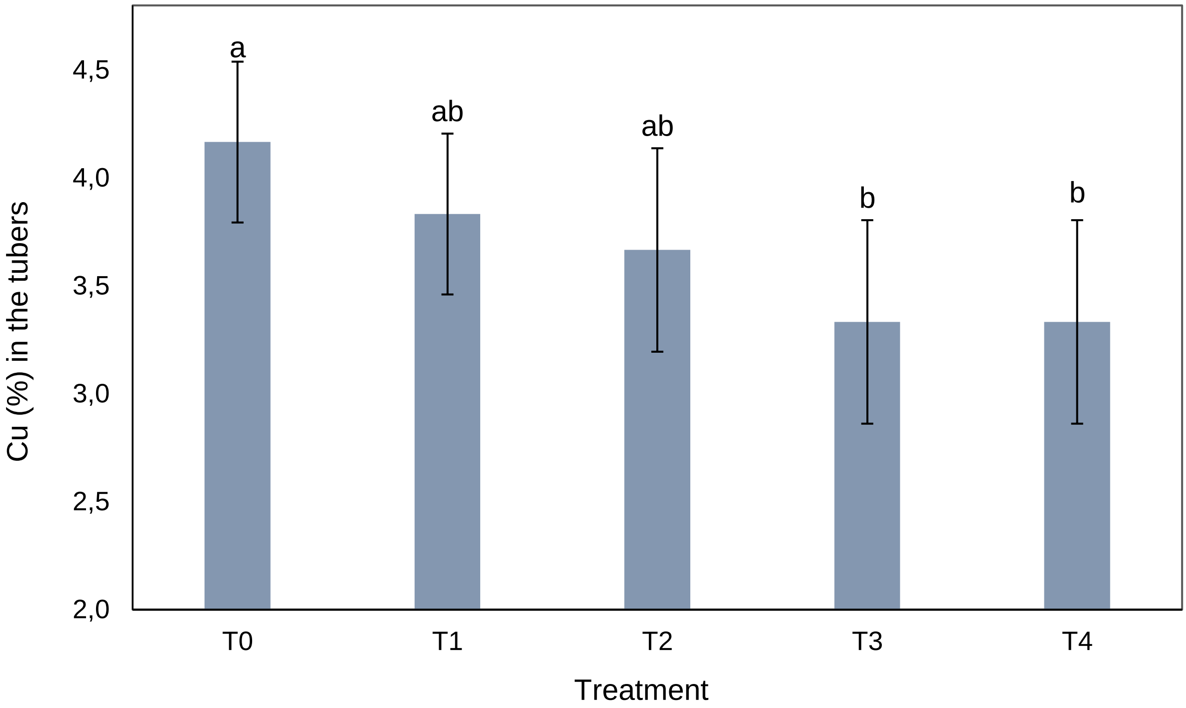

Figure 3.8 Mean copper content (%), with standard error bars, and the different letters indicative of the significant differences observed between the treatments.

The tuber nutrient concentrations, indicated by the grand mean, are shown in Table 3.8. There were no differences ($p > 0.05$) between treatments for the remaining nutrients shown. For more information, see Supplementary Table S-3 in the supplementary material supplied.

Table 3.8 Descriptive statistics of the chemical composition (dry mass basis; DM%) of the tubers.

Nutrient	F statistic	P value	Grand mean	Standard deviation
N (%)	0.891	0.485	1.34	0.17
P (%)	1.225	0.327	0.36	0.02
K (%)	1.973	0.131	2.41	0.11
Ca (%)	0.578	0.682	0.03	0.01
Mg (%)	1.503	0.233	0.09	0.01
S (%)	0.633	0.644	0.14	0.01
Fe (mg kg^{-1})	0.565	0.690	42.83	15.33
Mn (mg kg^{-1})	0.900	0.480	8.00	2.05
Zn (mg kg^{-1})	2.631	0.059	18.70	1.60
Mo (mg kg^{-1})	1.367	0.275	0.74	0.10
B (mg kg^{-1})	0.810	0.531	7.07	0.25

3.3.4 Crop yield and quality parameters of the tubers

The total tuber fresh yield was different ($p < 0.05$) between the Zeba™ treatments (Table 3.9). The mean per treatment, and the differences between the treatments are shown in Figure 3.9.

Table 3.9 Analysis of variance (ANOVA) table for the total tuber fresh yield.

Source of variation	Sum of squares	Degrees of freedom	F-value	p value
Replicates	28.04	1	1.192	0.286
Treatments	392.5	4	4.17	0.011
Residuals	564.78	24		

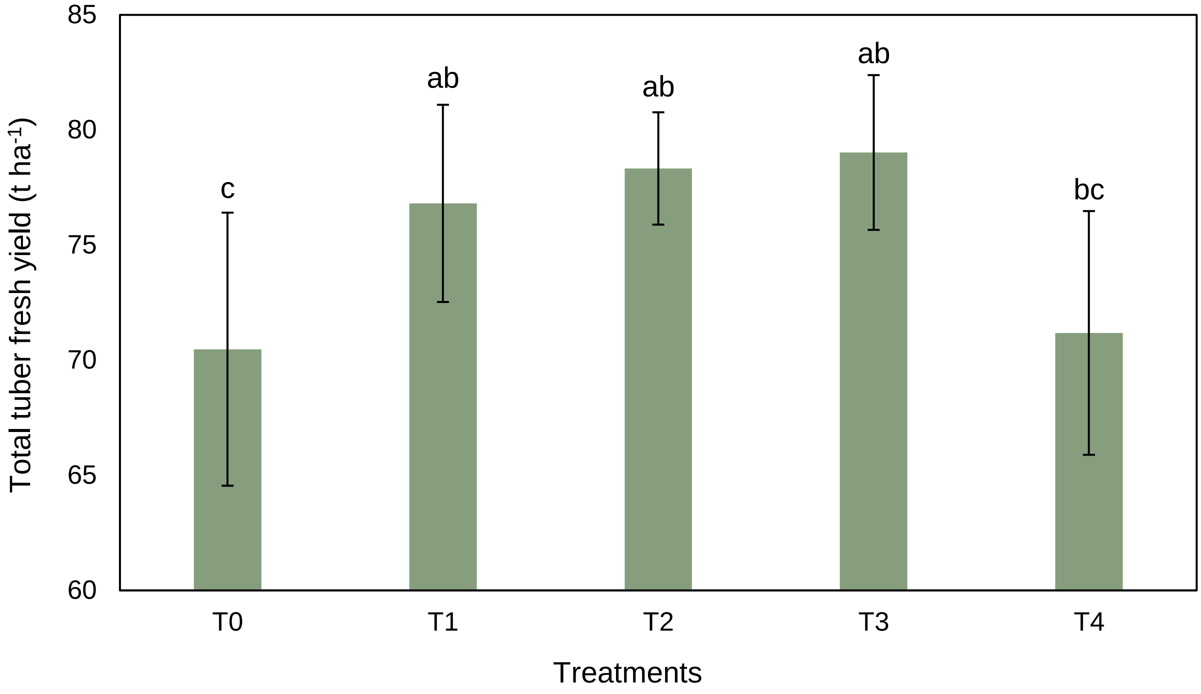

Figure 3.9 Mean tuber fresh yield achieved per treatment, with standard error bars. The different letters are indicative of the significant differences (P < 0.05) between treatments.

The pairwise comparison showed that all the treatments, except T4, differed from the control (T0) for the total tuber yields. The total tuber yields increased as the Zeba™ treatment rates increased, but only up to treatment T3, whereafter the addition of more product reduced the yield to a similar value as that of the control. The marketable tuber yields showed no significant differences ($p > 0.05$) between the treatments, and an average marketable yield of 69.6 t ha^{-1} was achieved in this trial.

When assessing the specific gravity, a significant difference ($p < 0.05$) between the treatments were found (Table 3.10). The mean of each treatment, along with the differences between them, is shown in Figure 3.10. The pairwise comparison of means showed that T1 and T3 were similar, and they differed from T2 and T4, which were also similar.

Table 3.10 Analysis of variance (ANOVA) table for the specific gravity of the tubers.

Source of variation	Sum of squares	Degrees of freedom	F-value	p value
Replicates	1.6×10^{-6}	1	0.516	0.479
Treatments	5.7×10^{-5}	4	4.577	0.007
Residuals	7.5×10^{-5}	24		

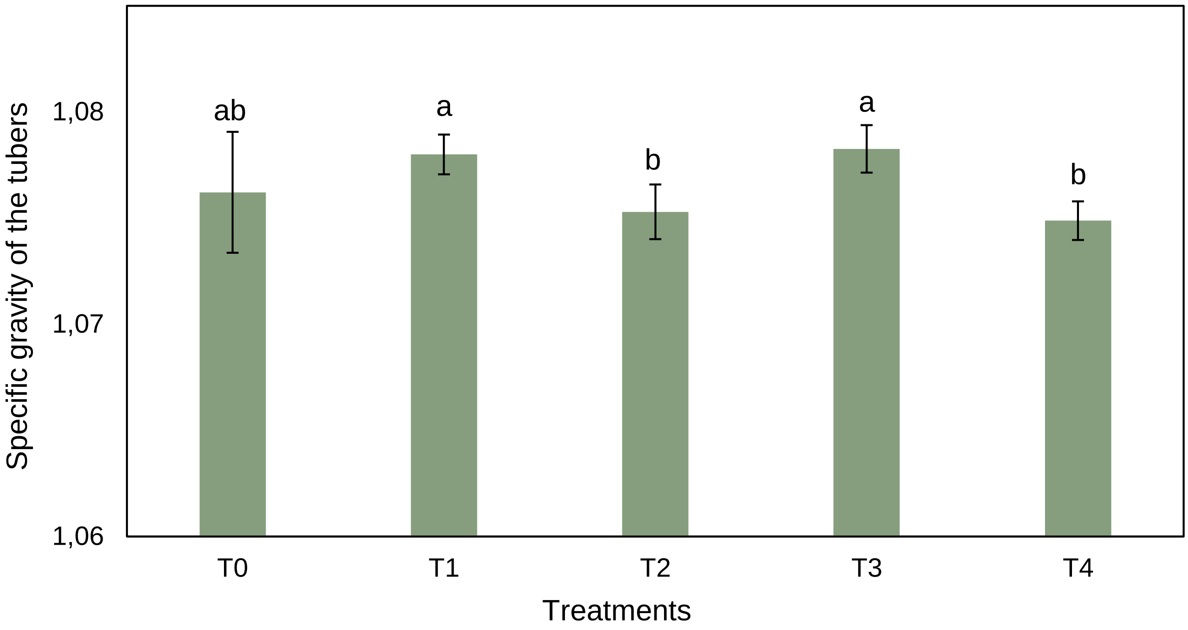

Figure 3.10 Mean specific gravity (SG) values, with standard deviation bars. The different letters are indicative of the significant differences between treatments.

The fry colour was significantly different ($p < 0.05$) between the Zeba™ treatments (Table 3.11). The mean fry colour per treatment, and the differences between the treatments are shown in Figure 3.11. Treatment T4 had the highest colour value (lightest colour), and treatment T1 the lowest. The chip frying colour generally increased with an increase in Zeba™ rate applied.

Table 3.11 Analysis of variance (ANOVA) table of the chip fry colour of the tubers.

Source of variation	Sum of squares	Degrees of freedom	F-value	p value
Replicates	0.0313	1	0.1331	0.7184
Treatments	3	4	3.1941	0.03084
Residuals	5.6354	24		

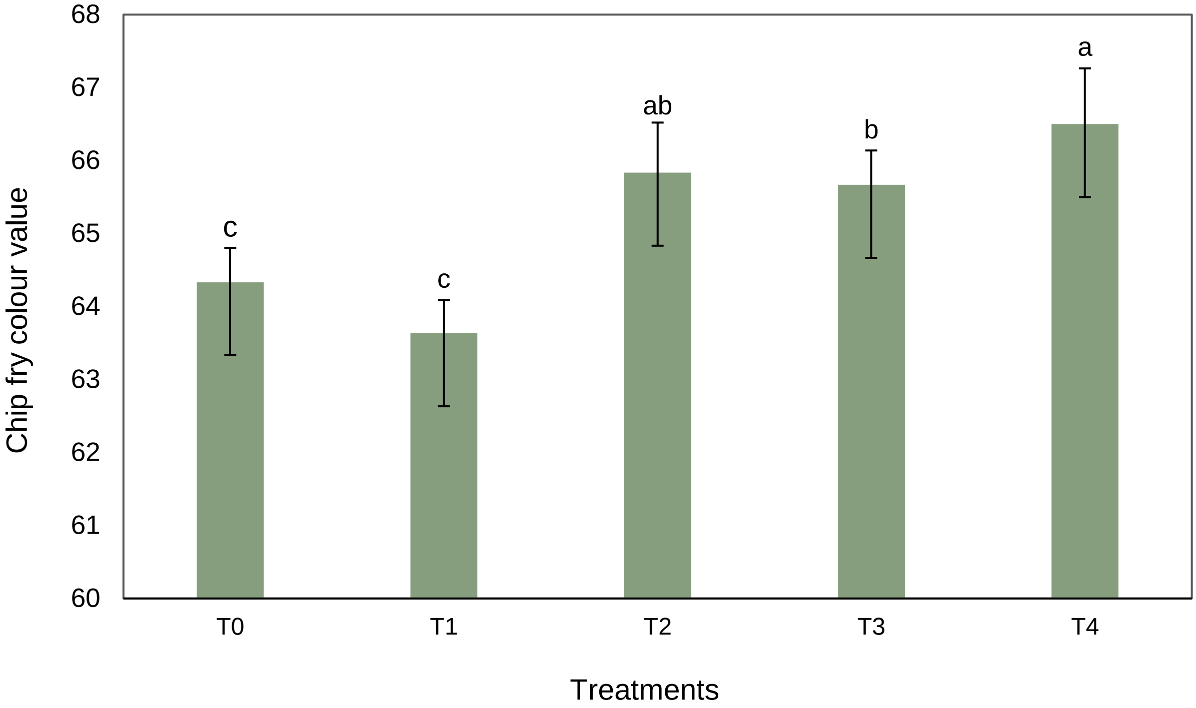

Figure 3.11 Mean chip fry colour, with standard deviation bars. The different letters are indicative of the significant differences between treatments.

The dry matter content of the tubers did not show significant differences ($p > 0.05$) between the different treatments, and a value of 20.3 %, averaged across all treatments, was found.

3.3.5 Resource use efficiencies

A total amount of 878 mm water was applied through irrigation, and 26.8 mm water was received from rainfall (from planting to crop senescence). The total evapotranspiration over the growth period was 832.6 mm.

The water use efficiencies (WUE), shown in Table 3.12, were calculated using the total tuber fresh yield, as well as the irrigation, rainfall and evapotranspiration values. The WUE for treatment T3 was the highest, with treatment T0 (control) having the lowest value (Table 3.12).

The nutrient use efficiencies were calculated only for the macronutrients (N, P, K) (Table 3.13). These efficiencies were calculated using the total tuber fresh yield, and the total amount of each nutrient applied, shown in Table 3.1. The highest nutrient use efficiencies were observed for treatment T3, and the lowest for treatment T0 (control), for all three macronutrients (Table 3.13).

Both the water use efficiency and the nutrient use efficiency increases were driven by the yield increases. The same pattern of increase, and then a decrease with treatment T4, that was observed with the total tuber yield (Figure 3.9), is observed here. For both sets of resource use efficiencies, the best efficiency was obtained for treatment T3, which had the highest tuber yield. The lowest efficiency was obtained for the control (0 kg ha^{-1}), which had the lowest tuber yield.

Table 3.132 Water use efficiencies calculated using the irrigation water applied, irrigation and rainfall, and calculated evapotranspiration.

Treatment	$WUE_{(I)}$	$WUE_{(I+r)}$	$WUE_{(ET)}$
T0	80.3	77.9	84.7
T1	87.5	84.9	92.3
T2	89.2	86.6	94.1
T3	90.0	87.3	94.9
T4	81.1	78.7	85.5

Table 3.13 Nutrient use efficiencies for the macronutrients, calculated using the total nutrients imported (from fertiliser application and through irrigation water applied).

Treatments	NUE	PUE	KUE
T0	208.5	320.4	129.3
T1	227.2	349.1	140.9
T2	231.7	356.0	143.7
T3	233.8	359.2	145.0
T4	210.6	323.5	130.6

3.4. Discussion

The volumetric water content, and therefore also the water holding capacity of the soil increased with an addition of the SAP Zeba™ (Figure 3.6). Super absorbent polymers are made up of three-dimensional polymeric crosslinked networks, which have functional groups on the backbone of the polymeric chains that are of hydrophilic nature (Ismail *et al.* 2013; Ahmed 2015; Chang *et al.* 2021). These hydrophilic monomers can be saturated with, and retain, water and the cross-linked nature of the polymeric chains prevents the disintegration of the polymer when saturated. This ultimately leads to the creation of a gel structure that holds large quantities of water (Qamruzzaman *et al.* 2022).

Hydraulic properties of soils, especially water holding capacity and water availability, are important to sustain crop growth. Observed increases of the water holding capacity of soils due to SAP applications are widely noted in literature and is one of the most important benefits that these polymers can contribute to agricultural production systems (Koupai *et al.* 2008; Yu *et al.* 2017; Saha *et al.* 2020b; Skrzypczak *et al.* 2020). Increases of water retention is especially pronounced in sandy soils, where bigger improvements in water holding capacity are observed with SAP applications, compared to soils with finer textures (Koupai *et al.* 2008; Narjary *et al.* 2012). This is because of the natural low water holding capacity of coarse textured soils due to their low clay- and organic matter content, compared to soils with finer textures. Smaller pore spaces, such as observed with fine textured soils, also prevent the polymers from expanding freely in the soil, thereby reducing their absorption capacities (Zhou *et al.* 2020).

The soil water contents of the 0 – 300 mm soil layer, as well as in the deeper 300-600 mm layer, both increased with the addition of Zeba™ (Figure 3.6). This indicates that the polymer has the potential to not only improve the water content in the 0-300 mm rooting zone but could also provide moisture to deeper soil layers. The addition of SAPs to soils decreases the hydraulic conductivity of the soil by reducing the pore sizes (Andry *et al.* 2009; Han *et al.* 2013). A reduction in hydraulic conductivity results in a reduction of the rate of water movement, which would ultimately lead to a reduced loss of water, either via drainage or evaporation. This could explain why the soil water content was improved even in the deeper layer where the SAP was not applied.

The Zeba™ rate significantly affected the total tuber yield of potatoes (Table 3.9). As the treatment rate increased, the yield increased (Figure 3.9). The increased yields achieved for potato crops in this trial, due to the amendment with SAP, is supported by several studies globally and locally (Eiasu *et al.* 2007; Xu *et al.* 2015; Hou *et al.* 2018; Salavati *et al.* 2018). Potato crops benefit greatly from soil with a higher water holding capacity, especially if that can be achieved in the rooting zone, because of their shallow rooting systems, which restrict the crop's ability to reach the water in deeper soil layers. Even brief periods of moderate water stress can have detrimental effects on the growth, yield and quality of potatoes (Onder *et al.* 2005; Wagg *et al.* 2021). This is due to physiological damage occurring from insufficient water during crucial growth phases (Steyn and Du Plessis 2012).

This yield increase, however, was only observed up until treatment T3, whereafter additional Zeba™ resulted in a yield similar to the control. This indicates that a maximum benefit exists whereafter the further addition of a SAP will either yield similar, non-significant results, or have a negative influence, depending on the factor observed. The hypothesised reasons for the steep reduction in yield from treatment T3 to T4 is that the SAP created an environment where too much water was retained by the soil. Potato yields are not only negatively affected by water stresses, but also by excess water (Benoit and Grant 1985). Several studies have demonstrated a reduction in tuber yield under excess water, however, the extent of the excess is likely to play a crucial role in the degree of the damaging effects. (Saue and Kadaja 2014; Jama-Rodzenska *et al.* 2021; Jiang *et al.* 2021). Some studies also showed very little, or no yield differences when there is excess water in the soil, but only when the excess occurred for a short period of time (Wagg *et al.* 2021).

The leaf samples taken in this study were used to determine whether differences in growth could be explained by differences in nutrient uptake by the treatments. The calcium content of the leaves that were sampled 120 DAP, was the only leaf nutrient that showed a significant difference between treatments (Table 3.4), from both sampling events. Although a difference between the treatments was observed, no clear justification could be provided to explain the response.

The values obtained for all other leaf nutrients for both sample dates (Tables 3.5 and 3.6), were within the nutrients concentration ranges expected for potato crops (Walworth and Muniz 1993; Steyn and Du Plessis 2012). This shows that the crop was not deficient in any nutrients during the growing season, but also that Zeba treatments did apparently not affect soil nutrient retention or uptake by plants.

The copper contents of the tubers showed a negative relationship with amount of Zeba™ applied, and the highest concentration was found in the tubers harvested from the control. The Zeba™ rate did not have a significant effect on the tuber content of any other nutrient.

The specific gravity (SG) of tubers are a very important postharvest quality indicator for processing potatoes and determines the storability, and baking and frying quality of processing potatoes (Laboski and Kelling 2007; Djaman *et al.* 2021). The tuber SG values obtained in this study showed significant statistical differences between treatments (Table 3.10) but did not follow any obvious trends (Figure 3.10). The SG of all the treatments fell within the suitable range (1.06 – 1.11) for processing, as suggested by Yuan *et al.* (2019). Factors affecting the growth of the tuber will generally also affect the SG thereof. Mature tubers have a higher SG value than young and undeveloped tubers, and factors that shorten the growth of the tubers will therefore also affect the SG (Hegney 2019).

Furthermore, an average tuber dry matter content of 20.3% was achieved in this trial. This is slightly higher than the 20% which is suggested as preferred for processing (Kirkman 2007). The SG of tubers is highly correlated with the dry matter content (DM; %) thereof (Schippers 1976; Mohammed 2016). A high tuber SG, and therefore high DM, is required by the processing industry, because a high DM content of tubers results in a lower oil absorption whilst frying. This leads to a higher chip yield (Lulai and Orr 1979; Naumann *et al.* 2020).

Another important quality standard for processing potatoes is the chip frying colour. Chips can become brown after frying due to the Maillard reaction. The browning is due to high reducing sugar contents in the tuber, which develops due to stress conditions. The browning that this reaction causes, affects the flavour, colour and smell of the product (Naumann *et al.* 2020). All the treatment in this study met the chip fry colour requirement for South Africa (chip fry colour > 50).

The evaporative demand of the crops, 832.6 mm, is higher than observed in other production areas. In their review study, Djaman *et al.* (2021) found that the water demand for potato crops are 320-800 mm across different areas and climatic conditions, whilst Lutaladio *et al.* (2009) stated a 500-700 mm water usage. The combined irrigation and rainfall (904.8 mm) exceed the evaporative demand. The evaporative demands and water applied, however, is similar to that applied in previous studies in the Sandveld (Kayes 2019).

The water and nutrient use efficiencies was improved with an increase in yield (Table 3.12 and 3.13), which generally occurred due to increases in the Zeba™ rate (with exception of treatments T4). Improving resource use efficiencies is imperative to ensure long term sustainability of potato production in environmentally vulnerable areas (Franke *et al.* 2011). Water availability and -use, and nutrient supply are interacting factors that affects the growth, and therefore yield of the crop (Li *et al.* 2011; Sharma *et al.* 2015; Ullah *et al.* 2019). The water content in the soil has a significant influence on the uptake of nutrients and the efficient use thereof (Ierna *et al.* 2011). When there is a shortage of soil water, some nutrients in the soil become immobile and cannot be taken up by plants, thereby reducing the NUE (Ullah *et al.* 2019). On the contrary, the improvement of crop nutrition improves the productivity of the plant, thereby also having the ability to improve the WUE (Hatfield 2015).

Each of the treatment, except the control, had better a $WUE_{(I+R)}$ than the average value of 78 $kg.mm^{-1}$, which was reported for the Sandveld from previous studies (Steyn *et al.* 2016). The $WUE_{(I+R)}$ of T1, T2 and T3 also had a higher value than the national average, 80 kg mm^{-1}, calculated across all of the production areas in South Africa (Steyn *et al.* 2016). A study conducted by Yu *et al.* (2004) also showed that the addition of a SAP increased the growth, yield and subsequently the WUE of potatoes grown in China, and Ostrand *et al.* (2020) reinforced this observation in their review of multiple studies, where they also reported improved WUE with the addition of SAP.

Maintaining, or improving WUE will ensure that the conversion of water used to produce into harvestable product occurs as optimally as possible. This is particularly important because water availability is one of the most limiting factors in agriculture. Treatment T1, T2 and T3 reached, and exceeded, the $WUE_{(I+R)}$ sustainability threshold of 80 $kg.mm^{-1}$, as proposed by Franke *et al.* (2011) for this area.

In their study, Steyn *et al.* (2016) reported the average amount of N, P and K applied through fertiliser in the Sandveld is 310 kg ha^{-1}, 169 kg ha^{-1} and 453 kg ha^{-1}, respectively. The N, P and K fertilised in this trial (Table 3.2) was higher than these averages. The N, P and K fertiliser inputs in this study were also much higher than the average inputs across all the production areas in South Africa (Steyn *et al.* 2016). These high fertilisation rates was due to the grower expecting high tuber yields.

Although the fertiliser inputs in this study were higher than other studies in this area, the yields were also higher, ultimately resulting in a higher nutrient use efficiencies. The NUE, PUE and KUE for all the treatments in this study were higher than the average NUE of 160 kg kg^{-1} N, the average PUE of 194 kg kg^{-1} P and KUE of 110 kg kg^{-1} K reported by Steyn *et al.* (2016) for the Sandveld. This is true, even for the control, which had the lowest yield. Franke *et al.* (2011) reported average NUE values of 166 kg kg^{-1} N, an average PUE of 486 kg kg^{-1} P and an average KUE of 116 kg kg^{-1} K for the Sandveld production region. The NUE and KUE values are similar to the findings of Steyn *et al.* (2016), whilst the reported PUE is much higher, with a very broad range of 98 – 995 kg kg^{-1} P. The NUE in this study was higher than the average NUE across all production areas in South Africa (NUE

= 209 kg kg^{-1} N), but the PUE and KUE was lower than the observed averages, 467 kg kg^{-1} P and 224 kg kg^{-1} K respectively (Steyn *et al.* 2016).

The use of chemical fertilisers, especially N, P and K fertilisers has significantly enhanced potato yields and tuber quality for decades (Davenport *et al.* 2005). In recent years, the environmental impact of these fertilizers has been a cause of great concern, especially the impact of N and P. The rise of fertiliser costs is also a threat to the economic sustainability of agricultural systems. It is therefore imperative that nutrients should be used as efficiently as possible.

The improved resource use efficiencies observed in this study, demonstrates that the application of a biodegradable SAP can improve the sustainability of potato production in the Sandveld, without having to change any of the other daily management practices on the farm.

3.5. Conclusion

The addition of the superabsorbent biopolymer, Zeba™, increased the water holding capacity of the sandy soil in the Sandveld. The increased water holding capacity likely provided the potato crop with an increased amount of available water and possibly an improved nutrient retention, nutrient uptake, and nutrient utilisation, although this is not evident from the results. All the treatments, except T4, that received a Zeba™ application, showed an increase in tuber fresh yield, compared to the control. The application of Zeba™ did not negatively affect the quality of the tubers, and all the treatments met the requirements for processing potatoes. Generally, the chip colour improved with an increase in Zeba™ rate, and the specific gravity responded although there was no clear trend. The increased yields resulted in improved resource use efficiencies. The water use efficiencies and nutrient use efficiencies were either higher, or comparable, to previous studies in the area. The improved resource use efficiencies should increase the sustainability of the production system without having to change any other daily management practices.

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Chapter 4: The indirect measure of degradation of a starch-based superabsorbent polymer over a twelve week trial period

4.1. Introduction

Super absorbent polymers (SAPs) are polymers capable of absorbing and retaining large amounts of water. The SAPs then release the water when required by the plant as the soil dries out (Koupai *et al.* 2008; Behera and Mahanwar 2020).

Super absorbent polymers show great potential across many different fields and have become a very prevalent research topic in recent decades (Ahmed 2015; Mignon *et al.* 2019; Behera and Mahanwar 2020; Saha *et al.* 2020). These polymers are mainly used in agriculture to absorb and retain water and nutrients in the soil. Super absorbent polymers can enhance water and fertiliser use, which are often limiting factors in agriculture (Ismail *et al.* 2013). However, the synthetic polymers commonly used are prepared from petrochemicals, which are not environmentally friendly. Biodegradable polymers could rather be utilised to overcome this problem, as they are environmentally friendly, and prepared from non-toxic, cheap materials (Qamruzzaman *et al.* 2022).

Biodegradable polymers are characterised as polymers that can degrade into compounds of low molecular weight, such as carbon dioxide, water, and methane. Biodegradation is a sequence of chemical processes (mainly via enzymatic action) that breaks down organic material in the presence of living organisms, such as bacteria, fungi, yeast, algae, and insects, under distinct conditions (Negim *et al.* 2014; Encalada *et al.* 2018). The biodegradation of SAPs will therefore be facilitated by microorganisms, and factors affecting the microbial activity in soils, might therefore affect biodegradation as well.

Due to its affordability and biocompatibility, starch is a popular material used for biodegradable SAP production (Koev *et al.* 2020). Starches, however, have limitations, particularly in terms of mechanical strength, thermal stability, and moisture absorption. Due to these limitations, starches are frequently combined with other materials, forming blends and more stable SAPs (Encalada *et al.* 2018; Ojogbo *et al.* 2020). Although biodegradable polymers are imperative for reducing the environmental impact of petroleum-based polymers, they still need to have satisfactory properties to improve agricultural production. An inverse relationship between the mechanical properties and the degradability of SAPs are usually observed (Encalada *et al.* 2018). Starch-blends are used to improve natural starch qualities and to ensure that polymers have the desired traits, while still being able to degrade over time.

Various studies assessed the degradation of biodegradable polymers. Many of these studies assessed degradation using a soil burial test (Thombare *et al.* 2018; Bora and Karak 2022; Gamage *et al.* 2022). All these studies assessed the degradation directly by measuring the physical properties of the polymer, mainly by measuring the polymer weight throughout the experiment. This pot trial aimed to assess the polymer degradation indirectly, by measuring and assessing the water holding capacity of the soil and polymer system (WHC_{S+P}) over the duration of the experiment.

One such a starch-based biodegradable SAPs, Zeba™, was assessed by conducting a twelve-week pot trial. The main objective of the trial was to assess the period for which positive effects of the polymer on the water holding capacity of the soil, could be observed. It was hypothesized that the water absorption ability of the polymer would decrease over time due to the degradation of the starch, but the extent and time of the degradation was unknown. Information on the decline in the polymer's water absorption ability with degradation will be valuable practical information for agricultural applications. The effect of different treatment rates on water holding capacity over the twelve-week period was also assessed.

4.2. Methods and Materials

4.2.1. Site description

A pot trial was conducted on the Welgevallen Experimental Farm, Stellenbosch, South Africa (33°56'32.6"S 18°51'58.1"E). The pot trial was conducted in a tunnel for the first eight weeks, and then moved to a glasshouse for four weeks. Sandy soil from the Sandveld region, Western Cape Province of South Africa, was collected and used in this experiment. The sand was used to fill green plastic pots with a 15 cm diameter. Each pot had three drainage holes at the bottom, allowing free drainage. The pots were placed in saucers to collect potential leachate.

4.2.2. Experimental design and treatments

The trial commenced on 13 September 2021, ran for a period of twelve weeks, and ended on 2 December 2021. The experiment was laid out as a randomised block design, consisting of two treatment factors and replicated in five blocks. The first treatment factor was the rate of Zeba™ applied, using the recommended field rate, and adjusting it for a 15 cm pot. The four tested rates are shown in Table 4.1. The Zeba™ was mixed with the top 10 cm of soil.

Table 4.4 Rate of Zeba™ applied for each treatment level, adjusted for a 15 cm pot from the recommended field rate

Treatment	Rate (kg ha^{-1})	15 cm pot (g)
T0	0	0.0
T1	5	0.1
T2	10	0.2
T3	15	0.3

The second variable tested was the different time intervals for which the experiment ran. The twelve week period was split into three intervals, namely time interval 1, 2 and 3, and each interval having a duration of four weeks. The means of the results per interval were assessed as an indirect measure of degradation of the Zeba™ polymer over time.

4.2.3. Trial management and data collection

Each pot was irrigated with 200 mL of distilled water at the start of the first week (D0). Each pot was weighed prior to the irrigation event, and then also weighed on day one (D1), and day three (D3) after the irrigation event. If leachate was present, the pots were weighed before and after the leachate was emptied from the saucer. The weight without the leachate was used in the water holding capacity equation.

The water holding capacity of the soil and polymer (WHC_{S+P}) was determined by subtracting the weight before irrigation (D0) from the weight of the pots on day one (D1), day three (D3) and day seven (D7) after the irrigation, respectively, according to Equation 4.1.

$$\mathrm{WHC}_{\mathrm{S+P}} = \text{weight of pot}_{\mathrm{D1,D3}} - \text{weight of pot}_{\mathrm{D0}}$$

Equation 4.1

The temperature inside the greenhouse/glasshouse was expected to rise along with the air temperature as the trial time progressed. To minimise the effect of the rising temperature on the WHC_{S+P}, water holding capacity ratios were calculated (WHC_R), which related each treatment group to the control group. These ratios were calculated by dividing each observation for treatment groups T1, T2 and T3, by the average of the control, T0, for each time interval, according to Equation 4.2.

$$\mathrm{WHC}_{\mathrm{R}} = \frac{\mathrm{WHC}_{\mathrm{S+P}}\,(\mathrm{T1, T2, T3})}{\mathrm{WHC}_{\mathrm{S+P}}\,(\mathrm{T0})}$$

Equation 4.2

4.2.4. Statistical analyses

Statistical analysis was performed with R studio, version 1.4.1106. Descriptive statistics was performed as well as a two-way analysis of variance (ANOVA). Pairwise comparison tests using Tukey’s Honest Significant Difference was performed. Normality was tested for by the Shapiro-Wilk test and homoscedasticity was tested for by the Bartlett Test. A 0.05 level of significance was used for all statistical tests.

4.3. Results

Day one (D1) after the irrigation event

The trends of WHC_{S+P} for all the treatment groups and across the three time intervals of the study, and for the first day after irrigation, are shown in Figure 4.1 (Time interval 1 represents week 1-4, interval 2 represents week 5-8, and interval 3 represents week 9-12). This figure was used to visually assess the general trends in the study. Generally, an increase in treatment rate increased the WHC_{S+P} within a time interval. The WHC_{S+P} decreased with as the time passed from interval 1 to 2 to 3.

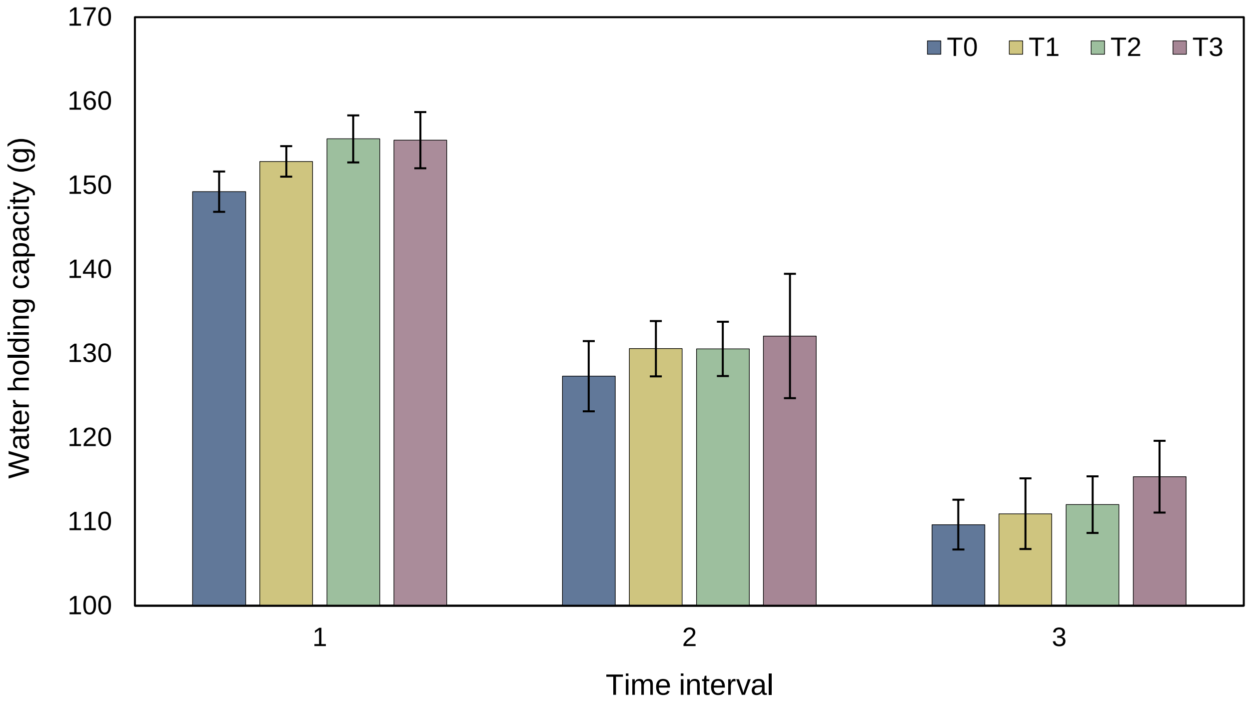

Figure 4.1 The mean water holding capacity (WHC_{S+P}) (g/pot), with standard deviation bars, of the soil and polymer system for the first day after irrigation (D1), for the treatment groups across the time intervals of the study. Time interval 1 represents week 1-4, interval 2 represents week 5-8, and interval 3 represents week 9-12.

The influences of the time intervals and treatment rates on the WHC_{S+P} on day one (D1) are also shown in ANOVA table presented as Table 2. The analysis indicated that there was no interaction ($p > 0.05$) between the two independent variables, time interval and treatment (Table 4.2).

Main effect analysis showed that time intervals ($p < 0.05$) and treatment ($p < 0.05$) both had a significant effect on the WHC_{S+P} for D1 (Table 4.2). The means of all three time intervals differed from each other ($p < 0.05$) (Figure 4.2). The WHC_{S+P} decreased as the time passed, with the highest value obtained for time interval 1, and the lowest value obtained for interval 3 (Figure 4.2).

Table 4.2 A two-way analysis of variance (ANOVA) table determining the effect of time and treatment rate on the water holding capacity of the soil and polymer system (WHC_{S+P}) on the first day after the irrigation event (D1).

Source of variation	Sum of squares	Degrees of freedom	F-value	p value
Time interval	17104	2	4.446	0.008
Treatment	246	3	462.784	< 0.001
Time interval:Treatment	33	6	0.298	0.935
Residuals	887	48		

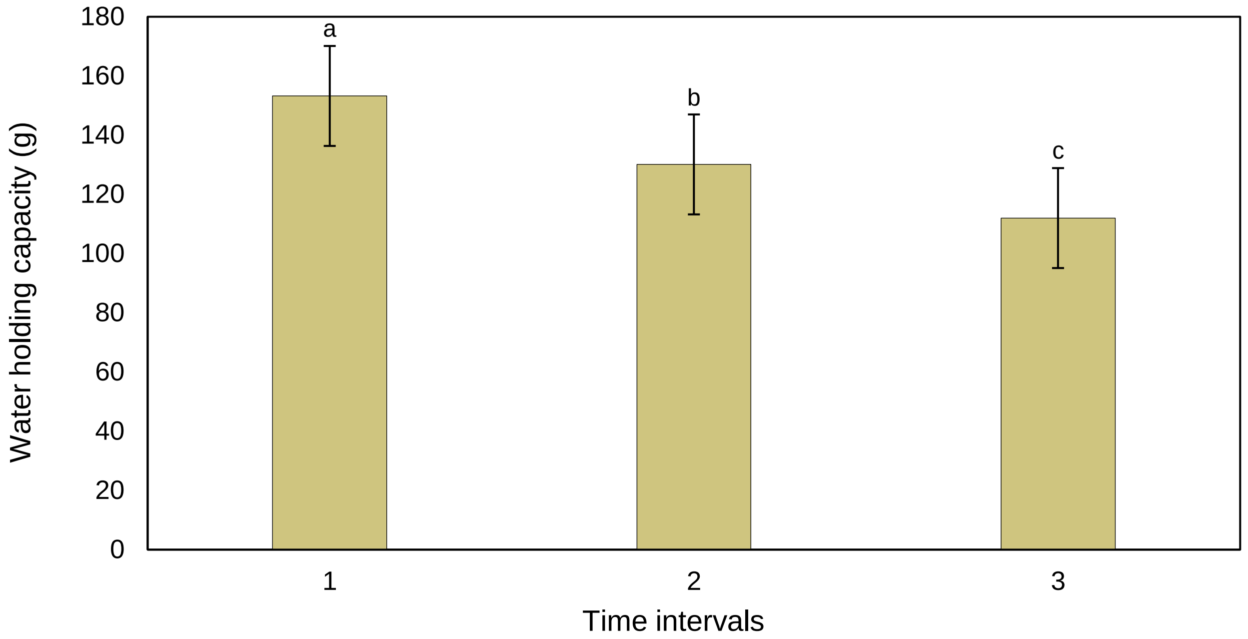

Figure 4.2 The water holding capacity (WHC_{S+P}), with standard deviation bars, of the soil and polymer system (WHC_{S+P}) as affected by the time intervals one day (D1) after the irrigation event. The letters above bars indicate significant differences ($p < 0.05$) between intervals. Time interval 1 represents week 1-4, interval 2 represents week 5-8, and interval 3 represents week 9-12.

The mean water holding capacity of treatment T0 (control) was significantly ($p < 0.05$) lower than the mean of treatment T3, whilst T0, T1 and T2, and T1, T2 and T3 were similar ($p > 0.05$) (Figure 4.3). The WHC_{S+P} generally increased as the rate of Zeba™ applied increased (Figure 4.3). The highest WHC_{S+P} value was obtained for treatment T3, and the lowest value obtained for treatment T0 (control) (Figure 4.3).

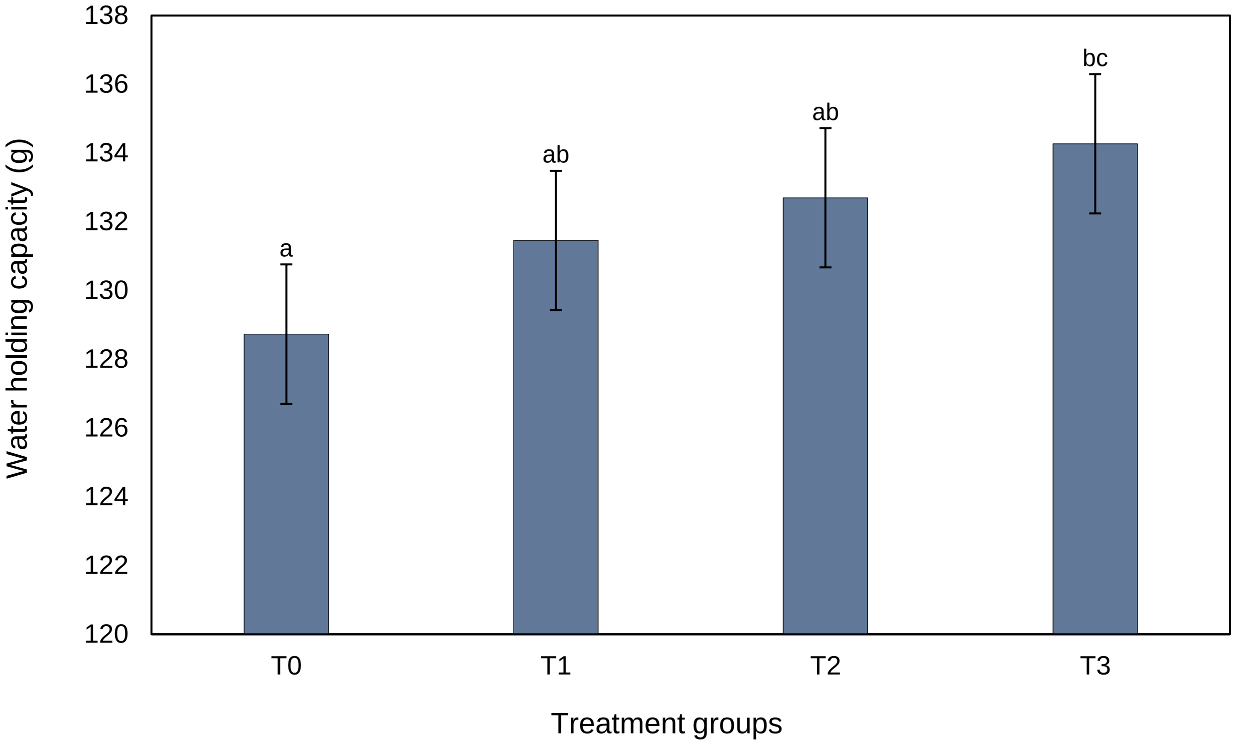

Figure 4.3 The water holding capacity (WHC_{S+P}), with the standard deviation bars, of the soil and polymer system as influenced by the treatment rate one day (D1) after the irrigation event. The letters above the bars are indicative of the significant differences ($p < 0.05$) between treatment groups.

Day three (D3) after the irrigation event

The trends of WHC_{S+P} for all the treatment groups and across the three time intervals of the study, and for the third day after irrigation, are shown in Figure 4.4. In Figure 4.4, the same general trends of increases and decreases of WHC_{S+P} are noted, as was observed at one day (D1) after irrigation (Figure 4.1). The WHC_{S+P} of D3 are much lower than for D1 (Figure 4.1 and 4.4), showing that the soil and polymer systems loses water quickly due to the high evaporation.

The ANOVA table indicates the influence of time, which is an indirect measure of degradation, and the treatment level on the WHC_{S+P} on the third day (D3) after the irrigation event, is shown in Table 3. There was no interaction ($p > 0.05$) between the two independent variables, time interval and treatment (Table 4.3).

The main effect analysis showed that both time interval ($p < 0.05$) and treatment ($p < 0.05$) had a significant effect on the WHC_{S+P} for day three (D3) (Table 2). The means of all three time intervals differed from each other ($p < 0.05$), and the WHC_{S+P} decreased over time (Figure 4.5). The highest WHC_{S+P} value was obtained for time interval 1, and the lowest value obtained for interval 3 (Figure 4.5).

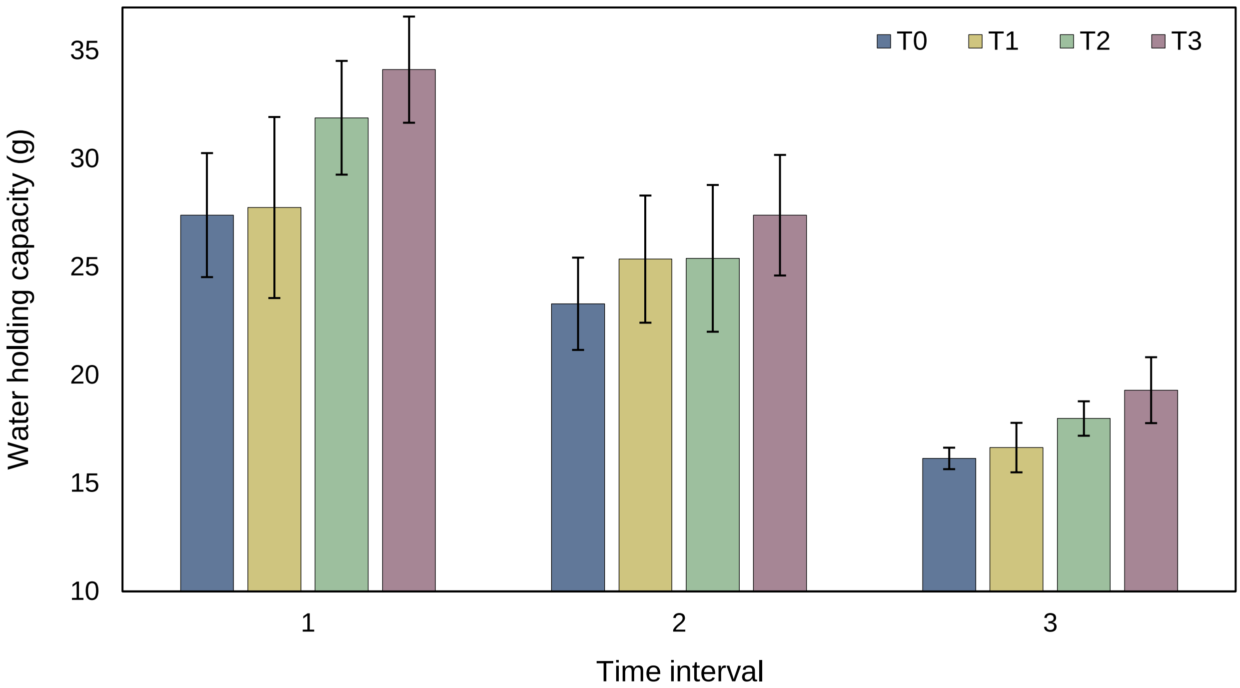

Figure 4.4 The mean water holding capacity (WHC_{S+P}) (g/pot), with standard deviation bars, of the soil and polymer system for the third day after irrigation (D3), for each of the four treatments across the three time intervals of the study. Time interval 1 represents week 1-4, interval 2 represents week 5-8, and interval 3 represents week 9-12.

Table 4.3 A two-way analysis of variance (ANOVA) table determining the effect of the time interval and treatment rate on the water holding capacity of the soil and polymer system (WHC_{S+P}) for the third day after the irrigation event (D3).

Source of variation	Sum of squares	Degrees of freedom	F-value	p value
Time interval	1720.9	2	186.441	< 0.001
Treatment	190.5	3	13.757	< 0.001
Time interval:Treatment	29.4	6	1.061	0.400
Residuals	207.7	45		

The mean WHC of treatment T0 (control) and T2 were similar to T1 ($p > 0.05$), whilst T0 and T2 differed from each other ($p < 0.05$) (Figure 4.6). Treatment T3 had a similar mean WHC to treatment T2 ($p > 0.05$) but differed from T1 and T0 ($p < 0.05$) (Figure 4.6). The WHC_{S+P} generally increased as the rate of Zeba™ applied increased (Figure 4.6). The highest WHC_{S+P} value was obtained for treatment T3, and the lowest value for treatment T0 (control) (Figure 4.6).

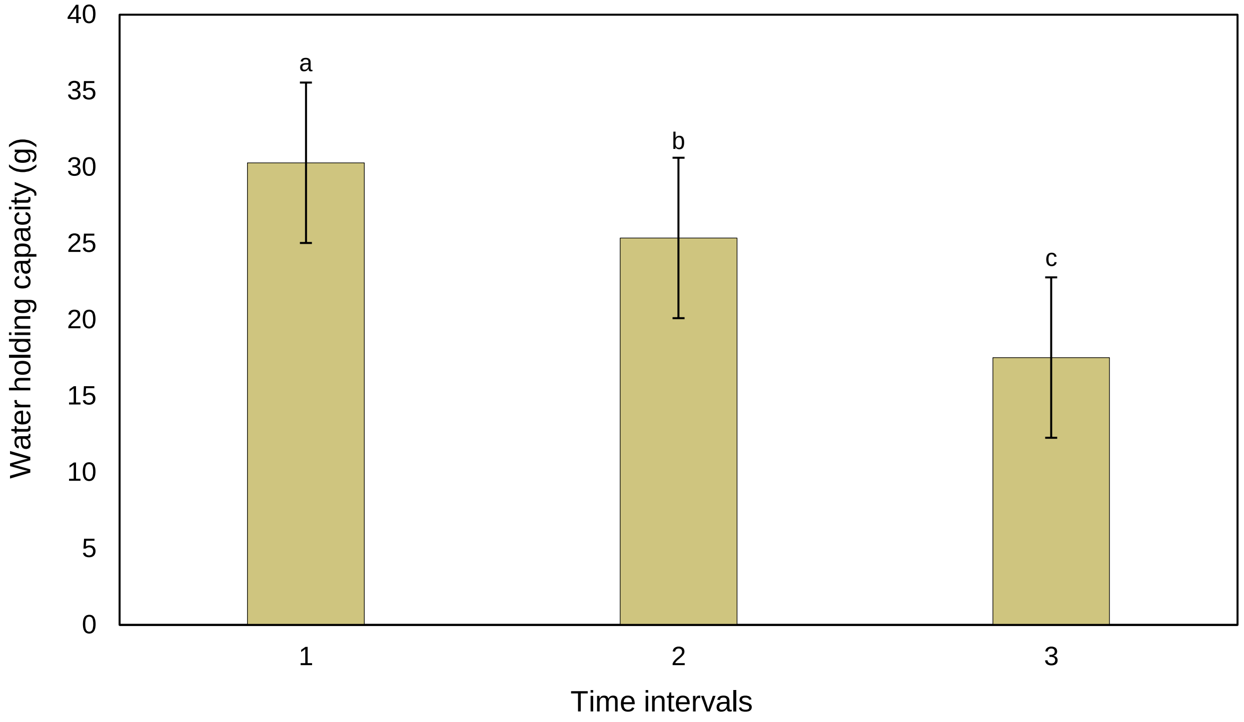

Figure 4.5 The water holding capacity (WHC_{S+P}), with the standard deviation bars, of the soil and polymer system as affected by the time intervals three days (D3) after the irrigation event. The letters indicate the differences at $p < 0.05$ between the intervals. Time interval 1 represents week 1-4, interval 2 represents week 5-8, and interval 3 represents week 9-12.

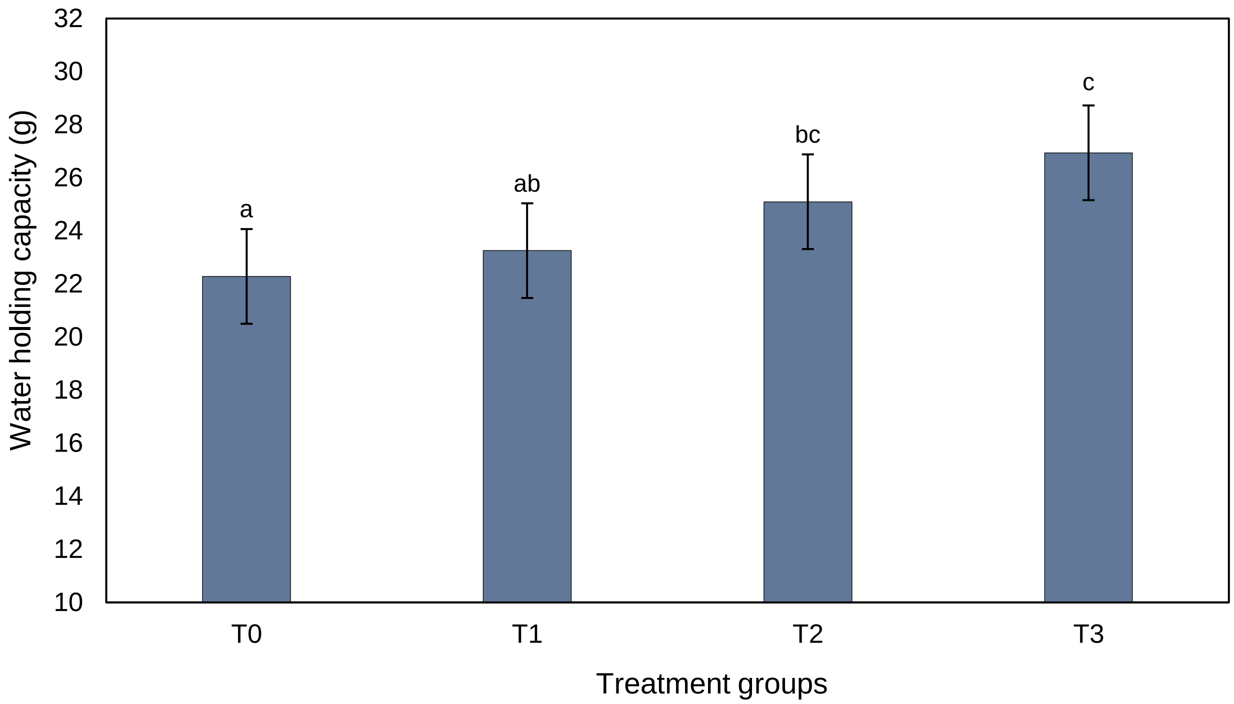

Figure 4.6 The water holding capacity (WHC_{S+P}), with standard deviation bars, of the soil and polymer system as influenced by the treatment rate on the third day (D3) after the irrigation event. The letters are indicative of the differences at $p < 0.05$ between the treatment groups.

The water holding capacity ratio

The effects that the time interval and the treatment groups have on the water holding capacity ratio (WHC_R) for both the first (D1) and the third day (D3) after the irrigation event are shown in ANOVA Tables 4.4 and 4.5, respectively. Both analyses showed that there was no interaction ($p > 0.05$) between the effects of the time interval and treatment rate (Tables 4.4 and 4.5).

Table 4.4 Two-way analysis of variance (ANOVA) table assessing the effect of time and treatment rate on the water holding capacity ratio (WHC_R) of the soil and polymer system, for the first day after the irrigation event (D1).

Source of variation	Sum of squares	Degrees of freedom	F-value	p value
Time interval	0.0005	2	0.171	0.844
Treatment	0.0040	2	1.503	0.236
Time interval:Treatment	0.0019	4	0.347	0.844
Residuals	0.0481	36		

Main effect analysis showed that there were no differences ($p > 0.05$) for time interval, as well as for treatment group for D1 (Table 4.4). The main effect analysis for D3 showed that there was also no difference ($p > 0.05$) for the time interval, while the difference ($p < 0.05$) between the treatment groups was significant (Table 4.5).

Table 4.5 Two-way analysis of variance (ANOVA) table assessing the effect of time and treatment rate on the water holding capacity ratio (WHC_R) of the soil and polymer system, for the third day after the irrigation event (D3).

Source of variation	Sum of squares	Degrees of freedom	F-value	p value
Time interval	0.0064	2	0.213	0.809
Treatment	0.1954	2	6.491	0.004
Time interval:Treatment	0.0365	4	0.606	0.661
Residuals	0.5418	36		

The means of treatment T1 and T3 differed significantly ($p < 0.05$) from each other at D3, whilst T1 and T2 were similar, and T2 and T3 were similar (Figure 4.7).

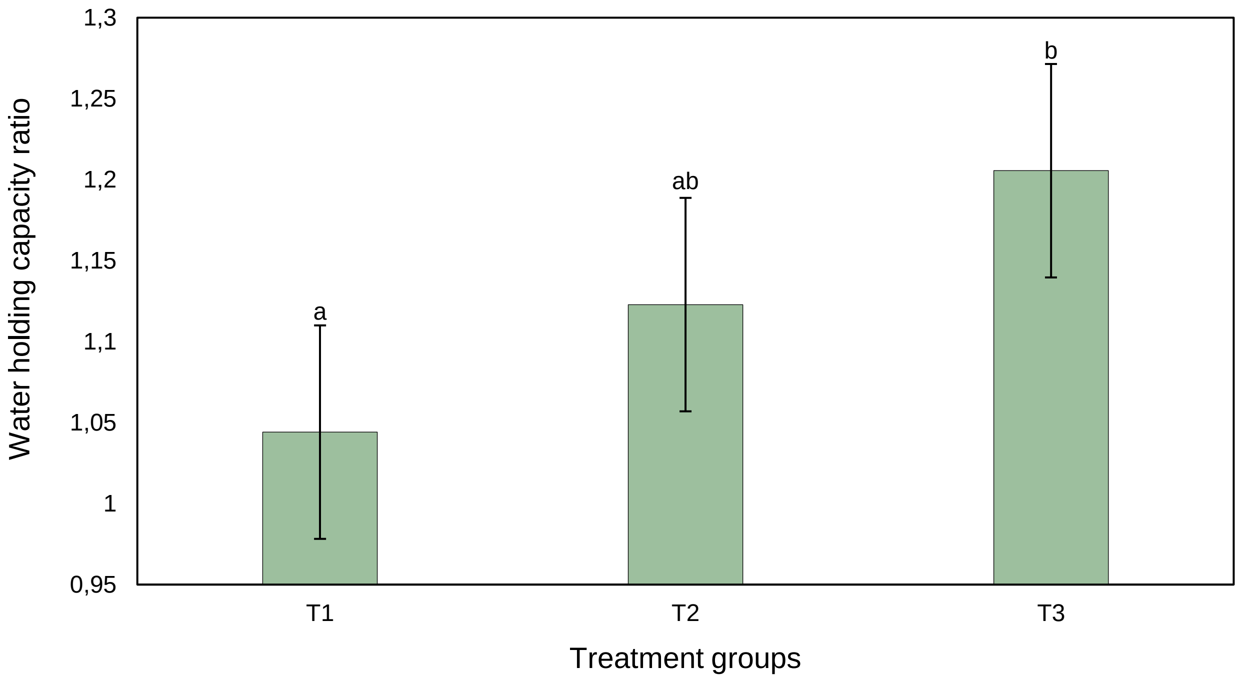

Figure 4.7 The water holding capacity ratio (WHC_R), with standard deviation bars, of the soil and polymer system as influenced by the treatment rate, three days (D3) after the irrigation event. The letters are indicative of the differences at $p < 0.05$ between the treatment groups.

Tables 4.6 and 4.7 show the mean WHC_R for the first and third day, respectively, after the irrigation event. The values for each treatment group across all three time intervals are shown. The ratios obtained for D3 were higher than for D1, except for treatment T1 for time interval 1. The difference between the ratios of the two days is especially pronounced when considering treatments T2 and T3. Treatment T3, and on D3, had the highest WHC_R in this trial (Table 4.7).

Table 4.6 Mean water holding capacity ratios (WHC_R) for the treatment groups across the three time intervals, for day one (D1) after the irrigation event. Time interval 1 represents week 1-4, interval 2 represents week 5-8, and interval 3 represents week 9-12.

Treatment	Time interval 1	Time interval 2	Time interval 3
T1	1.024	1.026	1.012
T2	1.042	1.026	1.022
T3	1.041	1.038	1.052

Table 4.7 Mean water holding capacity ratios (WHC_R) for the treatment groups across the three time intervals, for day three (D3) after the irrigation event. Time interval 1 represents week 1-4, interval 2 represents week 5-8, and interval 3 represents week 9-12.

Treatment	Time interval 1	Time interval 2	Time interval 3
T1	1.013	1.089	1.031
T2	1.164	1.090	1.114
T3	1.245	1.176	1.195

4.4. Discussion

Upon assessing the general trends of water holding capacity of the pot and soil (WHC_{S+P}) for the first day (D1) (Figure 4.1) and the third day (D3) (Figure 4.4), the WHC_{S+P} increases as the treatment rate of Zeba™ increases, while the WHC_{S+P} decreases for each of the treatment groups as the time progressed (from time interval 1 to 2 to 3). The pattern of WHC_{S+P} for all the treatment groups seems visually similar across the duration of the trial for both D1 and D3.

There was no significant interaction found between the two variables, time interval and treatment, for both D1 and D3 (Tables 4.2 and 4.3). However, both the time interval and the treatment rate had a significant effect on the WHC_{S+P}, for both days (Tables 4.2 and 4.3).

For both days, the WHC_{S+P} increased as the treatment rate increased (Figures 4.3 and 4.6), which was expected. The increase in water holding capacity with an increase in superabsorbent polymer (SAP) applied is widely reported in literature (Banedjschafie and Durner 2015; Yu *et al.* 2017; Abrisham *et al.* 2018; Saha *et al.* 2020). Superabsorbent polymers decrease the hydraulic conductivity of soils, thereby reducing movement and loss of water (Andry *et al.* 2009; Han *et al.* 2013).

For both days, the WHC_{S+P} decreased as the time progressed from time interval 1 to 3 (Figures 4.2 and 4.5), with all the time intervals significantly differing from each other. The control, seemingly following the same pattern as the treatment groups (Figures 4.1 and 4.4), makes it impossible to conclude that the polymer's ability to absorb water decreased over the period of the trial due to the degradation thereof. The major reduction in WHC_{S+P} over the trial period is likely due to increased evaporation, resulting from the increase in temperature.

Water holding capacity ratios (WHC_R) have therefore been calculated, where the treatment groups T1, T2 and T3 have been related to the control (T0). This ratio was used to eliminate the effects of the climatic conditions in the greenhouse/glasshouse on the WHC_{S+P}. The effects of the time intervals and the treatment groups on the WHC_R showed a non-significant interaction between these variables, for both D1 and D3 (Tables 4.4 and 4.5). There was no difference between the means of the treatment rates for D1, but a difference between the means of the treatment rates were observed for D3 (Figure 4.7). This observation, coupled with the higher ratios observed for D3 (Table 4.7), indicates that the polymers had a bigger effect on water retention as the time progressed after the irrigation event (from D1 to D3), i.e., the treatment groups retained more water compared to the control. This is due to the polymer's superior ability to retain water as the soil dries out, as opposed to the pores of untreated soil.

The effect of the time intervals on the WHC_R showed that there were no differences ($p < 0.05$) between the intervals, for both D1 and D3 (Table 4.4 and 4.5). There is therefore no clear indication that the polymer's absorption ability decreased over the trial period due to degradation. The reduction in WHC_{S+P} observed is ascribed to the increase in temperature over the period of the study, which led to increased evaporation from the soil surface.

It should be noted that this trial was done in soils with low carbon contents, which are associated with low soil microbial activity. Plant roots, and the exudates they release, affect soil microorganisms and microbial activities in various ways, especially in the rhizosphere (Parkinson 1967; Steinauer *et al.* 2016; Qu *et al.* 2020). It is therefore possible that actively growing plants and soils with more microbial activity may have a significant effect on the degradation of starch-based polymers and further research is needed to assess this.

4.5. Conclusion

The results indicated that the water holding capacity for the soil and polymer systems (WHC_{S+P}) was significantly affected by both the treatment rate, as well as the time intervals. The WHC_{S+P} increased with an increase in polymer level applied, as expected. The results also showed that the polymer had a more pronounced effect on the water holding capacity as the time progressed due to its increased ability to retain water compared to soil pores. The treatment groups therefore held more water, compared to the control on the third day, compared to the first day after the irrigation event. Although a decrease in WHC_{S+P} was observed over the period of the trial, there was no definitive evidence indicating that the absorption ability of the polymer declined over time due to degradation. The decrease observed is mainly ascribed to the increase in temperature, leading to higher evaporation rates later in the trial period.

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Chapter 5: Conclusion

5.1. Introduction

The Sandveld is an important potato production area in South Africa. Potato production in this region is heavily dependent on irrigation because dryland potato production is not economically feasible due to the semi-arid local climate. The Sandveld is also characterised by very sandy soils, which naturally have a low retention ability. The low water holding capacity of the soils, coupled with high irrigation and fertiliser inputs, result in high amounts of water and nutrients being lost through leaching out of the soil profile, which is of high concern in this ecologically sensitive area. Pollution from agricultural activities is also becoming a prevalent concern globally. Since farming is the most extensive land use and economic activity in the Sandveld, it is crucial that agricultural land use, resource usage, and biodiversity conservation should receive equal priority.

Potato crops have a poorly developed root system, which causes inefficient extraction of water from the already low plant available water (PAW) in sandy soils. Furthermore, the crop is very sensitive to drought stresses, with even short periods of stress leading to yield and quality reductions.

To address the problems experienced with potato production in this area, the use of a superabsorbent polymer was suggested. Limited research has been done on the use of superabsorbent polymers to support and optimise potato production. The aim of this trial was to evaluate the potential of the biodegradable superabsorbent polymer, Zeba™, to improve potato production systems in semi-arid, drought prone areas. This aim was approached through two objectives, from which the knowledge gained will be examined to recommend the use of this product in the Sandveld and other similar production systems.

<u>Objective one was to assess, by means of a field trial, the effects that the use of the superabsorbent polymer, Zeba™, has on the soil water content of sandy soils, the production parameters of processing potatoes, and the potential of the product to improve resource use efficiencies.</u>

The application of Zeba™ increased the water content of the sandy soils, in both the 0-300 and 300-600 cm soil layers. The highest application rate (15 kg ha^{-1}) of product, resulted in the highest soil water contents. Increases in tuber fresh yield was also observed with an increase in treatment rate, although the highest treatment rate gave a yield similar to that from the control. An optimal rate therefore exists, whereafter the further addition of polymer will result in a reduction in yields. The increases in tuber fresh yield have been attributed to the increases in soil water content in the soil profile.

There were limited differences in leaf and tuber nutrient contents observed between the treatments, and the tubers from all the treatments satisfied the quality requirements for the potato processing industry in South Africa. The application of Zeba™ therefore did not adversely affect the quality of the tubers.

The yield increases allowed for improved water and nutrient use efficiencies. Zeba™ enhanced the water and possibly the nutrients retained in the rooting zone, allowing for improved uptake and utilisation of these valuable resources. The improved growth and production ultimately increased resource use efficiencies. The treatments where Zeba™ was applied, allowed for the sustainability thresholds set for the area to be met for both the water and nutrient use efficiency.

The recommended optimal Zeba™ rate for application in the Sandveld is 10 kg ha^{-1} for potato production. The use of the superabsorbent polymer Zeba™ should enhance production in the Sandveld region, thereby improving resource use efficiencies

Objective two is to assess, by means of a pot trial, the duration for which the product, Zeba™ can provide improvements in absorption potential to the pot system, before degrading to the point where it can no longer retain water.

Overall, the water holding capacity of the pot and polymer system increased with an increase in product applied. It was also clear that the polymer had a more pronounced effect on the water holding capacity of the pot and polymer system as the soil dried out after an irrigation event, i.e., the pots with Zeba™ retained more water, compared to the control, three days after irrigation, compared to one day after irrigation.

The water holding capacity of the pot and polymer system decreased over the period of the trial. There was no indication that the reduction in retention ability was due to the degradation of the polymer and was rather attributed to the increase in temperature. In sandy soils, with low organic carbon contents and no growing plants, the polymer did not degrade to such an extent that its ability to retain water decreased.

5.2. General conclusion

The aim of this study was to evaluate the potential of the biodegradable superabsorbent polymer, Zeba™, to improve potato production systems in semi-arid, drought prone areas. Zeba™ successfully optimised potato production in the Sandveld by improving the water holding capacity of the sandy soils, increasing the fresh tuber yield, and improving the resource use efficiencies. In sandy soils, Zeba™ did not degrade over the course of twelve weeks and will theoretically be able to support potato crops throughout their entire growth cycle. The results obtained from the pot trial, however, may not necessarily apply to field conditions. In the field trial, a product rate of 10 kg ha^{-1} produced the best yield results, whilst in the pot trial, 15 kg ha^{-1} gave the best water retention results. The field trial is a more realistic representation of commercial potato production conditions, compared to the pot trial which was set up to limit various influencing factors. A treatment rate of 10 kg ha^{-1} is therefore recommended as the optimal application rate of Zeba™, to enhance and support potato production in the Sandveld region.

5.3. Limitations of the study

There are multiple factors affecting the absorption capacity of SAPs. Most studies saw an improvement in water retention with the addition of SAPs, regardless of soil texture, however, the improvement factor is highly influenced by the soil texture (Abedi-Koupai *et al.* 2008; Saha *et al.* 2020b). The use of SAPs will therefore not be economically feasible in all situations. Coarse textured soils gave a greater improvement, compared to fine textured soils. This is due to finer textured soils naturally having a better water retention ability. The pore spaces in fine textured soils also restrict the polymer to swell to its maximum capacity (Saha *et al.* 2020a; Zhou *et al.* 2020). The positive results obtained in this study can therefore only be used to make recommendations in areas that have the same, or very similar, soil texture properties. Having assessed the absorption ability of the polymer in different soil textures, may have provided enough additional information to be able to make recommendations for the use of Zeba™ in other areas in South Africa, as well as globally.

The hydrophilic backbone of SAPs interact with water upon contact, resulting in the formation of hydrogen bonds and hydration (Behera and Mahanwar 2020). Therefore, the ability of hydrogels to retain water varies according to the quantity of hydrophilic groups and the density of crosslinking (Ojogbo *et al.* 2020; Oladosu *et al.* 2022). There are multiple ways whereby natural starches are modified to make them suitable for use as SAPs (Behera and Mahanwar 2020; Gamage *et al.* 2022). There are also multiple factors, relating to the synthesis and composition of the SAP, that affect its properties (Ismail *et al.* 2013; Behera and Mahanwar 2020). There is very limited information regarding the synthesis and composition of many of the SAPs studied in the literature, making it very difficult to directly relate the findings of this study, and the various studies in literature, to another.

Leaf analyses were taken too infrequently during the growing season, and the significance of treatments on haulm nutrient removal and growth could not be observed during the span of the field trial. Measuring these indicators on a regular basis would have provided information that could have been used to assess and explain crop growth during the growing season. This information could have been used to determine the effects of the SAP, Zeba™, on the development and growth of the potato crops, and not just its effect on the final yield and quality parameters.

The relationship between SAP application and soil microbial properties is still poorly understood, and many important topics relevant to this aspect still require more research. The review, evaluating multiple studies, suggested that the use of SAPs, either alone, or used in conjunction with biological fertilisers, successfully improved soil physical qualities and generated a favourable environment for microorganisms (Jamal *et al.* 2022). Soil organisms facilitate the degradation of starch and starch blends in soil (Gamage *et al.* 2022). The microbiology in the soil, which is impacted by living roots, will therefore have an impact on the degradation of starch-based polymers. It would have been advantageous if the pot trial was designed to incorporate living plants. This would have resulted in the soil environment in the pot trial being closer to the conditions found in potato cropping fields, thereby giving a more accurate indication of the degradation of biodegradable SAPs in potato production systems.

It should also be noted that the pot trial was irrigated with distilled water. It is well known from literature that the water quality, and soluble salts present in the absorption solution affect the absorption ability of SAPs (Johnson 1984; Banedjschafie and Durner 2015; Ostrand *et al.* 2020; Chang *et al.* 2021). Soluble salts in irrigation water reduce the absorption of polymers, but to varying degrees. A study conducted by Banedjschafie and Durner (2015) also showed that salts permanently reduce the capacity of the polymer to absorb water after a few wetting and drying cycles. This limitation is important to consider when using these products in cropping systems, where there will be soluble salts present in the water and soil.

5.4. Recommendations for future research

The frequency of irrigation depends on the soil's reservoir and its capacity to store enough water to support the crop's evaporative demands (ETc). The use of SAPs in the Sandveld, by improving the water holding capacity of the sandy soils, could therefore potentially reduce the irrigation frequency (from daily irrigation to alternate day irrigation) in summer months by improving the water reservoir in the soil and by reducing the evaporation. Further research is needed to evaluate whether a reduced irrigation frequency could reduce the total irrigation amounts, maintain the tuber yields, improve the water use efficiency, and would still be economically feasible.

Super absorbent polymers (SAPs) induce the establishment of nutrient reservoirs, either by increasing the soil cation exchange capacity (CEC) and/or by physically limiting soluble nutrient transport through water retention (Jahan and Nassiri Mahallati 2020; Ostrand *et al.* 2020; Oladosu *et al.* 2022). The SAPs retain the dissolved fertiliser, and release it as the polymer desorbs, acting as a slow release fertiliser (Dhanapal *et al.* 2020). This improves the efficiency of plant uptake, reduces the nutrient requirement of cultivated soils, and reduces the leaching losses (Egrinya Eneji *et al.* 2013; Jahan and Nassiri Mahallati 2020; Elshafie and Camele 2021). Further research should be conducted to determine whether the use of SAPs can reduce the fertiliser inputs, whilst still achieving good tuber yields with optimal quality parameters, for potato production in the Sandveld.

The possible reduction of these two inputs resulting from the use of SAPs, is a big opportunity, especially in areas such as the Sandveld where the cost of inputs is very high. Reductions could be feasible, seeing that high losses of water and nutrients, via drainage, were reported for potato production in this region (Kayes 2019). The reduction of fertiliser, energy used for irrigation, and water used for irrigation could not only possibly have a significant economic benefit, but will also have a positive effect on the environment, and the overall sustainability of the farm.

It is also recommended to conduct research assessing the biodegradation and biodegradation rate of this SAP in field conditions. Soil burial tests, whereby the SAP is buried and assessed frequently, are common ways to determine the structural degradation (Azahari *et al.* 2011; Thombare *et al.*

2018; Ojogbo *et al.* 2020; Bora and Karak 2022). For this method, however, it is very challenging to determine the absorption decline associated with the structural degradation, which in my opinion is important when assessing if the SAP will be advantageous over time. I propose doing a pot trial, where the system will be irrigated with an artificial root exudate cocktail to simulate soil microbial activity found in cultivated potato fields, without having to grow a plant, which complicated the measurement of water retention (Steinauer *et al.* 2016). A fertilisation strategy similar to conventional production systems should also be followed. The absorption capacity of the SAP can then be measured over time in a similar way as was done in the pot trial in this study. This enables the environment to be a better representation of field conditions, even though it is still being controlled.

5.5. References

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Supplementary Material

Supplementary Table S-15 The nutrient content (dry mass basis; DM%) of potato leaves sampled 80 days after planting.

Nutrient	Treatment				
	T0	**T1**	**T2**	**T3**	**T4**
N (%)	4.58	5.51	5.16	5.16	4.99
P (%)	0.360	0.430	0.403	0.400	0.413
K (%)	3.08	3.69	3.11	3.17	2.78
Ca (%)	2.46	2.08	2.54	2.59	2.71
Mg (%)	1.09	0.92	1.06	1.07	1.18
Na (mg/kg)	3975	1827	2196	2283	2428
S (%)	0.270	0.300	0.300	0.303	0.297
Fe (mg/kg)	114.7	116.3	102.0	120.3	113.0
Mn (mg/kg)	114.0	174.3	154.0	141.7	178.0
Cu (mg/kg)	4.33	4.67	4.00	4.00	4.33
Zn (mg/kg)	15.0	15.7	13.3	13.7	14.3
Mo (mg/kg)	1.63	1.78	1.41	1.66	1.49
B (mg/kg)	65.3	55.0	57.3	57.3	60.0

Supplementary Table S-6 The nutrient content (dry mass basis; DM%) of potato leaves sampled 120 days after planting.

Nutrient	Treatment				
	T0	**T1**	**T2**	**T3**	**T4**
N (%)	3.34	3.56	3.60	3.20	4.21
P (%)	0.250	0.267	0.263	0.237	0.323
K (%)	2.57	3.11	2.85	2.74	3.14
Ca (%)	2.49	2.13	2.15	2.38	2.23
Mg (%)	1.06	0.97	1.05	1.09	1.00
Na (mg/kg)	7756	6041	6499	7814	6028
S (%)	0.237	0.240	0.233	0.240	0.260
Fe (mg/kg)	116.3	117.3	134.0	118.0	134.0
Mn (mg/kg)	73.67	93.67	90.67	70.00	118.33
Cu (mg/kg)	9.33	7.67	9.33	8.33	7.67
Zn (mg/kg)	13.0	11.0	12.7	12.0	15.3
Mo (mg/kg)	1.66	1.26	1.57	1.68	1.45
B (mg/kg)	61.3	58.3	61.3	63.3	63.3

Supplementary Table S-7 the chemical composition (dry mass basis; DM%) of the tubers.

Nutrient	**Treatment**				
	T0	**T1**	**T2**	**T3**	**T4**
N (%)	1,30	1,39	1,39	1,25	1,36
P (%)	0,363	0,360	0,365	0,350	0,352
K (%)	2,40	2,35	2,50	2,41	2,38
Ca (%)	0,033	0,035	0,035	0,035	0,032
Mg (%)	0,093	0,090	0,097	0,095	0,090
S (%)	0,138	0,133	0,135	0,133	0,133
Fe (mg/kg)	46,67	37,67	47,50	45,00	37,33
Mn (mg/kg)	8,83	7,33	8,67	8,17	7,00
Cu (mg/kg)	4.17	3.83	3.66	3.33	3.33
Zn (mg/kg)	19,50	19,50	18,33	17,17	19,00
Mo (mg/kg)	0,78	0,68	0,76	0,71	0,78
B (mg/kg)	7,17	7,00	7,17	7,00	7,00