Phosphorus fertiliser source and its effect on potato (*Solanum tuberosum L.*) production

By

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Declaration

By submitting this dissertation electronically, I declare that the all work contained therein is my own original work, I am the owner of the copyright thereof (unless to the extent explicitly otherwise stated) and to the best of my knowledge contains no materials previously published, all literatures consulted have been properly acknowledged.

Date: December 2017

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Abstract

Potatoes are an essential component in the diet of millions of consumers in developing countries such as South Africa. Potatoes play a major role in national food security, nutrition, poverty alleviation and income generation through their role in the processing industries. The potato crop requires a lot of soil nutrients, particularly phosphorus (P) and low soil fertility is one of the major factors responsible for reduced crop yields. Polyphosphates are increasingly being favoured as inorganic P source used to increase crop productivity. In order to evaluate the response of potatoes to P sources and P application levels a series of pot experiments were conducted in the summer of 2015 and the winter of 2016, with the aim of evaluating the growth, yield and quality of potatoes in response to different P sources orthophosphate (mono-potassium phosphate – MKP) and polyphosphate with varying pH levels.

In the first experiment conducted in the summer of 2015 four potato cultivars (Mondial, Sifra, Lanorma and Innovator) as prescribed by Potato South Africa were grown with different P sources. Treatments consisted of: T1) 100% orthophosphate, T2) 25% orthophosphate + 75% polyphosphate, T3) 50% orthophosphate + 50% polyphosphate and T4) 100% polyphosphate. This experiment was repeated in the winter of 2016 but using cultivars Eos and Destiny due to immediate availability. Morphological and yield parameters showed responses to P source, which was reflected during both seasons. In both seasons total tuber yield was highest when potato plants were fertilised with 100% orthophosphate. Phosphorus utilization efficiency (PUE) and tuber defects were not affected. Phosphorus-uptake efficiency was significantly different between cultivars in both seasons. Tuber and leaf analysis revealed that P applied as 50% polyphosphate showed high percentage of N content for tubers, and applying P as 100% and 50% polyphosphate resulted in higher P leaf content. Overall results of the two-season study show that orthophosphate had a superior effect on potato growth and yield compared to applying polyphosphates.

To study the effect of pH on the uptake of P, potato plantlets (cultivar Mondial) were fertilised with: T1: Control – 100% of P applied as orthophosphate (mono-potassium phosphate) at pH levels 5.5, 6.5 and 7.5 and T2: P applied as polyphosphate at pH levels 5.5, 6.5 and 7.5. Results showed that interaction between P application and pH levels significantly influenced shoot dry mass and total yield. The orthophosphate showed higher shoot dry mass in comparison to the polyphosphate. Total fresh tuber yield was not affected by the pH of the solution when P was applied as orthophosphate. For most other parameters no difference was
observed between the orthophosphates and polyphosphates and pH levels. Interaction effects between P treatments and pH levels for tuber and leaf analysis were however noted; polyphosphate at pH of 7.5 gave higher tuber N and Zn content, while the highest B content for tubers was obtained with orthophosphates, at pH 6.5. The overall results of the pH experiment showed that the orthophosphates and the polyphosphates did not differ in terms of crop yield.

These results add valuable information for optimizing potato fertilisation to enhance productivity.
Uittreksel

Aartappels is 'n noodsaaklike komponent in die dieet van miljoene verbruikers in ontwikkelende lande soos Suid-Afrika. Aartappels speel 'n belangrike rol in die nasionale voedselsekerheid, voeding, armoedeverligting en inkomstegenererering deur middel van hul rol in die verwerkings-nywerhede. Die aartappelplant vereis baie voedingsstowwe in die grond, veral fosfor (P) en lae grondvrugbaarheid is een van die belangrikste faktore wat verantwoordelik is vir verminderde oesopbrengste. Poli-fosfate word toenemend verkies as anorganiese P-bron waar dit gebruik word om produktiwiteit te verhoog. 'n Reeks pot eksperimente is uitgevoer in die somer van 2015 en die winter van 2016 om die reaksie van aartappels op P bronne en P toedieningspeile te evalueer.

In die eerste eksperiment (somer 2015) is vier aartappelkultivars (Mondial, Sifra, Lanorma en Innovator) gekweek met verskillende P bronne. Behandelings het bestaan uit: T1) 100% ortofosfaat, T2) 25% ortofosfaat + 75% polifosfaat, T3) ortofosfaat 50% + 50% polifosfaat en T4) 100% polifosfaat. Hierdie eksperiment is herhaal in die winter (2016), maar kultivars Eos en Destiny is gebruik. Morfologiese parameters en opbrengs is beïnvloed deur die P behandelings in beide seisoene. In beide seisoene was die totale knolmassa die hoogste vir plante behandel met 100% ortofosfaat. Fosfor gebruik-doeltreffendheid (PUE) en knol defekte is nie beduidend beïnvloed nie. Fosfor-opname-doeltreffendheid het beduidend verskil tussen kultivars en tussen die twee seisoene. Knol- en blaarontledings het getoon dat knolle 'n hoë persentasie N het wanneer P toegedien word as 50% polifosfaat. Daarteenoor was die P inhoud van die blare hoër wanneer P toegedien is as 100% en 50% polifosfaat. Algehele resultate van die studie oor die twee seisoene toon dat ortofosfaat n beter uitwerking op plant groei en aartappelopbrengs gehad het.

Om die effek van pH op P opname te evalueer is aartappelplantjies (kultivar Mondial) behandel met: T1: kontrole - 100% P toegedien as ortofosfaat (mono-kaliumfosfaat) by pH 5.5, 6.5 en 7.5 en T2: P toegedien as polifosfaat by pH 5.5, 6.5 en 7.5. Resultate het 'n interaksie getoon tussen P toediening en pH-vlakke op die halm droëmateriaal en die totale opbrengs. Vir ander parameters was geen verskil waargeneem tussen die P behandelings en pH-vlakke nie. Knol N en Zn inhoud was egter hoër waar polifosfaat by pH van 7.5 toegedien is, terwyl die hoogste B inhoud vir knolle gemeet is waar ortofosfate by pH 6,5 toegedien is.

Hierdie resultate lewer waardevolle inligting vir die optimalisering van aartappel bemesting om produktiwiteit te verbeter.
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The referencing style in this thesis for all chapters was written according to the requirements of the South African Journal of Plant and Soil. This thesis represents a compilation of manuscripts where each chapter stands as an individual unit. Repetition between chapters that may occur was thus unavoidable.
Chapter 1

Introduction and literature review

Introduction

Globally the potato (Solanum tuberosum L.) is the fourth most important food crop after rice (Oryza sativa), corn (Zea mays) and wheat (Triticum aestivum) (Douches et al. 1996). Potatoes can be considered as one of the most important food crops in African countries (Tshisola et al. 2014). In South Africa potatoes are grown all year round in all nine provinces under different climatic conditions (Department of Agriculture 2013).

Unfortunately, potato production is limited by a number of factors such as high temperatures, short day lengths, low light intensities and most importantly low soil fertility (Jones and Wendt 1994). Ozanne (1980) reported that P is one of the most yield limiting factors in most soils. Food security is a major problem, especially with the ever rising population (Nawaz 2012). However, the goals of food security cannot be achieved without optimum supply of soil nutrients (Chen 2006; Ali et al. 2008). Along with nitrogen (N) and potassium (K), P is one of the major nutrients essential for plant growth and development. Phosphorus (P) plays an irreplaceable role in several key functions (Al-Abbas and Barber 1964). In contrast to N and K, P is immobile in most soils due to precipitation and adsorption to mineral surfaces (Wild 1988). Therefore, it is unusual that greater than 25% of the P applied to the soil for plant nutrition prior to planting is withdrawn by the plant in the first year of the growing season. In addition, Sommerfeld and Knutson (1965) and Sharma and Arora (1987) reported that P application increases potato yields up to certain levels (application rates), but with P application beyond those rates, yield losses are apparent. Polyphosphate, a P form which has been reported to increase soil P availability and plant P uptake due to its ring structure (Philen and Lehr 1967 and Engelstad and Terman 1980), may address food security by increasing crop productivity per hectare.

Phosphorus fertilisers differ in formulation (liquid or solid granules) and in chemical composition or form (orthophosphate or polyphosphate) (Ottman et al. 2005). The majority of fertilisers such as nitro phosphate (NP), phosphoric acid (PA), mono-ammonium phosphate (MAP), di-ammonium phosphate (DAP) and triple superphosphate (TSP) contain P in orthophosphate form. As soon as orthophosphates are dissolved in the soil solution they become available for crop uptake, usually as a primary orthophosphate ion (H$_2$PO$_4^-$ at a pH of <7 in soil solution) or as a secondary orthophosphate ion (H$_2$PO$_4^{2-}$ at a pH of >7 in soil solution) (Noack et al. 2010).
Polyphosphate fertilisers are made up of both orthophosphates and polyphosphates. In the formulation about half exist as orthophosphates the other half exists as polyphosphate chains made up of orthophosphates (Rehm et al. 1998). Given sufficient water, polyphosphate hydrolyses or breaks down into simple orthophosphate form. Polyphosphates are water soluble (Robertson 2004). However, the time needed for polyphosphate to break down into orthophosphates varies with soil acidity or alkalinity (Robertson 2004) and soil temperature (Coetzee 2013). Temperature has the most influential effect on the rate of hydrolysis of polyphosphates. The rate of hydrolysis can range between 42 and 84% within 72 hours at temperatures of 5, 20 and 35°C. However, hydrolysis takes longer under dry conditions. When 80% of polyphosphates have dissolved in water their efficiency is equal to that of orthophosphate. However, some studies have reported that polyphosphate efficiency is regarded not better than that of orthophosphates (Robertson 2004). The different forms of P as well as soil reactions could ultimately influence potato response to the different P sources.

Literature review

The role of phosphorus in potato production

Phosphorus (P) is a very important macro element. Phosphorus plays a major role in many physiological processes including photosynthesis, respiration, energy storage and transfer, cell division, cell development and carbohydrate metabolism. Most significant metabolic reactions are possible because of phosphate derivatives (Marschner 1995; Mullins 2009). Phosphorus is part of the structures of deoxyribonucleic acid (DNA), ribonucleic acid (RNA), adenosine triphosphate (ATP) and phospholipids in membranes (Ekelöf 2007). Adenosine di-phosphates and adenosine triphosphates (ADP and ATP) are created and regenerated when there is enough P. When P from ATP or ADP is broken off, energy is created, which is used by plants to convert other nutrients into usable building block which enables plant growth (Marschner 1995). Appropriate amounts of P will ensure early root development (Department of Agriculture 2013) and sufficient P supply during the early growth stage of potatoes will ensure proper crop development and reproduction (Wallace 1943). In grain crops P ensures faster crop growth, mainly because enough supply of P accelerates grain maturity and improves stem strength (Haberle et al. 2008).
Tuberization and total number of tubers as affected by phosphorus application

Tuberisation is a complicated process which involves a number of significant biological systems (Hannapel et al 2004). Sufficient P in the soil is essential for early potato development (Jenkins and Ali 2000), tuber set and total number of tubers (Jenkins and Ali 2000, Rosen and Bierman 2008) and tuber maturity (Stark and Love 2003). Although Ekelöf (2007) reported no clear effect of P fertilisation on tuber set, studies by Tukaki and Mahler (1990) and Grewal et al. (1993) indicated that the number of tubers formed have a positive correlation with P concentration in the potato crop. O’Brien et al. (1998) found that amount of light absorbed by the crop during the first week of tuber initiation correlated with the total number of tubers initiated, thus it is possible that P fertilisation could have a positive effect on tuber set under certain conditions (Tukaki and Mahler 1990). A study by Tukaki and Mahler (1990) found that tuber set increased continuously when P concentration in the nutrient solution was increased from 0 to 10 μg P/ml, although, increasing the P content in the nutrient solution from 10 to 55 μg P/ml did not result in a greater number of tubers produced per plant. Allison et al. (2001) reported an increase in number of tubers in three out of 22 field experiments. Phosphorus fertilisation had a significant impact on tuber number, exclusively at sites where P fertiliser had an impact on tuber fresh yield. Increase in total number of tubers was not due to an increase of stems per plant but an increase of tubers per stem.

The effect of phosphorus on tuber quality

Very few studies have been found that actually show that P fertilisation is positively correlated with tuber quality. However, Ekelöf (2007) and Berisha et al. (2014) reported that P fertilisation prevents discoloration of tubers; they also noted that fertilisation with P increased starch concentration. According to Ekelöf (2007), P has a positive effect on citric acid production and cell expansion; however the properties of the cell wall will stay the same. Variations amongst average tuber sizes are characteristics which are important with regard to tuber quality and since P sometimes influences tuber set, P may be seen as a factor which influences quality. Ekelof (2007) deduced that P affects tuber quality but limited information is available regarding whether P deficient soils will yield potatoes with negative quality characteristics. In addition, shortages of P may lead to poor quality tubers with a low shelf life (Department of Agriculture 2013). Various other literature sources also alluded that insufficient P may significantly reduce tuber quality, yield and size (Westermann and Kleinkopf 1985; Stark and Ojala 1989; Hopkins et al. 2010a; 2010b; 2010c). On the contrary, Zelalem et al. (2009) reported that P is not expected to have an effect on internal quality as compared to Ca.
**Symptoms of phosphorus deficiency**

When P is deficient in potato plants, the formation of chlorophyll is less affected compared to cell and leaf expansion, resulting in the top side of the leaf becoming dark green. The stem and lower side of the leaves turn purplish and sometimes yield losses may be observed without these symptoms (Hahlin and Ericsson 1981, Bennett 1993). Deficiency symptoms in potatoes may include stunted plants with short internodes and a poor developed root system. However, purple colouring may be observed even though potatoes are not P deficient, depending on the cultivar in question (Department of Agriculture 2013).

**Importance of phosphorus fertilisation and phosphorus uptake by potato plants**

It is relatively expensive to produce potatoes, with seed potatoes accounting for more than 30% of the total production expenses (Correa et al. 2008), followed by fertiliser costs, which account for approximately 20 % of the total production expenses. This is because potatoes require relatively more nutrients than other crops (Stark et al. 2004, Munoz et al. 2005). In addition to the shallow roots of potatoes, many potato genotypes have a low water and nutrient use efficiency (Sattelmacher et al. 1990, Love et al. 2003). Potatoes are also sensitive to having a steady nutrient supply and poor fertilisation practises often result in poor quality tubers (Stark et al. 2004, Westermann 2005, Laboski and Kelling 2007). According to Tanner et al. (1982), potato roots reside in the top 60 cm of the soil, with most of the roots residing in the upper 25 cm. Different crops have different root systems and therefore the type of root system a plant has influences how a specific crop responds to P application. Other crops such as wheat have deeper roots with a higher root density that is evenly distributed in the soil (Coetzee et al. 2013). Wheat responds well to newly applied P before planting, it has an adventitious root system and if there is enough P wheat takes up P from the plough layer. Other crops such as groundnuts have a taproot and can take up P beyond the plough layer; so groundnuts can thrive on left over P from the previous season (Havlin et al. 1999, Marschner 1995, Brady and Weil 2008).

Potatoes respond well to once-off applied P or P applied before planting since P does not easily leach from the soil (Department of Agriculture 2013). Previous studies by Duncan and Ohlrogge (1958) and Miller and Ohlrogge (1958) concluded that N fertilisation resulted in increase in P uptake. They reported that the increase in P uptake due to N was due to greater root development. Phosphorus fertilisers are important for optimum plant growth since most agricultural soils have low total and available P content (Hammond et al. 1990).

continuously throughout their growing season until harvest maturity. However, the amount of P taken up daily varies depending on the particular growth stage (Ekelöf 2007). Studies conducted by Kolbe and Stephan-Beckmann (1997a) and Kolbe and Stephan-Beckmann (1997b) revealed that the daily maximum P uptake rate in potatoes is 1.4 kg ha\(^{-1}\) day\(^{-1}\) and occurs predominantly between 30 and 45 days after emergence. Grewal et al. (1993) observed that the daily P tuber uptake rate is 0.2 kg ha\(^{-1}\) and occurs between 30 and 80 days after emergence. Phosphorus requirement for potatoes is high, about twice that of other plant species (Ekelöf 2014), but the P-use efficiency of potato is low (Van der Zaag 1981). Sikka (1982) noted that a normal potato plant removes approximately 90 to 192 kg ha\(^{-1}\) of N, 13.8 to 25.8 kg ha\(^{-1}\) of P and 150 to 250 kg ha\(^{-1}\) of K from the soil but this uptake is dependent on soil water content supply, management practices and soil type. During tuber formation and tuber development stages P uptake rate is very high in the stem, leaves and tubers (Covarrubias-Ramírez et al. 2005). After 80 days, P levels in the stem continuously decrease until harvest maturity. During senescence, negative P uptake rates in the leaves will be observed because during senescence nutrients are translocated from the foliage to the roots and tubers (Ekelöf 2014).

Potato tubers have a high demand for K, higher than that of N (Oosthuysie 2012). A specific crop’s P application rate is dependent on the amount of nutrients in the soil prior to planting. In South Africa, P rates can be as high as 205 kg ha\(^{-1}\) for high yielding potential areas of about 80 t ha\(^{-1}\) (Steyn and Du Plessis 2012a). Brink (2016b) reported that typical P application rates range from 50 to 150 kg P ha\(^{-1}\) or 110 to 350 kg P\(_2\)O\(_5\) ha\(^{-1}\). In Limpopo, Polokwane, farmers may apply a total of 80 kg ha\(^{-1}\) of P through the growing season (12-16 weeks) (Du Raan and Boneschanas 2016). In the Sandveld farmers may apply a total of up to 182 kg ha\(^{-1}\) of P throughout the growing season. Such applications in the Sandveld are usually spread over the 16 weeks in doses of about 11 kg ha\(^{-1}\) per week (Brink et al. 2016a). Farmers in the Sandveld apply more P than farmers in Limpopo. This could be because of the soil texture. The Sandveld area is dominated by sandy soil which has a low nutrient and water holding capacity as was verified by Steyn and Du Plessis (2012b). Soil texture is an important factor to consider when applying P. For example, when P is applied on clay soil it becomes unavailable due to P fixation. That is in contrast to sandy soils; when P is applied to sandy calcareous soils, P becomes available to plants for longer (Havlin et al. 1999). Potatoes can be grown on different soils with different soil textures (ratio of clay to silt and sand), although deep, well drained soils with light texture are preferable. Potatoes grown in sandy soils are easy to harvest and they also have a
higher infiltration rate but sandy soils have a low water holding capacity, which may result in leaching of nutrients. Generally light loamy soils or soils with a coarse texture are ideal for potato production (Steyn and Du Plessis 2012b).

Phosphorus plays a major role in the growth and development processes of plants (Sultenfuss et al. 1999), however, P uptake is often limited by availability (Goldstein et al. 1988). Phosphorus is mainly moved by diffusion from the soil to the roots of the plant (Hodges 2010). If there is no P in the soil, sufficient P fertiliser should be applied to the P deficient soil, depending on the soil analysis. Fertiliser recommendations can be made after soil analysis to ensure high yields. Hammond et al. (1990) stated that P is very important in improving soil fertility for optimum crop growth and although crops require a considerably lower amount of P in comparison to other essential elements, P is essential for many plant functions (Mullins 2009).

**Phosphorus uptake mechanisms**

Inorganic P can be taken up from the soil solution through diffusion, root interception and mass flow (Havlin et al. 1999).

**Diffusion**

Bistow (2002) reported that diffusion occurs when ions in the soil solution move from a high concentration to places with a low concentration. This means a nutrient concentration gradient is formed that results in ions to diffuse to the vicinity of the roots of the plant. The nutrient requirement of the plant is directly proportional to the concentration gradient. Thus when the plant’s nutrient requirement is high the concentration gradient is also high, which causes a high rate of ion diffusion from the soil solution to the roots of the plant. There are a number of soil properties that influence diffusion of nutrients to the plant roots; however the size or rate of diffusion gradient is the most important (Havlin et al. 1999). If the diffusion rate is high, then the diffusion coefficient (De) is high, which in turn determines how far the nutrients will diffuse to the root system. Diffusion’s principle is that as the soil water content increases the diffusion coefficient increases, thus increasing the diffusion rate.

\[
De = D_\omega \theta (1/T) (1/b)
\]

1.1

where

\(D_\omega = \text{diffusion coefficient in water}\)

\(\theta = \text{volumetric soil water content}\)
\( T = \text{tortuosity factor} \)

\( b = \text{soil buffer capacity} \)

The above equation shows that the soil water content (\( \theta \)) is directly proportional to the diffusion coefficient (\( D_\omega \)), which causes an increased diffusion rate (Coetzee et al. 2013). Furthermore, Brady and Weil (2008) reported that when the soil water content is reduced, films which are found around the soil particles shrink in size and the diffusion of ions becomes tortuous. It was also noted that when soils have been irrigated to field capacity, transport of nutrients towards the roots is very effective.

Temperature has the most influential effect on nutrient uptake by diffusion. Ideal temperatures for optimum diffusion range from 10 to 30°C. Fluctuations in temperature affects ion absorption, which means increase in temperature from 10°C results in increased rate of ion absorption. Most of the P (80%) moves within the soil to the plant roots through diffusion (Havlin et al. 1999; Brady and Weil 2008).

**Root interception**

According to Havlin et al. (1999) and Brady and Weil (2008) root interception is an essential mechanism for ion absorption and is improved when new roots form and spread in the soil. When roots mature and become more exposed to a larger soil volume, the total root mass comes in contact with soil solution ions, and these ions will be absorbed through direct contact. Within the soil solution cations such as hydrogen, located at the surface of root hairs will exchange with other cations like calcium (Ca), which are located on the surface of clays and organic matter (Weisenseel et al. 1979).

Weisenseel et al. (1979) reported that the amounts of nutrients that are absorbed by the crop are dependent on rate of growth and the volume of the roots. However, roots usually occupy less or equal to 1% of the soil volume, but may occupy close to 3%, depending on soil porosity and nutrient status of the soil in question (Walker et al. 2003; Brady and Weil 2008).

Root interception can be improved by making use of mycorrhizae, where the hyphae threads of these mycorrhizae connect to the roots of the plant system, which causes greater soil contact. Most fungi develop in the cortex of the roots and nutrients are transported to arbusculars because the majority of agricultural crops' roots have vesicular arbuscular mycorrhizae. The greater the nutrient absorption surfaces, the more nutrients will be absorbed (Havlin et al. 1999).
**Mass flow action**

Mass flow action takes place when dissolved substances are moved by the flow of water towards the surface of the roots or when nutrient ions within the soil solution are transported to the root surface as a result of the transpirational water uptake by the plant. However, the proportions of nutrients that reach the roots of the plant through mass flow action are dependent on the flow of water or rather the amount of water that is being consumed by the plant. In addition, the average nutrient concentration in the soil water solution plays a big role in transportation of nutrients to the surface of the roots. When the soil water, moving towards the roots of the plant decreases, as the atmospheric temperature decreases as well, transportation of nutrients by mass flow action also decreases due to reduced plant transpiration (Havlin et al. 1999; Brady and Weil 2008).

Havlin et al. (1999) reported that in soils with a low P content mass flow only provides a small amount of the total P required by the plant (about 1%) but in soils which have been properly fertilized and have a P solution of higher than 0.05 mg kg$^{-1}$ mass flow can provide up to 20% of P to the roots of the crop. Phosphorus uptake is encouraged by both mass flow action and diffusion, although Havlin et al. (1999) concluded that diffusion is the primary mechanism for P uptake.

**Phosphorus efficiency**

Graham (1984) and Wang et al. (2010) defined P efficiency as the ability of plants to attain high yield under P limiting environments. Phosphorus efficiency can be expressed as phosphorus uptake efficiency and phosphorus-utilization efficiency (PUE). Phosphorus uptake efficiency is the capacity of plants to take P up from the soil, whereas P-utilization efficiency is the ability of the plants to produce biomass or product of economic interest (e.g., grain and tuber) using the P taken up (Wang et al. 2010). High P-utilization efficiency can also refer to the plant’s ability to yield high biomass in proportion to the amount of P it has removed from the soil. High P-utilization efficiency can be observed in non-agricultural ecosystems, where forest plants produce large biomass with low P. This is achieved by physiological, morphological and metabolic responses. It has also been reported that certain agricultural crops are more productive than others when grown in low P soils (Osborne and Rengel 2002; Ozturk et al. 2005; Korkmaz et al. 2009).

Phosphorus fertilisation is important to reduce yield losses in the field. However, most of the P applied to the soil during the growing season may become unavailable to the crop due to
conversion of P to unavailable forms which cannot be taken up by the plant. Potato cultivars which are P efficient with the ability to grow and produce optimum yields in deficient soil should be identified (Hash et al. 2002; Wissuwa et al. 2002; Yan et al. 2004). Since differences in P uptake differs among potato cultivars as verified by Lee (2013). Lee (2013) reported that potato cultivar “Satina” is a P-efficient cultivar based on high productivity and PUE for both shoot and tuber in non P amended soil. Disbursement of such P efficient cultivars in both small scale and commercial farming systems would reduce associated P fertiliser cost, maintain P resources since P is scarce and reduce environmental pollution (Cakmak 2002; Vance et al. 2003).

Mechanism of improving phosphorus utilization efficiency in plants

Phosphorus utilization efficiency (PUE) was defined earlier as the ability of the plants to produce biomass or product of economic interest (e.g., grain and tuber) using the P taken up (Wang et al. 2010). In response to low soil P, plants have developed different mechanisms to cope with P deficient soils, such as enhanced P uptake under low P conditions and enhanced ability to produce high above-ground biomass for every unit of P taken up. Such mechanisms involve increased plant P uptake efficiency, modified root architecture (Balemi and Schenk 2009), more secondary roots (Zhu and Lynch 2004), increased root hairs and thinner roots for increased nutrient acquisition (Föhse et al. 1991, Bates and Lynch 2000) and enhanced root exudates (Bhattacharyya et al. 2013). All of these mechanisms can contribute to increased P uptake efficiency of the potato plant. Many of these mechanisms have been reported in enhancing P-utilization efficiency. Alternative P independent enzymes have enhanced ability to translocate P in the roots to other plant parts (Czarnecki et al. 2013).

Phosphorus concentration in the plant is measured to calculate total P uptake per plant and P-utilization efficiency (PUE) as follows:

\[
\text{Total P uptake per plant (mg plant}^{-1}\text{)} = \text{Total P concentration (tuber + leaves) (mg/g) \times dry matter yield(g/plant)} \quad (\text{Akhtar et al. 2008})
\]

Phosphorus use efficiency (PUE) can be calculated using shoots or tubers, depending on the plant part of interest. Some studies may use tubers, provided the shoots grown from the seed potatoes in question did not germinate uniformly, thus maximizing variability in shoot growth.

\[
\text{PUE} = \frac{\text{Tuber dry matter yield (g plant}^{-1}\text{)}}{P \text{ (mg plant}^{-1}\text{)}} \quad (\text{Elloitt and White 1994})
\]
Plants with a high above-ground biomass are considered P use efficient because of their low internal P requirement. Crops with high P content and high above ground biomass are regarded as P uptake efficient because they use various methods in order to increase P uptake in low P soils or environments (Föhse et al.1991).

**Phosphorus application methods**

Instead of applying relatively high amounts of P fertilisers it may be advisable to seek new ways of improving P-utilization efficiency through timing and using different P application methods (Hopkins 2010a). Timing and application methods of P fertilisers are very important factors when investigating crop response.

*Broadcasting*

According to Ekelöf (2014), broadcasting is the most inefficient method of P application from a plant perspective; however it is one of the most commonly used fertiliser application methods after band application. Availability of machinery reduces the costs of fertiliser application and this is the reason why farmers broadcast fertilisers. The current knowledge is that broadcasting P results in much more fertiliser-soil contact, but not only does broadcasting result in P precipitation and P sorption; it also decreases its availability (Jones and Jacobsen 2003). A study found that P banding is more efficient than broadcasted P, because banding increases the possibility of active roots to come in contact with P, instead of decreasing fertiliser-soil contact area (Sleight et al. 1984). In addition, the results of the study further showed that P fertiliser might be well distributed within the root layer, instead of being tightly banded in the soil and this increase in P distribution may increase P availability and crop yield. Broadcasting of P followed by soil incorporation is less effective in comparison to band placing P. Therefore broadcasting requires double or more the recommended rate of band applications (Hammond et al. 1990).

*Band application*

Phosphorus placement (banding) near the potato roots is the most commonly used method. Banding reduces the contact area with the soil, thus reduced soil binding (Marschner 1995). Therefore, banding may decrease the P sorption rate, affecting P uptake in a positive way and in turn lead to decreased P fertiliser recommendation by up to 50% (Ekelöf 2014). According to Grewal et al. (1993), instead of placing the P fertiliser below the seed potato or mixing the P fertiliser into the ridges, high potato yield can be obtained if P is placed 5 cm to the side of the seed potato. Hammond et al. (1990) reported that band placing P also increases P concentration within the area where the developing root is located. Leikam et al. (1983) reported
that banding P before planting as P pentoxide (P$_2$O$_5$) doubled yields when the P$_2$O$_5$ was banded as pre plant fertiliser instead of broadcasting P. A study conducted over two consecutive years in nine different locations on soils with a low to medium soluble total P, compared four depths of banded P as ammonium polyphosphate placed 15.2 cm to the side of the seed (McConnell et al. 1986). The study found that P banded at (5.1, 10.2 and 15.2 cm) to the side of the seed produced significantly higher yield than P banded at the original soil surface (before creating a furrow) and P banded at 10.2 cm away resulted in the highest average yield (McConnell et al. 1986). Phosphorus-utilization efficiency (PUE) was found to be significantly higher when P was banded 10.2 cm deep in comparison to banding at the original soil surface (5.1 cm) (McConnell et al. 1986). Phosphorus placed near the seedling and banded P applications were found to significantly increase PUE over broadcasted P (Sander et al. 1991). These results are not surprising since broadcasting P is one of the most inefficient methods of P application as pointed out above (Ekelöf 2014).

Phosphorus fertiliser efficiency for a specific plant is dependent on its capability to supply the plant with P higher than the crop can obtain from a P deficient soil. The P rate is also important - it should be such that it meets the crop demand to ensure maximum root development. Phosphorus is immobile and may be prone to fixation, depending on the type of soil it is being applied to, thus the best method for P application is band placement near the surface of the roots (Hammond et al. 1990).

**Liquid phosphorus fertiliser**

Fertigation is the latest innovation technologies where fertilisers are applied simultaneously with irrigation water. This creates new possibilities for controlling nutrient and water supplies to the plants since the desired concentrations are maintained as well as the distribution of water and nutrients in the soil (Bar-Yosef 1999). Application of P in potato production using drip irrigation has had some disadvantages in the past due to its high clogging potential, which results in limited movement in the soil. However, a recent study by Fanish (2013) reported on the growth of maize as influenced by various fertigation treatments. Orthophosphates were used as a source of P and results of the study showed positive response on root characteristics and dry matter production. Drip fertigated maize showed a yield increase of 39% in comparison to the conventional method. According to Singh et al. (2004), PUE can be enhanced by up to 45% using fertigation in comparison to broadcasting and by 25% in comparison to banding (placement). Dry matter accumulation, leaf area index and productivity can be increased if P is
applied through drip irrigation, compared to conventional fertiliser application methods. Fanish (2013) concluded that the cost of planting using drip irrigation and fertigation was higher than the surface irrigation method of applying soil fertilisers, although drip irrigation may compensate for the high costs with high yields.

**Foliar phosphorus application**

According to Alexander (1986) the rate in which plants take up nutrients through the leaves is dependent on the current nutrient status of the plant, size of water particle and amount of liquid applied to the plant leaf during nutrient uptake. The climatic conditions also play a significant role because during the day evaporation is usually high, thus more drying up of the spray which does not favour foliar uptake. Oosterhuis (2009) reported that foliar application should not be made to water stressed plants. According to Franke (1967) a gradual increase in negative charge from the epicuticular wax (outer part of the leaf surface) to the pectin layer increases the movement of cations and water molecules, thus increasing nutrient uptake. Grewal et al. (1993) and Fageria et al. (2009) reported that foliar P application increased the number of potato tubers per plant and thus the total yield. Foliar application of 2 kg ha\(^{-1}\) P is recommended when potato plants are being cultivated on soils with no P (Ekelöf 2014). Prasad and Brereton (1970) and Marschner (1995) noted that not all plant species have the ability to take up P through their leaves, but potatoes possess this ability. After three to four weeks of plant sprouting there is rapid uptake of P because of the high demand of P at this stage of the crop's life cycle in comparison to other stages of growth. Fortunately P forms that are soluble in water discharge a larger proportion of P when they come in contact with water (Lindsay and Stephenson 1959).

The most popular method is to apply the recommended P rate during planting (Hammond et al. 1990). The rate of P application is also dependent on the type of cultivar. If P deficiency is noticed during the growing season P may be applied as a foliar spray (Havlin et al. 1999; Lafond et al. 2003). It is essential to know the amount of P required by a plant to produce a unit yield as this helps in providing an approximate of the total P demand required by the crop.

**Sources of phosphorus**

Havlin et al. (1999) reported that most organic P is applied in the form of manure and it has been found to be less immobile in comparison to inorganic P fertilisers. Ammonium phosphate (AP), rock phosphates (RP), phosphoric acid (PA), and superphosphates (SP) are the major P sources used in South Africa. When rock phosphate has been processed and purified its P content ranges from 11.5 to 17.5% and none of it is soluble in water. Processed and purified rock phosphate is used directly as P fertiliser. However, rock phosphate is more effective on
soils with low pH, generally pH less than 6 (acidic soils) or if the application rate is two to three times more than the application rate of superphosphate fertilisers. The finely ground (processed and purified) rock phosphate can also be used in reclamation of soils with a low P content. Factors such as long growing seasons, soils with high water content and areas with warm climates increase rock phosphate effectiveness (Brady and Weil 2008).

According to Havlin et al. (1999) agricultural phosphoric acid contains 17 to 24% of P. Phosphoric acid (H₃PO₄) is produced when the raw rock RP is treated with sulphuric acid, also forming gyspum (CaSO₄·2H₂O). Single superphosphate (SSP) is also produced using the same technique, thus reacting RP with sulphuric acid (Marschner 1995). The agricultural phosphoric acid can then be applied to the plant through fertigation or band application. It is mostly favourable in alkaline or calcareous soils because of its acidification effects (Havlin et al. 1999).

According to Haynes and Naidu (1998) SP are neutral, thus they do not affect the pH of the soil in comparison to fertilisers which contain NH₄⁺ and phosphoric acid.

Single superphosphate (SSP) is not preferred because it has a low P content (Marschner 1995). Concentrated superphosphate and triple super phosphate (TSP) are produced to increase the P content of SSP by using the technique of reacting rock RP with phosphoric acid (Havlin et al. 1999). In terms of P content, SSP contains about 7 to 9.5% of P, with most of the P (about 90%) being soluble in water, thus available for plant uptake (Marschner 1995).

Triple super phosphate is known for its high P content and for this reason it is produced in granular form and blended with other material. It contains about 17 to 23% P and it can also be directly injected into the soil. Ammonization of single superphosphate and triple super phosphate is done to produce mono-ammonium phosphate (MAP) (NH₄H₂PO₄). Not only does ammonization decrease the proportion of water soluble P in the product but it also provides nitrogen (N) source (Havlin et al. 1999).

The use of MAP has increased over the last 10 years. MAP is a granular fertiliser which is soluble in water and contains about 11% N and about 21 to 24% P (Beaton et al. 1963). Di-ammonium phosphate (DAP) is also a granular fertiliser that is completely soluble in water and is the most popular P fertiliser (Beaton et al. 1963; Havlin et al. 1999). According to Havlin et al. (1999), caution must be taken during fertiliser placement using DAP because NH₃ is formed and may result in injury to the seed.
Orthophosphates

According to Coetzee (2013) orthophosphates are negatively charged ions and the form in which P is taken up by the plant roots from the soil. Similar to most agricultural fertilisers, orthophosphates are highly soluble in water and when dissolved in water the phosphate ions will become available for plant uptake. If the pH is less than 7.0, mainly primary orthophosphate ions (H$_2$PO$_4^-$) will be present, while secondary orthophosphate ions (HPO$_4^{2-}$) will dominate if the pH is greater than 7.0 (Noack et al. 2010).

Polyphosphates

Polyphosphates can be thought of as a chain of orthophosphate anions linked together by chemical bonding. Many orthophosphoric acid molecules are joined together by condensation and these molecules can become larger molecules through dehydration (removal of water). Through this process polyphosphates can be obtained (Robertson 2004). According to Mcbeath et al. (2007a) and Mcbeath et al. (2009) ammonium polyphosphate fertilisers (APP) are becoming the most used liquid fertilisers in agriculture. This may be because ammonium polyphosphate fertilisers contain both orthophosphate and polyphosphate, thus plants use fertilised more effectively (Coetzee 2013). In addition, polyphosphate fertilisers are rapidly gaining popularity - this may be due to their reported significant yield increases (Holloway et al. 2004; McBeath et al. 2005). Most common ammonium polyphosphate fertilisers also contain nitrogen (N), with an N: P: K ratio of 9:15:0 or 10:15:0. Ammonium polyphosphate fertilisers are preferred because they are stable under a wide range of temperatures. They have a high nutrient content, enhanced storage life, are crystal free and can be mixed with other nutrients, making them an excellent carrier for micro nutrients such as zinc (Coetzee 2013). Half of the P in polyphosphates exists as chained polymers and the other half as orthophosphates; although these chains are broken down into simpler P molecules by soil microorganisms, while the remaining other half of P which exists as orthophosphates can easily be taken up by the plant. After a few weeks polyphosphate molecules will be converted to orthophosphates by hydrolysis. Use of granules or fluid fertilisers is usually based on availability, price and field practices (Coetzee 2013). It is also essential to understand the chemistry behind polyphosphates as well as how it behaves in the soil (Blanchar and Hossner 1969a; Hashimoto et al. 1969; Mnkeni and MacKenzie 1985; Al-Kanani and MacKenzie 1991). Potatoes respond well to the application of both orthophosphates and polyphosphates, however higher yields related to polyphosphate applications have been reported in several crops, such as wheat (Venugopalan and Prasad...
1989), rice (Rao et al. 1991), chickpea (Billore and Bargale 1991), soybean (Jain and Kushwaha 1993) and Black gram (Ghosh et al. 1996).

**Hydrolysis of polyphosphates**

According to Robertson (2004), ammonium polyphosphate fertilisers are reasonably soluble in water. Water hydrolyses (breaks down) polyphosphates into orthophosphates, provided there is enough water, although the time needed for polyphosphates to be broken down or hydrolyse is also dependent on many factors, the acidity of the soil also has an effect (Robertson 2004). Coetzee (2013) reported that soil temperature has the most influential effect on the rate of hydrolysis of polyphosphates. The rate of hydrolysis can range between 42 and 84% within 72 hours at temperatures of 5 to 35°C; however hydrolysis takes longer under dry conditions. When 80% of polyphosphates is soluble in water their efficiency is equal to that of orthophosphate, however its efficiency is regarded not better than that of orthophosphates.

McBeath et al. (2007b) reported that the amount of P in different P sources and different P forms does not remain constant due to the hydrolysis reactions; this means that more condensed forms of P react with water (H$_2$O) to form less condensed forms of P. McBeath et al. (2007b) also noted that the most essential hydrolysis reaction aspect is the one that causes polyphosphate fertiliser conversion from polyphosphate to orthophosphates. Polyphosphate compounds are generally expected to be less reactive in soils than orthophosphates.

**Polyphosphates versus orthophosphates**

*Sorption characteristics*

Torres-Dorante et al. (2006) reported that the sorption capacity of soils for polyphosphates is greater than for orthophosphate which is in agreement with studies by Blanchar and Hossner (1969b); Hashimoto et al. (1969); Mnkeni and MacKenzie (1985); Al-Kanani and MacKenzie (1991), who compared soil sorption characteristics of orthophosphates and polyphosphates. Their studies found that polyphosphates showed a greater sorption affinity in comparison to orthophosphates in different soil types (McBeath et al. 2007b). Generally, addition of polyphosphates in soils with a low pH results in a reduction of other macro nutrients such as Ca and an increase in iron (Fe) concentration. Philen and Lehr (1967) and Engelstad and Terman (1980) found that polyphosphates are less reactive. They provide sufficient and balanced P for optimal plant productivity (Chen 2006).
Concentration in the soil
Torres-Dorante et al. (2006) reported that after polyphosphate fertiliser application low orthophosphate concentrations in the soil can be expected, however if polyphosphate compounds are completely hydrolysed, equal or high orthophosphate concentration in the soil solution can be expected. According to Torres-Dorante et al. (2006), in silty-loam soils after 7 days of polyphosphate application, orthophosphate concentration is unusually high and stays high/constant after a month. Torres-Dorante et al. (2006) also noted that 1 to 3 days after polyphosphate application on sandy soils, initially the orthophosphate concentration will be low but will increase daily and will reach the same level of concentration as orthophosphate treatment after 60 days of application. Generally, the rate in which polyphosphate is broken down or adsorbed is higher in silty-loam soil than in sandy soil. Dick and Tabatabai (1986) noted that phosphatase activity, which is involved in the breakdown of polyphosphates, thus increasing the orthophosphate concentration, shows its optimum in neutral soils.

Phosphorus in plant systems
All soils virtually contain P, but the amount present varies amongst soils. To make up for P unavailability growers have started applying P-containing materials to soils. After the 1900s, use of P fertilisers has increased greatly. However, P sorbs with soil constituents. To overcome P unavailability, other P sources have been tested in contrast to the conventional P fertilisers (orthophosphate). Phosphorus sources added to soils have shown greater soil penetration than orthophosphate compounds. Polyphosphates have been found to possess characteristics that could improve P fertiliser use efficiency. Polyphosphates remain soluble in the presence of metal ions, such as Ca$^{2+}$, Mg$^{2+}$ and Ba$^{2+}$. In addition, polyphosphates are not easily sorbed by soil reactions. Apart from pyrophosphate, little information has been documented on hydrolysis of polyphosphates in plant root-soil systems and their effect on potato production. Plant roots do pose the ability to break down some P compounds. This is essential since potato roots could break down polyphosphates and would not have to depend solely on hydrolysis reactions in soils in order to take P in polyphosphate form (Dick 1985). Studies are needed that would compare the effect of conventional P fertiliser (orthophosphate) and polyphosphate on potato productivity.
Objectives of this study

Under South African conditions, especially that of the Sandveld which is a major potato production area, the use of alternative P sources may have benefits in terms of positive growth responses as well as increased P use efficiency. This has to our knowledge not been evaluated yet. Therefore the main objective of this study was to conduct a series of controlled experiments to:

i. Evaluate the growth and yield of potatoes grown with different orthophosphate polyphosphate ratios during different growing seasons.

ii. Evaluate the tuber quality of potatoes grown with different orthophosphate polyphosphate ratios during different growing seasons.

iii. Determine growth, yield, quality and nutrient compositions of potato plants at a range of soil solution pH levels when applying P as orthophosphate or polyphosphate.
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Chapter 2

The effect of different orthophosphate and polyphosphate ratios on growth and yield of selected potato (*Solanum tuberosum L.*) cultivars.

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Abstract
Successful potato cultivation depends on a variety of factors, of which fertilisation forms an important component. Phosphorus fertilisers differ not only in formulation (solid or liquid), but also in chemical form (orthophosphate or polyphosphate). To evaluate the response of potatoes to P sources a pot study was initiated to assess the productivity of potatoes under different ratios of orthophosphate and polyphosphate as P fertiliser. Six potato cultivars (Mondial, Sifra, Lanorma, Innovator, Destiny and Eos) were grown over two seasons 2015/2016 using either 100% orthophosphate, 75% orthophosphate + 25% polyphosphate, 50% orthophosphate + 50% polyphosphate or 100% polyphosphate. Plants demonstrated a rapid vegetative development at the beginning when supplied with a balanced nutrient solution at an EC of 1.5 mS cm\(^{-1}\). In both seasons the best yields in terms of total tuber yield where realised when potato plants were fertilised with 100% orthophosphate. Phosphorus applied as either 100% orthophosphate or 100% polyphosphate resulted in an increase in tuber number (24.5 and 20.8 tubers per plant respectively) compared to 17.5 and 15.4 tubers per plant when 25% and 50% of the P was applied as polyphosphate. The results indicate that applying orthophosphate had a superior effect on potato growth and yield, compared to applying polyphosphate.

Keywords: cultivars, orthophosphate, polyphosphate, potato.
**Introduction**

Potatoes (*Solanum tuberosum L.*) are an essential component in the diet of more than 500 million consumers in developing countries such as South Africa (Lung’aho et al. 2007). Potatoes are very important as both food and cash crops in Africa and play a major role in national food security and in the production and processing industries (Lung’aho et al. 2007). One of the main constraints in the cultivation of the potato is low soil fertility status (Coetzee 2013). In addition, potatoes have a high demand for nutrients, especially for phosphorus (P) as a result of their short growth period and high productivity (Fernandes et al. 2011, Soratto et al. 2011). Apart from nitrogen (N), potassium (K), and calcium (Ca) that will be taken up in large quantities, P is also essential for maximum tuber yields (Freeman et al. 1998, Alvarez-Sánchez et al. 1999, Nava et al. 2007, Rosen and Blorman 2008, Fleisher et al. 2013). Phosphorus is an essential nutrient element for plant growth, vital for energy transfer in all living organisms.

Phosphorus is also one of the least available and immobile nutrient elements (Goldstein et al. 1988) and the total amount of P present differ widely amongst soils (Dick 1985). To correct the low P plant availability, it has been applied at high rates in potato cultivation, with the aim of attaining higher yields (Fernandes and Soratto 2012, Luz et al. 2013) and larger tubers (Fernandes et al. 2015b). However, when P is applied at high rates in soils, a large proportion of the applied P becomes unavailable for plant uptake due to sorption or fixation, thus only a small fraction (10-30%) of the P applied to the soil may be utilized or taken up by the plant. To rectify the fixation problem, farmers have tried to explore alternatives such as applying condensed inorganic P (poly phosphate) instead of granular conventional P fertiliser (orthophosphate compounds). Polyphosphates possess characteristics which may improve P fertiliser use efficiency (Dick 1985). In contrast to orthophosphates, polyphosphates have a ring structure and therefore they do not leach, thus immobility, which results in increased temporary mobility of P and P availability to plants (Philen and Lehr 1967, Engelstad and Terman 1980). Application of P as polyphosphate instead of orthophosphate to potatoes may therefore address food security by increasing potato productivity. The objective of this study was to assess the effect of different P sources, orthophosphates and polyphosphates, on the growth and yield of potatoes in order to identify the best P source for potato production.
Materials and methods

Location and cultivar details

The experiment was carried out at Welgevallen experimental farm of Stellenbosch University, South Africa. In the first summer season (2015) seed potatoes of four cultivars, Mondial, Sifra, Lanorma and Innovator, were used as planting material for this study. Mondial is a medium maturing cultivar which generally takes 90 to 110 days to mature, with a short dormancy period of 50 to 60 days. Mondial is a strong, tall grower with semi-erect to slightly spreading shoots. Sifra has a short to medium growth duration of about 80 to 100 days and has a high yield potential with a medium to long dormancy period (Visser 2012). Lanorma is a short to medium grower and grows only 80-90 days from emergence until the foliage dies off. Lanorma generally has a long dormancy period and it can produce very high yields under favourable conditions. Innovator is a medium to early maturing cultivar and grows for about 90 to 110 days. Innovator has a medium dormancy period and the foliage develops rapidly but with few shoots. Innovator is a high-yielding cultivar and contains a medium to high dry matter content. In the second winter season (2016) the potato cultivars Destiny and Eos instead of Sifra and Innovator, were used. These cultivars were used due to their availability in the winter time when the second trial was planted. Eos is a medium grower and grows about 90-110 days after emergence till natural foliage die-off. Destiny is a medium grower and grows about 110 days after emergence till natural foliage die-off (Du Raan and Van den Berg 2016).

Preparation of planting material

Homogenous sprouts were cut from the seed potatoes and planted in seeding trays in a glasshouse on the 25th August 2015. A seedling mix containing coco-peat, vermiculite and perlite was used as a growing medium for the potato seedlings. The seedlings were irrigated every other day with municipal water. Seedlings were transplanted at three leaf stage into 20 L growing bags filled with silica sand on the 8th of October 2015. A light loamy soil with a coarse texture was preferred since it is ideal for potato production as verified by Steyn and Du Plessis (2012b). However, silica sand was used as a growing medium instead, due to immediate availability to the experimental farm. A standard nutrient solution with four different ratios of orthophosphates and polyphosphate as P fertiliser were applied through drip irrigation. These treatments consisted of 1) 100% orthophosphate, 2) 25% orthophosphate + 75% polyphosphate, 3) 50% orthophosphate + 50% polyphosphate and 4) 100% polyphosphate (Table 2.1). The nutrient solution was adjusted so to keep the total P application rate constant in all four nutrient solutions. The electrical conductivity was also the same in all four nutrient solutions as well as the cation: anion balance.
The second trial (2016) was planted on the 6th of April 2016 and transplanted after 3 weeks at the 3 leaf stage. All production methods were the same as in season one (2015). The results of the two seasons stand out clearer when the two seasons are combined in one graph. Therefore the data from the two seasons were combined although the same cultivars were not used in both seasons. The values for each year are only compared to other values for that year. The years themselves are not directly and statistically compared although there were differences within the seasons. Thus, for statistical analysis, season one (2015) was denoted by small letters and season two (2016) was denoted by capital letters. A total of four months were allocated to each experiment. Season 1 was planted in the summer time in (2015) and season 2 was planted in winter of (2016). “Trial one”/ “season 1 (2015)” and “trial two”/ “season 2 (2016)” are used interchangeable in the text.

Table 2.1 Fertiliser application levels of the four nutrient solutions used to fertigate potato plants. The total P content remained the same in all four solutions.

<table>
<thead>
<tr>
<th>Macronutrients</th>
<th>100% Ortho-P</th>
<th>25% Poly-P</th>
<th>50% Poly-P</th>
<th>100% Poly-P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyphosphate (ml)</td>
<td>0</td>
<td>80</td>
<td>158.8</td>
<td>317.5</td>
</tr>
<tr>
<td>KNO₃</td>
<td>242.4</td>
<td>262.6</td>
<td>262.6</td>
<td>282.8</td>
</tr>
<tr>
<td>K₂SO₄</td>
<td>191.4</td>
<td>200.1</td>
<td>208.8</td>
<td>226.2</td>
</tr>
<tr>
<td>KH₂PO₄</td>
<td>108.8</td>
<td>81.6</td>
<td>54.4</td>
<td>0</td>
</tr>
<tr>
<td>Ca(NO₃)₂.2H₂O</td>
<td>660.0</td>
<td>650.0</td>
<td>650.0</td>
<td>650.0</td>
</tr>
<tr>
<td>MgSO₄.7H₂O</td>
<td>369.0</td>
<td>369.0</td>
<td>369.0</td>
<td>369.0</td>
</tr>
<tr>
<td>CaSO₄.2H₂O</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>56.0</td>
</tr>
</tbody>
</table>

In the first trial 500 ml nutrient solution was applied to the plants at 9:30 and again at 14:00 during the first two months (October to November). During the last 2 months (December to January), 500 ml nutrient solution was applied at 09:30, 12:30, 14:00 and 16:00. In the second trial, plants were fertigated using the same intervals as in trial one but using 500 L tanks instead of 5000L tanks. This was to facilitate more frequent (every two weeks) replenishment of the nutrient solution to keep the polyphosphate solution fresh. Pans were placed under each bag to measure the volume and EC of drainage water. The measured drainage percentage averaged between 20-50% of the applied nutrient solution initially, to 0-10% later in the season, while the EC in the drainage solution was on average 3.0 mS cm⁻¹. This relatively high EC could be
attributed to the salts which accumulated at the bottom of the bag and leached into the pan with each irrigation event. During both seasons temperature and relative humidity inside the greenhouse was measured (Table 2.2).

In order to sustain the large vegetative shoots, strings where attached at each plant from the base of shoot and plants trellised (Plate 2.1).

**Measurements and analysis**

In the first trial at harvesting the shoot, root, tuber fresh and dry mass were measured. Total tuber number was determined per plant and tubers were grouped into small (<20 g), medium (20-80 g) and large (>80 g) tubers.

Plate 2.1 Plants trellised 10 weeks after transplanting into the greenhouse in season 1 (2015).

Harvest index (HI) was determined as the ratio of dry yield of tubers to the total dry biomass yield at harvest (Woldgiorgis 2014).
Table 2.2 Minimum, maximum and average temperature and relative humidity in the greenhouse throughout the first (2015) and second (2016) growing seasons.

<table>
<thead>
<tr>
<th></th>
<th>Temperature (°C)</th>
<th>Relative humidity (RH, %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Reading</td>
<td>8.3</td>
<td>1.3</td>
</tr>
<tr>
<td>Maximum Reading</td>
<td>47.9</td>
<td>36.2</td>
</tr>
<tr>
<td>Average Reading</td>
<td>22.7</td>
<td>14.8</td>
</tr>
<tr>
<td>Average Minimum</td>
<td>14.70</td>
<td>8.90</td>
</tr>
<tr>
<td>Average Maximum</td>
<td>34.04</td>
<td>26.13</td>
</tr>
</tbody>
</table>

Treatments and experimental design
Each treatment combination (cultivar and P ratio) was repeated six times (4 X 4 X 6) and treatments were laid out as a completely randomised design with one plant per repetition. Data was analysed using two-way analysis of variance (ANOVA). Data was checked for normality, homogeneity was also tested and means compared (P<0.05) using the general linear model of Statistica 12 software (Statistica 2012).

Results and discussions
Shoot dry mass
There was no interaction between the main effects on the shoot dry mass in the first season (2015), although the treatments did differ significantly (Table 2.3). The 100% orthophosphate differed significantly from the 25% and 50% polyphosphate. However, the 100% orthophosphate did not differ from the 100% polyphosphate (Figure 2.1). In the first season (2015) shoot dry mass ranged from 129.0 g plant\(^{-1}\) and 48.8 g plant\(^{-1}\) as influenced by the different P sources. Steyn (1992) found stem dry mass values between 35 g m\(^{-2}\) to 50 g m\(^{-2}\). The shoot dry mass in the current study is higher, this could be because Steyn (1992) measured the leaves and the stem mass separately. Interaction effects between main effects were noted in the second trial (2016) (Table 2.3). Generally Mondial gave higher shoot dry mass when fertilised with 100%
orthophosphate instead of the polyphosphate. Destiny seemed to respond better when fertilised with 100% orthophosphate and 25% polyphosphate. There were no significant differences between Lanorma and Eos across all the P sources. However, Mondial had significantly higher shoot dry mass than Eos across all the P sources (Figure 2.2). Tshisola (2014) found shoot dry mass values of 7.01 g plant\(^{-1}\) and 5.28 g plant\(^{-1}\) of cultivars in response to fertilisation, although the values found by Tshisola (2014) were lower in comparison to the present study. This could be because the study by Tshisola (2014) was aimed at mini tuber production. Powon et al. (2005) observed that shoot dry mass content responded well to both application of organic and inorganic P during the cultivation of potatoes in Kenya. Chowdahury et al. (2002) reported that efficient use of fertiliser increases the above ground mass of potato. Woldgiorgis (2014) reported that increasing P applications to higher levels beyond optimum levels does not increase shoot dry mass. Mondial gave higher shoot dry mass and also gave high yields (Figure 2.4). The results confirm that Mondial is a high yielder as verified by Visser (2012), who reported that Mondial is a strong, tall grower with semi-erect to slightly spreading shoots.

**Figure 2.1:** The means of shoot dry mass measured on four potato cultivars grown with four different P source combinations under greenhouse conditions in season 1 (2015).
**Figure 2.2** Interactions between P application treatments and potato cultivars on shoot dry mass. Treatment means followed by different letters differ significantly (P<0.05) season 2 (2016).

**Table 2.3** ANOVA table for shoot dry mass per plant during for the first (2015) and second (2016) season, testing different P sources on four potato cultivars.

<table>
<thead>
<tr>
<th>Treatment*Cultivar</th>
<th>Season 1 (2015) ANOVA</th>
<th>Season 2 (2016) ANOVA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F-value</td>
<td>Pr&gt;F</td>
</tr>
<tr>
<td>Treatment</td>
<td>3.00</td>
<td>0.03</td>
</tr>
<tr>
<td>Cultivar</td>
<td>2.08</td>
<td>0.12</td>
</tr>
<tr>
<td>Treatment*Cultivar</td>
<td>0.66</td>
<td>0.73</td>
</tr>
</tbody>
</table>

Any significant interactions between main effects that emerged for parameters measured are presented in graphs *p < 0.05; ns, not significant at p > 0.05

**Fresh tuber yield**

In both the trials in season 1 (2015) and season 2 (2016) the fresh tuber yield was significantly influenced by the phosphate application treatments (Table 2.4). The crop yielded higher tuber yield when fertilised with the 100% orthophosphate (mono-potassium phosphate; control). Applying part of the phosphate as polyphosphate resulted in a reduction in tuber yield, with the lowest yield realised when substituting 50% of the orthophosphate with polyphosphates (Figure 2.3). Potatoes yielded fresh higher tuber yield when fertilised with 100% orthophosphate (2338.7 g plant⁻¹) instead of 100% polyphosphate (1900.99 g plant⁻¹). In the second trial (2016) the 100% orthophosphate (control) again gave the highest tuber yield (Figure 2.3). The reason why the orthophosphates gave higher yield in both seasons may be because Coetzee (2013)
reported that the efficiency of polyphosphates is considered to be equal to, but not better than, orthophosphates. Robertson (2004) also reported that polyphosphate efficiency is regarded not better than that of orthophosphates. These results are, however, in disagreement with several studies that reported higher yields related to polyphosphate applications in several crops, such as wheat (Venugopal and Prasad 1989), rice (Rao et al. 1991), chickpea (Billore and Bargale 1991), soybean (Jain and Kushwaha 1993) and black gram (Ghosh et al. 1996). These results are also in disagreement with several studies by Dobson et al. (1970), Jung and Jugens-Gschwind (1975), Terman (1975), Engelstad and Terman (1980), and Dick and Tabatabi (1987), where it was reported that potatoes produce high yields in response to the application of both orthophosphates and polyphosphates. Optimum P nutrition of potato is essential to promote tuber growth as reported by Houghland (1960); Alvarez-Sánchez et al. (1999); Jenkins and Mahmood (2003). Bereke (1988) also noted that fertilisation with P\textsubscript{2}O\textsubscript{5} resulted in a tuber yield increase. Similarly, Harris (1978) and Giardini (1992) and De La Morena et al. (1994) reported that the yield increase due to P fertilisation can be attributed to the effect of P on average tuber yield.

In the current study potato plants did not respond positively to polyphosphates in comparison to its counterpart orthophosphate. This could have been because of a number of factors such as low cation exchange capacity (CEC). Since washed silica sand was used as growing medium; the typical CEC in sandy soil is very low, but different countries use different ranges of cations when assessing the CEC (Brink 2016). Cation exchange capacity (CEC) provides a good indication of soil nutrient holding capacity. Thus, low CEC in the sandy soil used in the present study may have caused P leaching due to reduced nutrient holding capacity, thus reduced P uptake in the polyphosphate treatments and consequently low yields. In addition, orthophosphates are the form in which P is taken up by the plant. Polyphosphate needs to be broken down (hydrolysed) to simple orthophosphates before taken up by the plant. The major factor that ensures polyphosphate breakdown is the rate in which polyphosphates are broken down into orthophosphates, which in turn is dependent on chemical and biochemical group of enzymes called phosphatases. Polyphosphate hydrolysis is closely linked with mineralization of organic matter within the soil (Dick 1985). Hydrolysis of polyphosphates by microorganism is faster within a warm soil (Coetzee 2013). Brink (2016) reported that typical organic matter levels for sandy soil is less than 0.8%. This means the sandy soil used in the current study had very low organic matter and may also have inhibited or contributed to reduced polyphosphate hydrolysis. Breakdown of polyphosphates is also dependent on temperature. Temperature is
very essential in determining the availability of polyphosphates. Hydrolysis of polyphosphates is inhibited in soils with cool temperatures. Such cool temperatures experienced in the second season (2016) may have inhibited potato growth, due to reduced polyphosphate hydrolysis, thus reduced P availability and uptake. Other factors such as metal ion-mediated reactions, cations, colloidal gels, pH and enzymes probably also inhibited polyphosphate breakdown (Dick 1985). Lee (2013) reported tuber yields of up to 200 g plant\(^{-1}\) of potatoes after P fertilisation. Woldgiorgis (2014) conducted research and found high yields of up to 25.9 t ha\(^{-1}\) after P fertilisation. Detebo (2014) found potato yields of up to 33.08 t ha\(^{-1}\). The results from Lee (2013) are more comparable to the current study since Lee (2013) conducted a pot experiment although the results of both seasons in the present study are higher than the results by Lee (2013). This could be because of the differences in climates and cultivars. Especially in the first season (2015), where we experienced a prolonged season, since the first season was planted in the summer time. Unfortunately limited studies have looked at the effect of polyphosphate and orthophosphate on potato tuber fresh yield for direct comparison to the present study.

Tuber yield was also significantly different between cultivars during both 2015 and 2016 (Table 2.4). During the first season (2015), Mondial had the highest tuber yield in comparison to the other cultivars. Sifra and Lanorma were significantly lower than Mondial, but significantly higher than Innovator. Innovator gave the lowest tuber yield (Figure 2.4). During the second season (2016), similarly Mondial gave highest yield (Figure 2.4). In both seasons Mondial had significantly higher yield than all the other cultivars. This was expected since Mondial is an easy growing variety that can develop well under various growing conditions (Visser 2012). Kratzke and Palta (1992) also reported in their studies with eight different cultivars subjected to similar environmental conditions, that cultivars displayed different results, indicating the inherent genetic variability in determining the adaptability of a crop.

The 100% orthophosphate treatment gave a higher yield in both seasons, although tuber yield as influenced by the treatments and cultivars was significantly lower in the second season. This can be attributed to the low average temperatures recorded during this growing season (autumn/winter season) (Table 2.2). Potato production is limited in autumn/winter due to short day lengths and low light intensities (Ozanne 1980). The reduced light intensity inside the greenhouse, coupled with already low overall light levels during winter when the second trial was planted, could have caused reduced photosynthesis. This can cause lower tuberisation and consequently yields. During the 2016 growing season the average light intensity for a particular week was 190 µmol m\(^{-2}\) s\(^{-1}\) inside the greenhouse and close to 1500 µmol m\(^{-2}\) s\(^{-1}\) outside the
greenhouse. The low soil temperatures may have further decreased yield in the second (2016) season, since P availability is reduced by low soil temperatures (Brink 2016). Brink (2016) reported that low/cold temperatures result in reduced P uptake, thus induce P deficiency symptoms in potatoes, even when there is sufficient P in the soil. Since low temperatures were experienced throughout the season, plants may have not recovered well, resulting in the lower yields obtained during the (2016) winter season. Mondial still gave higher yields in comparison to the other cultivars in both seasons, indicating that even in limiting environments such as reduced temperatures and low P unavailability noted in the second season (2016), Mondial still performed better compared to the other cultivars evaluated. Tsegaye et al. (2014) noted that the effect of cultivar significantly affected average tuber yield in two different locations. In the second season Mondial gave the highest tuber yield followed by Destiny, whereas Eos and Lanorma yielded the lowest tuber yields per plant (Figure 2.4). It seems that Lanorma yielded a lot less during the second (2016) winter season than the first summer (2015) season, compared to Mondial in the two seasons (Figure 2.4). This could be because of the unfavourable conditions (low temperatures, reduced light intensity and shorter days) in the winter time, since Lanorma can produce high yields under favourable conditions (Du Raan and Van den Berg 2016). Pushkarnath (1976) reported that cultivar productivity in terms of growth and yield is determined by the climatic conditions and soil type. The observed high tuber yield in Mondial in response to P fertilisation could be attributed to increased energy storing, cell division and cell development in the tubers (Mullins 2009). Even under similar growing conditions cultivars’ yield potential differs, which could have ultimately led to the observed yield difference amongst the potato cultivars (Pushkarnath 1976).
Figure 2.3: The average fresh tuber yield per plant measured on potato cultivars grown with four different P combinations under greenhouse conditions in season 1 (2015) and season 2 (2016). Treatments with different letters within the same season differed significantly (P<0.05).

Figure 2.4: The mean fresh tuber yield per plant measured on six potato cultivars grown with four different P application combinations under greenhouse conditions in season 1 (2015) and season 2 (2016). Cultivars with different letters within the same season differed significantly (P<0.05).
Table 2.4 ANOVA table for tuber fresh yield per plant during for the first (2015) and second (2016) trial, testing different P sources on four potato cultivars.

<table>
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<tr>
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<tbody>
<tr>
<td></td>
<td>F-value</td>
<td>Pr&gt;F Significance</td>
<td></td>
</tr>
<tr>
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<td></td>
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<tr>
<td></td>
<td>12.34</td>
<td>0.00 *</td>
<td></td>
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<tr>
<td>Cultivar</td>
<td>17.38</td>
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</tr>
<tr>
<td>Treatment*Cultivar</td>
<td>1.05</td>
<td>0.40 ns</td>
<td></td>
</tr>
</tbody>
</table>

Any significant interactions between main effects that emerged for parameters measured are presented in graphs * p < 0.05; ns, not significant at p > 0.05

**Tuber dry mass yield**

In both seasons the main effects influenced tuber dry mass yield (Table 2.5). In the first season (2015), the 100% orthophosphate treatment gave higher dry mass yield in comparison to the 25%, 50% and 100% treatments. In the second season (2016) the 100% orthophosphate treatment gave higher tuber dry mass yield than its counterpart polyphosphate (Figure 2.5). High dry mass production of potato plants grown under optimum P is because of greater development of lateral branches, higher leaf number and photosynthetic leaf area promoted by P, thus more dry matter portioning (Jenkins and Mahmood 2003, Fleisher et al. 2013). Houghland (1960) suggested that P is important in the dry matter allocation to tubers, since P plays a role in the formation of carbohydrates and its storage in the tubers. Karikari (2015) also reported that P applications increase dry matter production and also influence dry matter distribution. Cultivars differed significantly with regards to their tuber dry mass yields. Torres-Dorante (2006) reported minimum and maximum dry matter values of 10 to 25 (g pot⁻¹) in response to orthophosphates and polyphosphate applications planted in silty-loams and sandy soils. In the first season (2015), Mondial and Lanorma did not differ; however, Mondial differed significantly from Sifra and Innovaror. In the second season (2016) Mondial and Destiny gave higher tuber dry mass yields in comparison to Eos and Lanorma. Eos and Lanorma gave the lowest tuber dry mass yields (Figure 2.6). Iwama et al. (1975) noted that longer days (typically summer) and prolonged seasons tend to increase shoot (stem and leaves) dry mass production considerably. This could explain the higher dry mass yields noted in the first season (2015), which was planted in the summer time. Dry matter partitioning and dry matter production are key in measuring crop response to environmental conditions and plant performance (Karikari 2015). In the second season it seems as if fertilising plants with orthophosphate instead of polyphosphate resulted in higher tuber dry mass yields. Modisane (2007) noted that apart from nutrition, temperature has an effect on dry mass yield. In the present study higher dry mass
yield was obtained in the first summer season (2015). Cao and Tibbitts (1992) established the highest production of plant dry mass and tuber yield at 20°C. The different P sources influenced tuber dry mass. Modisane (2007) also found that different Ca sources influenced tuber dry mass yield. In the second season tuber dry mass yield ranged from 93 to 70 g plant⁻¹ (Figure 2.5). Steyn et al. (1992) obtained tuber dry mass yield values between 100 g m⁻² and 200 g m⁻². Similar findings were obtained by Modisane (2007). Soratto (2015) found tuber dry mass average values of 80.5 and 127.5 g plant⁻¹ of different potato cultivars after P fertilisation. The results of the above authors are similar to the results of the second season (2016), when all the values were below 200 g plant⁻¹. However, the results in the first season (2015) were very high and went up to 465.53 g plant⁻¹. This could be because of the favourable conditions in the summer season when the first trial (2015) was planted.

![Figure 2.5](https://scholar.sun.ac.za)

**Figure 2.5** The mean tuber dry mass yield per plant measured on six potato cultivars grown with four different P application combinations under greenhouse conditions in season 1 (2015) and season 2 (2016). Cultivars with different letters within the same season differ significantly (P<0.05).
Figure 2.6 The mean tuber dry mass yield per plant measured on six potato cultivars grown with four different P application combinations under greenhouse conditions in season 1 (2015) and season 2 (2016). Cultivars with different letters within the same season differed significantly (P<0.05).

Table 2.5 ANOVA table for tuber dry mass yield per plant during the first (2015) and second (2016) trial, testing different P sources on four potato cultivars.

<table>
<thead>
<tr>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F-value</td>
<td>Pr&gt;F</td>
<td>Significance</td>
<td>F-value</td>
</tr>
<tr>
<td>Treatment</td>
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<td>0.00</td>
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<td>4.04</td>
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<tr>
<td>Cultivar</td>
<td>8.36</td>
<td>0.00</td>
<td>*</td>
<td>21.11</td>
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<tr>
<td>Treatment*Cultivar</td>
<td>1.08</td>
<td>0.38</td>
<td>ns</td>
<td>0.91</td>
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</tbody>
</table>

Any significant interactions between main effects that emerged for parameters measured are presented in graphs * p < 0.05; ns, not significant at p > 0.05

Total number of tubers

During the first (2015) season the different P application combinations significantly influenced the total number of tubers per plant (P < 0.001) (Table 2.6). The total number of tubers when fertilised with 25% polyphosphate and 50% polyphosphate was significantly lower compared to that of the control where 100% orthophosphate (mono-potassium phosphate) was used as the source of P. The 100% polyphosphate did not differ significantly from the 100% orthophosphate, nor did the 25% polyphosphate (Figure 2.7). There was no difference in total number of tubers in the second season (2016) as influenced by P fertilisation (Table 2.6). Jenkins and Ali (2000)
reported that P is important for early tuberization, increased tuber number and early crop development. Zelalem et al. (2009) reported that applications of P fertilisers increase marketable tuber numbers and that P significantly increases tuber numbers of potato. Phosphorus is known to increase tuber yield through its influence on the size of tubers and total number of tubers (Zelalem et al. 2009). According to Jenkins and Ali (2000) an adequate supply of P ensures that an optimum number of tubers are formed. In contrast, Rhue et al. (1981) stated that polyphosphate and orthophosphate sources do not differ in terms of crop yields. Phosphorus applied as either 100% orthophosphate or 100% polyphosphate resulted in an increase in tuber number (24.5 and 20.8 tubers per plant respectively), compared to 17.5 and 15.4 tubers per plant when 25% and 50% of the P was applied as polyphosphate. Woldgiorgis (2014) found increasing total number of tubers (6 and 8 t ha\(^{-1}\)) with increasing P applications. Tshisola (2014) found average tuber numbers of 14.10 and 52.05 g plant\(^{-1}\) of four potato cultivars in response to fertilisation.

In both seasons cultivars differed significantly with regards to the total number of tubers (P < 0.001) (Table 2.6). During season 1 (2015) Mondial had the highest number of tubers per plant, followed by Lanorma. Innovator and Sifra had the least tubers per plant (Figure 2.8). During season 2 (2016) Mondial and Destiny yielded more tubers than Lanorma and Eos (Figure 2.8). This observed difference in cultivars can also be because potato yield is influenced by a number of factors, which include the very type of cultivar, climatic conditions and the geographic location the cultivar is adapted to (Barry et al. 1990; Arsenault et al. 2001).

The average total number of tubers in the winter season 2 (2016) trial was lower compared to the summer season 1 (2015) trial. These could be because extremely low temperatures can reduce tuber growth (Haverkort et al. 2008). This could have exerted an effect in determining the tuber number set by the potato cultivars and ultimately caused the observed differences in cultivars in the current study. In addition, increases in day or night temperatures above optimum levels can decrease total tuber yields. Gregory (1956) noted that high night temperatures are more harmful to the potatoes. Manrique et al. (1991) noted that low temperatures (10°C), caused stolon initiation to occur normally but more frequently although tuber growth is delayed.
**Figure 2.7** The mean tuber number per plant measured on potato cultivars grown with four different P application combinations under greenhouse conditions for the first season (2015). Treatments with different letters differed significantly (P<0.05).

**Figure 2.8** Differences in total number of tubers per plant for six potato cultivars after being cultivated with four different P application combinations. Season 1 (2015) and season 2 (2016). Cultivars with different letters within the same season differ significantly (P<0.05).
Table 2.6 ANOVA table for total number of tubers per plant during season 1 (2015) and season 2 (2016), testing different phosphorus sources on four potato cultivars.

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td></td>
<td>F-value</td>
<td>Pr&gt;F</td>
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<tr>
<td>Treatment</td>
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<td>Cultivar</td>
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<tr>
<td>Treatment*Cultivar</td>
<td>1.50</td>
<td>0.16</td>
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</table>

Any significant interactions between main effects that emerged for parameters measured are presented in graphs * p < 0.05; ns, not significant at p > 0.05

Tuber size distribution

In both seasons the tuber size distribution was not significantly affected by P treatments. In the first season the cultivars significantly differed with regards to tuber size distribution (Table 2.7). Mondial and Innovator showed relatively uniform distribution in the small, medium and large categories. Lanorma had higher percentage of small and medium tubers, but lower proportion of large tubers, while on the contrary Sifra showed lower small and medium tuber percentages, but gave higher proportion of large tubers, which can be seen by the different letters on the large tuber category of each cultivar (Figure 2.9). During the second season medium and large tuber percentages did not differ amongst the cultivars (P = 0.52) and (P = 0.25), although significant differences were noted for the small tuber category (Figure 2.10 and Table 2.7). In the small tuber category Mondial and Destiny did not differ significantly and gave higher proportion of small tubers and Lanorma and Eos did not differ significantly and gave lower proportion of small tubers (Figure 2.10). The lowest percentage of small tubers was also observed in Eos and Lanorma (Figure 2.10), which is in agreement with several cultivar evaluation trials in South Africa that have shown that Lanorma variety bulks early with many uniform tubers and a low percentage of small tubers (Du Raan and Van den Berg 2016). Perrenoud (1993) reported that the ideal potato crop at harvest should have uniform sized tubers, in addition tubers should not be too large or defected, small tubers are usually not used for market purposes. In trials conducted across two areas, Tsegaye et al. (2014) reported that potato cultivars differed significantly in the percentage production of small, medium and large potato tubers. In the first season (2015) the main effect of cultivar influenced large potato tubers. This is in agreement to Tsegaye et al. (2014), who reported that the main effect of cultivar had a significant effect on the production of large potato tubers at two different locations. Differences between cultivars such as the ones observed in the current study were expected, since every cultivar will have a different proportion of small, medium and large percentage. Posthumus (1973) also reported...
that optimum environmental conditions differ for tuber growth, initiation and maturation, amongst different plant types and cultivars.

**Figure 2.9** Differences in small, medium and large tuber sizes for four potato cultivars after being cultivated with different P application combinations. Cultivars with different letters within the same size/class differed significantly (P<0.05) in season 1 (2015).

Phosphorus treatments did not influence tuber percentages (Table 2.7). In contrast to the findings in the present study, Perrenoud (1993) noted that effect of fertilisation on tuber size is complex since fertilisation may affect the number of tubers formed and ultimately average size. The aforementioned effects differ with potato cultivars and soil fertility. Generally N and K usually increase tuber size whereas P tends to increase total tuber number. Phosphate application has also been shown to result in yield increases of small and medium size tubers (Hanley et al. 1965, Sommerfeld and Knutson 1965). Woldgiorgis (2014) found that the main effect of P influenced the production of medium sized potato tubers and that P application increased the medium size tuber of potato by 0.33%. The author also noted that the main effect P as well as the interaction significantly affected the large tubers; they noted that increasing P application increased large tubers from 1.75 to 3.63%. This was not apparent in the present study. The percentages of small tubers in the first summer trial (2015) were higher than the percentage of small tubers in the second winter trial (2016). This can be attributed to the low temperatures that inhibited potato growth, thus lower percentage of small tubers in the winter
trial (2016). Sharma and Arora (1987) and Mulubrhan (2004) reported significant interaction between N and P, which influenced medium and large tuber size but did not significantly affect small tuber of potato.

Figure 2.10 Differences in small, medium and large tuber percentages for four potato cultivars after being cultivated with four different P application levels. Cultivars with different letters within the same size/class differed significantly (P<0.05) season 2 (2016).

Table 2.7 ANOVA table for small, medium and large tuber percentages during season 1 (2015) and season 2 (2016), testing different phosphorus sources on four potato cultivars.

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<th></th>
<th>Small tuber yield</th>
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<td>Cultivar</td>
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<tr>
<td>Treatment*Cultivar</td>
<td>0.94</td>
<td>0.49 ns</td>
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### Large tuber yield

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<tbody>
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<td>Pr&gt;F</td>
<td>Significance</td>
<td>F-value</td>
</tr>
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<td>ns</td>
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<tr>
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<td>0.00</td>
<td>*</td>
<td>1.40</td>
</tr>
<tr>
<td>Treatment*Cultivar</td>
<td>1.48</td>
<td>0.17</td>
<td>ns</td>
<td>0.40</td>
</tr>
</tbody>
</table>

Any significant interactions between main effects that emerged for parameters measured are presented in graphs **p < 0.1, * p < 0.05; ns, not significant at p > 0.05**

### Root dry mass

The different P sources did not influence the root dry mass (Table 2.8). This was not expected since P application can lead to increase in lateral root length development, as verified by Singh and Sale (2000) Williamson et al. (2001). Phosphorus concentration and P availability are essential because these factors determine root yield and length. Murphy and Smucker (1995) and Costa et al. (2000) noted a positive interactive relationship between root dry mass and root length.

In both seasons root dry mass was highly influenced by cultivars (Plate 2.2; Table 2.8). In the first season (2015) Lanorma had a significantly higher root dry mass in comparison to Mondial, Sifra and Innovator (Figure 2.11). In the second winter (2016) trial Destiny differed significantly from Lanorma and Eos (Table 2.10). Soratto (2015) found average root dry mass values of 9.2 and 11.1 g plant\(^{-1}\) of different cultivars, as influenced by the different P levels. The root dry mass for the first season (2015) (11.11, 10.40 and 5.05 g plant\(^{-1}\)) (Figure 2.11), are similar to those values by Soratto (2015), except for Lanorma. Lanorma had unusually high root dry mass (44.00 g plant\(^{-1}\)) as is evident in Plate 2.2. In the second season the dry mass values were extremely low (Figure 2.11) and are incomparable to the above findings by Soratto (2015). This could be because of the low temperatures in the greenhouse (Table 2.2) that inhibited potato growth. Van Tonder (2008) reported that cultivars which have high root mass have a well-developed root system and thus better adsorptive area and a better capacity of the cultivar to utilize soil nutrients than other cultivars. Adequate water and nutrient uptake is dependent on the area in which the plant roots come into contact with the available nutrients, which in turn is showed by the total root length and root mass (Zuo et al. 2004). According to Mulubrhan (2004) and Zewide et al. (2012), P fertiliser applications have a significant effect on potato root mass as verified by Brady and Weil (2002) who noted that P is necessary in large amounts in new cells, such as root tips where metabolism is high, to ensure a rapid cell division and development of roots. Since the major functions of roots is to extract nutrients and water and also to anchor the plant (Fitter et al. 2002).
Figure 2.11 Differences in root dry yield of four potato cultivars during summer and winter season 1 (2015) and season 2 (2016). Plants were cultivated with four different P application combinations. Cultivars with different letters within the same season differed significantly (P<0.05).

Plate 2.2 Roots at harvest 14 weeks after transplanting the potato seedlings into the greenhouse in season 1 (2015).
Table 2.8 ANOVA table for root dry yield in the first (2015) and the second (2016) season, testing different phosphorus sources on four potato cultivars.

<table>
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</thead>
<tbody>
<tr>
<td></td>
<td>F-value</td>
<td>Pr&gt;F</td>
<td>Significance</td>
<td>F-value</td>
</tr>
<tr>
<td>Treatment</td>
<td>0.11</td>
<td>1.00</td>
<td>ns</td>
<td>2.32</td>
</tr>
<tr>
<td>Cultivar</td>
<td>6.16</td>
<td>0.00</td>
<td>*</td>
<td>3.20</td>
</tr>
<tr>
<td>Treatment*Cultivar</td>
<td>0.22</td>
<td>1.00</td>
<td>ns</td>
<td>1.59</td>
</tr>
</tbody>
</table>

Any significant interactions between main effects that emerged for parameters measured are presented in graphs * p < 0.05; ns, not significant at p > 0.05

**Harvest index**

In first season (2015) the P application treatments had no significant effect on the harvest index (HI). In the second season the P treatments influenced HI (Table 2.9). The 50% and 100% polyphosphate treatments differed from the 100% orthophosphate and the 25% polyphosphate treatments (Figure 2.12). This was not expected since the tuber yield was higher for plants fertilised with 100% orthophosphate in comparison to the plants fertilised with the 50 and 100% polyphosphate (Figure 2.3). In addition, the 50% and 100% polyphosphate treatments did not perform well in all other measured yield and morphological parameters in comparison to the 100% orthophosphate, which means these results are in agreement with Gawronska et al. (1984). Gawronska et al. (1984) reported that though HI is an essential tool used by breeders and plant physiologists to measure the ratio of assimilates assigned to harvested organs and also in the selection of high yielding cultivars, harvest index (HI) may not necessarily correlate with high yields. As a result, a low HI may not imply low yields or high HI may not imply high yields.

Detebo (2014) reported that a decrease in HI due to P fertilisation did not appear to be closely related to a decrease in tuber yield. Zewide et al. (2012) reported that increase in P application rate increased HI of potatoes but this had a non-significant effect. On the contrary, Woldgiorgis (2014) noted that the effect of P on HI was highly significant as affected by P fertilisation.

In the present study minimum and maximum HI values as influenced by the treatments were 0.79 and 0.85. Woldgiorgis (2014) noted that the lowest 0.19 and the highest 0.58 HI of potato were recorded when 0 P$_2$O$_5$ kg ha$^{-1}$ and 138 P$_2$O$_5$ kg ha$^{-1}$ were applied respectively. The author also noted that increase in P application from 0 P$_2$O$_5$ kg ha$^{-1}$ increased harvest indexes of potato from 0.51 to 0.58. The author attributed those findings to the effect of P in increasing tuber production more than the vegetative part of the potato plants, whereas Detebo (2014) noted that increasing N and P applications reduced HI values from 0.91 to 0.64. The author
attributed that finding to the fact that effect of high levels of N might have promoted vegetative growth at the expense of tuber growth. That finding by Detebo (2014) concurs with studies by Millard and Marshall (1986), who noted that N application increases vegetative mass of potato. Biemond and Vos (1992) reported that N fertilisation increased partitioning of assimilates to the shoots rather than to the tubers.

In both seasons HI differed significantly between cultivars (Table 2.9). Mondial, Sifra and Innovator had the highest HI in comparison to Lanorma in the first season (Figure 2.13). In the second season Eos and Lanorma cultivars gave higher HI. Mondial and Destiny gave the lower HI when compared to Eos and Lanorma (Figure 2.13). Fernandes et al. (2010) reported that highest HI observed in cultivars may be attributed to the higher rate of dry matter accumulation in the tubers of these cultivars grown under sufficient P supply. The cultivars Mondial, Sifra and Innovator gave the highest HI in response to P applications in the first season (2015) (Figure 2.13), however, Sifra gave lower dry matter content. In the second season (2016) Eos and Lanorma cultivars gave lower tuber fresh yield but gave higher HI. Mondial and Destiny gave higher tuber fresh yield (Figure 2.4) but they had a lower HI in comparison to Eos and Lanorma (Figure 2.13). Thus, these results are also in line with Gawronska et al. (1984) who noted that HI may not necessarily correlate with high yields.

**Figure 2.12** Differences in harvest index for potato cultivars after being cultivated with different P source application combinations in season 2 (2016). Treatments with different letters differed significantly (P<0.05).
Figure 2.13 The harvest index measured on potato cultivars grown with four different P combinations under greenhouse conditions during the summer and the winter in season 1 (2015) and season 2 (2016). Treatments with different letters within the same season differed significantly (P<0.05).

Table 2.9 ANOVA table for harvest index testing different P sources on four potato cultivars in season 1 (2015) and season 2 (2016).

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<tbody>
<tr>
<td></td>
<td>F-value       Pr&gt;F</td>
<td>Significance</td>
</tr>
<tr>
<td>Treatment</td>
<td>1.00          0.40</td>
<td>ns</td>
</tr>
<tr>
<td>Cultivar</td>
<td>5.48          0.00</td>
<td>*</td>
</tr>
<tr>
<td>Treatment*Cultivar</td>
<td>1.05          0.41</td>
<td>ns</td>
</tr>
</tbody>
</table>

Any significant interactions between main effects that emerged for parameters measured are presented in graphs * p < 0.05; ns, not significant at p > 0.05
Conclusions

Phosphorus is essential for many physiological processes; such as photosynthesis, respiration, energy storing, cell division and cell development (Mullins 2009). Overall the results in both the trials indicated that different P sources influenced tuber fresh and dry yield per plant. In both the seasons cultivar highly influenced root dry yield. Tubers from plants which were fertilised with 100% orthophosphate showed higher tuber fresh yield in comparison to treatments containing polyphosphate. This was not expected, as previous studies showed that the two P sources do not differ in terms of crop yields. Regarding total number of tubers, in the first trial 100% orthophosphate and the 100% polyphosphate treatments did not differ significantly. Mondial performed better in terms of tuber yield. In the first season Lanorma showed higher average root dry yield than all other cultivars. This high average root dry yield shows that Lanorma had a well-developed root system and denser roots. Mondial plants produced both higher number of tubers at harvest and a higher tuber fresh yield. Mondial gave higher yields in both seasons when fertilised with orthophosphate instead off polyphosphate fertilisers. This may imply that Mondial reacts well to orthophosphate fertilisers instead off polyphosphate fertilisers. Mondial and orthophosphate combination may have a potential advantage in potato production. Variations within potato cultivars offer potato producers and consumers the option of choosing a high-ranking cultivars in terms of mineral content and yield (Andre et al. 2007), depending on the final use.

It was clear that 100% orthophosphate treatments were superior to polyphosphate treatments and there were quite significant differences between the orthophosphate and polyphosphate treatments.
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Chapter 3

The effect of different orthophosphate and polyphosphate ratios on tuber quality of selected potato (*Solanum tuberosum L.*) cultivars.

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Abstract

To determine the quality of potatoes in response to P sources, seed potatoes (*Solanum tuberosum L.*) of cultivars Mondial, Sifra, Lanorma, Innovator, Destiny and Eos fertilised with either 100% orthophosphate, 75% orthophosphate + 25% polyphosphate, 50% orthophosphate + 50% polyphosphate or 100 polyphosphate, from a previous two season study were obtained and used for the present study. Upon harvest tubers were graded into different sizes: small tubers, <20g, medium, 20–80g and large >80g. Treatments and cultivars did not influence phosphorus-utilization efficiency (PUE), defects or specific gravity. Total P uptake per plant was significantly influenced by the cultivars in both seasons. In both seasons the dry matter content was influenced by the cultivars, with Sifra having a lower dry matter content in the first season. Destiny gave the highest dry matter content in the second season. The potato cultivars were analysed for essential nutrient elements, both leaves and tubers. The results indicated that in both seasons all the nutrient levels recorded in the present study were within the acceptable ranges for the potato crop, as indicated by the tuber and leaf chemical analysis results. Application of the different P sources had no negative impact on potato quality.

Keywords: cultivars, orthophosphate, polyphosphate, potato, tuber quality.
Introduction

Globally potatoes are one of the most essential crops, ranking fourth in yearly production (Fernie and Willmitzer 2001). Potatoes can be grown in a wide range of climates, even in non-conducive climates but are still able to produce high nutritious yields in comparison to other major food crops (Lutaladio and Castaldi 2009). In order to maintain high productivity, potatoes require substantial nutrient inputs to achieve sufficient yield and quality (Tein 2015). Potatoes require more than 13 nutrient elements, both macro elements such as nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sulphur (S) and trace elements such as chlorine (Cl), Iron (Fe), Manganese (Mn), Boron (B), Zinc (Zn), Copper (Cu) and Molybdenum (Mo) (Harris 1992; Tein 2015). Elements such as Ca are important for quality and elements such as N, P and K are the major elements and they are the ones that determine yields (Dreyer 2014).

Phosphorus rock is a raw material for P fertilisers. The P rock is a non-renewable resource and will consequently be depleted in a few years to come (EcoSanRes 2008). Phosphorus utilization efficiency (PUE) is the ability of the plants to produce biomass or product of economic interest (e.g., grain and tuber) using the P taken up (Wang et al. 2010). Therefore, it is essential to improve P use efficiency in potato production in order to apply lesser amounts of P fertilisers in the soils (Soratto 2015). Since not all potato cultivars have the ability to take up P from soils with a low P status (P inefficient) (Dechassa et al. 2003), another option may be to identify cultivars with high P efficiency in order to attain high yields in soils with low total available P (Sanchez and Uheara 1980; Balemi 2011). Therefore research on P efficiency is also necessary for sustainable potato production, particularly in soils with low total P.

Fertilisation by inorganic fertilisers must be maintained in order to prevent mineral deficiencies or toxicities. Inadequate fertilisation can inhibit potato productivity and thus tuber quality, whereas excess mineral nutrient concentrations may limit growth due to toxicity (White et al. 2007). Deficiencies within the potato plant cause the potato to be vulnerable to diseases caused by infectious potato pathogens (Agrios 2005) and this results in reduced tuber growth (McCollum 1978; Czajkowski et al. 2011). This is because when the potato plant is nutrient deficient its natural ability to resist diseases is reduced (Mulder and Turkensteen 2005). Nutrient status is very important as it influences plant physiology (Dordas 2008). In addition, nutrients such as P are very important for plant growth (Marschner 1995; Mullins 2009). Sufficient P concentrations within the potato plant will ensure thicker tuber skin. Optimal P concentrations...
also encourage higher dry matter contents and starch (Mulder and Turkensteen 2005). Thus, the present research was aimed at evaluating the quality of potatoes in response to different P sources, namely orthophosphates and polyphosphates in order to identify the best P source for high quality potatoes.

**Materials and Methods**

Tubers from the previous two-season growth and yield study in season 1 (2015) and season 2 (2016) were obtained and analysed for quality. Thus all production methods were the same as for chapter 2 and chapter 3. For the production methodology, refer to chapter 2.

**Measurements and analysis**

In the first (2015) and the second (2016) season, at harvested tubers were analysed for micro and macro elements. Dry matter content was also determined. Tubers were also grouped into small (<20 g), medium (20-80 g) and large (>80g) classes in order to determine specific gravity per tuber category (medium and large). Specific gravity for the small tubers was not measured since small tubers are usually not used for industrial purposes. Phosphorus-utilization efficiency (PUE) and total phosphorus uptake per plant was subsequently calculated. Upon harvest all tubers were visually inspected for defects such as external growth cracks and internal physiological disorders such as internal brown spot, hollow heart and brown centres. Specific gravity was only evaluated for the second trial. For macro and trace element determinations, skin and medullary tissue samples were taken from four tubers per treatment combination and processed following the procedures described by Kratzke and Palta (1986) and Soltanpour et al. (1996). Samples were dried in an oven (49 °C) for 5 days, grounded to pass a 40-mesh (0.635mm) screen, weighed, ashed at 450 °C for 8 hours, dissolved in 2 N HCl, and diluted with a lanthanum chloride (LaCl$_3$/$x$H$_2$O) solution and distilled in deionized water to obtain samples in 0.2 HCl and in Lanthanum (La) at 2000 μg/mL. Macro and trace element concentration were determined by atomic absorption spectrophotometry as described by Karlsson and Palta (2006).

The dry matter percentage was calculated according to Williams (1968) using the following equation.

\[
\text{Tuber dry matter content (\%)} = \frac{\text{tuber dry mass (g)}}{\text{tuber fresh mass (g)}} \times 100
\]

3.1
The P concentration in the plants was determined as stated above to calculate total P-uptake per plant and P-utilization efficiency (PUE) as follows:

Total P-uptake per plant (mg plant$^{-1}$) = Total P concentration (tuber + leaves) (mg/g) × dry matter yield (g/plant) (Akhtar et al. 2008) 3.2

PUE = \[ \text{Tuber dry matter yield (g/plant)} \over \text{P (mg/plant)} \] (Elloitt and White 1994) 3.3

Specific gravity as a measure of processing quality was measured by dividing tuber mass by the total volume of water displaced by the tubers when they were lowered in a beaker. The mass of the tuber was then divided by the volume of water displaced to obtain SG using the equation:

\[ \text{SG} = \frac{\text{tuber mass (g)}}{\text{volume of water displaced (mL)}} \] (Tabatabaeefar 2002) 3.4

Treatments and experimental design

Each treatment combination (cultivar and P ratio) was repeated six times (4 X 4 X 6) and treatments were laid out as a completely randomised design with one plant per repetition. Data was analysed using two-way analysis of variance (ANOVA), data was checked for normality, homogeneity was also tested and means compared (P<0.05) using the general linear model of Statistica 12 software (Statistica 2012).

Results and discussion

Tuber dry matter content

In both seasons the four P treatments had no significant effect on the tuber dry matter content (Table 3.1). On the contrary, several studies reported that P affects tuber dry matter content. Coetzee et al. (2013) reported that P sources (orthophosphate and polyphosphates) significantly influenced dry matter content production in a study conducted across two seasons. They noted that the plants fertilised with orthophosphate (mono-ammonium phosphate) yielded plants with a significant greater dry matter content compared to polyphosphate fertilised plants. Torres-Dorante (2006) reported that orthophosphate applications resulted in higher dry matter than polyphosphates in sandy soil. Fernandes et al. (2015a) also reported that high levels of orthophosphate based fertiliser increased tuber dry matter content. Woldgiorgis (2014) noted that increasing P levels increased the dry matter content of potato tubers by 6 %. They reported that this increment could be due to P affecting the underground biomass development as compared to aboveground biomass. However, the results in the current study are in agreement
with those of Zelalem et al. (2009), who observed no significant effect of P fertiliser source on tuber dry matter content and specific gravity. Sparrow et al. (1992) also reported no significant effect on the dry matter content of tubers due to P application.

In both seasons the cultivars differed significantly with regards to their dry matter content (Table 3.1). In the second season Destiny gave higher tuber dry matter content. Lanorma also gave good results but had significantly lower dry matter content than Destiny. Mondial and Eos gave the lowest tuber dry matter contents (Figure 3.1). This is in disagreement with findings by Soratto et al. (2015), who showed that Mondial had a higher dry matter content compared to four other cultivars. In the first season there were no significant differences between Lanorma, Innovator and Mondial; however Sifra showed lower dry matter content. Sifra was not significantly different from Mondial (Figure 3.1). Du Raan and Van den Berg (2016) reported that Innovator contains a medium to high tuber dry matter content. Tuber dry matter content in the present study ranged from 14.6 to 21.83 % (Figure 3.1). These results are similar to findings by Woldgiorgis (2014). Woldgiorgis (2014) found that applying 0 P$_2$O$_5$ kg ha$^{-1}$ and applying a maximum of 138 P$_2$O$_5$ kg ha$^{-1}$ gave a dry matter content of 10.66 to 16.74% respectively.

Burton (1966) observed that the tuber dry matter content of early maturing cultivars in most cases is usually lower than those of late maturing cultivars. These results are inconsistent with those findings since Lanorma, Innovator and Mondial had higher tuber dry matter contents, but Lanorma is an early maturing cultivar (80-90 days) while Mondial and Innovator require about 90 to 110 days reaching harvest maturity. Sifra, which requires more days to reach harvest maturity (80-100), had lower dry matter contents in comparison to Lanorma, which requires only 80-90 days. However, it is important to note that days to maturity are not the only factors that affect dry matter content as verified by Storey and Davies (1992). Storey and Davies (1992) reported that tuber dry matter content is also affected by a number of environmental factors such as light intensity, soil water content and the soil upon which the plant grows. In trials conducted at two different locations, Tsegaye et al. (2014) reported that cultivars differed significantly ($P < 0.01$) in dry matter content. Significant differences in cultivars concerning tuber dry matter content can be attributed to the fact that genetic differences do occur among cultivars Tsegaye et al. (2014) and Burton (1966) noted that these genetic differences have an essential impact on the ability of a potato cultivar to produce solids.
Figure 3.1 Differences in tuber dry matter content for six potato cultivars after being cultivated with four different P source combinations. Cultivars with different letters within the same season differed significantly (P<0.05) in season 1 (2015) and season 2 (2016).

Table 3.1 ANOVA table for tuber dry matter contents in harvest season 1 (2015) and season 2 (2016), testing different P sources on six potato cultivars.

<table>
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<tbody>
<tr>
<td></td>
<td>F-value</td>
<td>Pr&gt;F Significance</td>
<td>F-value</td>
<td>Pr&gt;F Significance</td>
</tr>
<tr>
<td>Treatment</td>
<td>1.10</td>
<td>0.39 ns</td>
<td>0.42</td>
<td>0.74 ns</td>
</tr>
<tr>
<td>Cultivar</td>
<td>4.50</td>
<td>0.00 *</td>
<td>4.35</td>
<td>0.01 *</td>
</tr>
<tr>
<td>Treatment*Cultivar</td>
<td>0.93</td>
<td>0.50 ns</td>
<td>0.74</td>
<td>0.67 ns</td>
</tr>
</tbody>
</table>

Any significant interactions between main effects that emerged for parameters measured are presented in graphs * p < 0.05; ns, not significant at p > 0.05

Specific gravity

Interaction between treatment and cultivar was non-significant for specific gravity (SG). Phosphorus treatments did not affect the SG and neither were any differences between cultivars tested observed (Table 3.3). The non-significant effects on SG noted in this present study are unlikely. These may be attributed to the method used to determine SG (3.4). Initially the mass-in-air/mass-in-water method to determine specific gravity was preferred but due immediate availability to the experimental farm the SG was measured using the equation in (3.4). Specific gravity (SG) values in the current study ranged from 1.011 to 1.040. Such extreme low values
noted in Table 3.2 are not expected since SG was measured when the tubers were mature and tubers at harvest maturity have higher SG values in comparison to SG values noted in the present study, as was verified by Modisane (2007). Modisane (2007) found SG values for mature tubers ranging from 1.085 to 1.090 with an average value of 1.087. Gumede (2017) used the same method as the one used in the present study (3.4) and also found extremely low SG values, as low as 1.00 and 1.09, while some values were even less than one. The results of the present study may imply that the method used in the present study (3.4) tends to underestimate SG values.

Zelalem et al. (2009) suggested that P fertilisation did not significantly affect tuber SG. However, the results in this study are in opposition to Woldgiorgis (2014), who noted that the main effect of P significantly increased the specific gravity of potato tubers from 1.03 to 1.066. Tsegaye et al. (2014) also conducted two experiments in two different locations and reported that cultivars significantly (P < 0.01) differed with regards to their specific gravity.

Berga et al. (1994) noted that SG of potatoes for chip processing industry must be or greater than 1.080 and any value of less than 1.075 is not suitable for further processing. In this study the average specific gravity for the cultivars ranged from 1.018 to 1.025 for medium tubers and 1.011 to 1.040 for large tubers (Table 3.2), but since SG values were underestimated, thus the methodology determine SG flawed, it is unclear whether the tubers in the present study may have been suitable for further processing.

**Table 3.2** The means of specific gravity measured on four potato cultivars grown with four different P source combinations under greenhouse conditions in the second season (2016). Cultivars with different letters differed significantly (P<0.05).

<table>
<thead>
<tr>
<th>Cultivars</th>
<th>Specific gravity 2016 (Medium tubers)</th>
<th>Specific gravity 2016 (Large tubers)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mondial</td>
<td>1.025&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.011&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Destiny</td>
<td>1.018&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.017&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Lanorma</td>
<td>1.022&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.012&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Eos</td>
<td>1.021&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.040&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

ns ns
Table 3.3 ANOVA table for specific gravity in season 2 (2016), testing different P sources on four potato cultivars.

<table>
<thead>
<tr>
<th>ANOVA</th>
<th>F-value</th>
<th>Pr&gt;F</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment</td>
<td>1.70</td>
<td>0.17</td>
<td>ns</td>
</tr>
<tr>
<td>Cultivar</td>
<td>0.23</td>
<td>0.90</td>
<td>ns</td>
</tr>
<tr>
<td>Treatment*Cultivar</td>
<td>0.45</td>
<td>0.90</td>
<td>ns</td>
</tr>
</tbody>
</table>

Any significant interactions between main effects that emerged for parameters measured are presented in tables ns, not significant at p > 0.05

Defects

In the both trials in season 1 (2015) and season 2 (2016) the different P treatments and cultivars did not result in any tuber defects (P>0.05) and the interaction between treatment and cultivar was non-significant. This was not expected since Ekelöf (2007), reported that P has a positive effect on citric acid production and cell expansion. Ekelof (2007) also reported that P affects tuber quality but limited information is available regarding whether P deficient soils will yield potatoes with negative quality characteristics. Woldgiorgis (2014) found that effect of P was not significant for unmarketable tubers. Rosen and Bierman (2008) also noted that continuous P applications increased marketable tubers. A well-balanced nutrient solution was used in the present study to continuously supply nutrients to the potato plants; this may have encouraged formation of healthy defect free tubers, since some nutrient deficiencies are known to cause physiological disorders and ultimately defected tubers.

Phosphorus utilization efficiency and uptake

Phosphorus-utilization efficiency

In both the first summer (2015) and second winter (2016) trials the P sources and cultivars did not significantly affect phosphorus-utilization efficiency (PUE) (Table 3.4). Although not significant, PUE values in the present study as influenced by the treatments ranged from 7.30 to 14.62 g mg\(^{-1}\) (minimum and maximum) in the first season (2015) and 40.42 to 48.44 g mg\(^{-1}\) in the second season (2016). As influenced by the cultivars PUE ranged from 7.21 to 14.97 g mg\(^{-1}\) in season 1 (2015) and 39.57 to 45.14 g mg\(^{-1}\) in season 2 (2016). Lee (2013) found that PUE as influenced by seven cultivars ranged from 0.3 to 0.6 mg P. These values are a lot lower than the values obtained in the present study this could be because the study by Lee (2013) was done under P starvation. The difference in cultivars may also have contributed to the observed
differences. The non-significant effects noted in the present study show that the PUE was not affected by the different P sources and the different cultivars as such. According to literature PUE differences are more common in circumstances where low, medium and high P is applied or in situations where a soil has low total P or the soil P is in unavailable forms or non-labile. P-utilization efficiency according to Wang et al. (2010) is the ability of the plants to produce biomass or product of economic interest (e.g., grain and tuber) using the P taken up. Therefore, cultivars that produce high biomass or product of economic interest (e.g., grain and tuber) using the P taken up from the P are regarded to have a high P-utilization efficiency. The P-utilization efficiency might have been masked in the present study since a well-balanced nutrient solution was used to fertilise potato plants. The main aim was to determine whether the two P sources differ with regards to crop yields. Future trials can focus on different application rates (such as low, medium and high P). The different sources should also be included to establish whether they will have an effect on the PUE. It might be that when P is applied at low concentrations there will be differences in PUE between the sources. Since orthophosphates showed higher yields, they may ultimately show higher PUE.

Table 3.4 ANOVA table for phosphorus-utilization efficiency in the first (2015) and second (2016) season, testing different phosphorus sources on four potato cultivars.

<table>
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<tbody>
<tr>
<td></td>
<td>F-value</td>
<td>P&gt;F Significance</td>
<td></td>
</tr>
<tr>
<td>Treatment</td>
<td>0.64</td>
<td>ns</td>
<td></td>
</tr>
<tr>
<td>Cultivar</td>
<td>0.57</td>
<td>ns</td>
<td></td>
</tr>
<tr>
<td>Treatment*Cultivar</td>
<td>1.02</td>
<td>0.45</td>
<td>ns</td>
</tr>
</tbody>
</table>

*ns, not significant at p > 0.05*

Total P-uptake per plant

In both trials P sources and the interaction between treatments and cultivars did not significantly affect potato Total P uptake per plant. Cultivars had a significant effect on total P-uptake per plant, in the first summer season (2015) at 10% level of significance (P<0.1) and at 5% level of significance in the second winter season (2016). The P values were found to be 0.07 and <0.001 respectively (Table 3.6). Lanorma, Mondial and Innovator did not differ in terms of P-uptake efficiency and had average total P-uptake per plant values of 116.34 g mg⁻¹, 104.27 g mg⁻¹ and 103.70 g mg⁻¹ respectively. Sifra and Lanorma differed significantly (Table 3.5). Similarly, in the winter trial Destiny and Lanorma did not differ in terms of total P-uptake per plant. Destiny and Lanorma gave average total P-uptake per plant of 73.38 g mg⁻¹ and 67.90 g mg⁻¹ respectively. Eos and Mondial did not differ significantly in total P-uptake per plant with average values of
64.31 g mg\textsuperscript{-1} and 59.49 g mg\textsuperscript{-1} respectively. Destiny differed significantly from Mondial and Eos (Table 3.5). These values show that in the first trial from the P available in the soil, an average of 116.34 g mg\textsuperscript{-1}, 104.2 g mg\textsuperscript{-1}, 103.7 g mg\textsuperscript{-1}, 94.20 g mg\textsuperscript{-1} in the first season and 73.38 g mg\textsuperscript{-1}, 67.90 g mg\textsuperscript{-1}, 64.31 g mg\textsuperscript{-1}, 59.49 g mg\textsuperscript{-1} in the second season respectively was extracted by the potato cultivars (Parentoni et al. 2005). According to Blair (1993) and Gahoonia and Nielsen (1996) and Bhadoria et al. (2004), total P-uptake per plant is related to higher P-uptake rate per unit of root length. In the current study, there were significant differences in total P-uptake per plant of the cultivars (Table 3.6). Root yield did notably differ among cultivars. In the first season Lanorma had a higher total P-uptake per plant in comparison to Sifra (Table 3.5) and Lanorma also had higher root dry yield than all the other cultivars. Similarly, Destiny had a higher total P-uptake per plant in the second season in comparison to Eos (Table 3.5) and Destiny also had a higher root dry yield than Eos. This agrees with the observation that longer, denser roots with a higher root yield increase P-uptake as well as the extension of the depletion zone from the root surface into the soil (Balemi and Schenk 2009). In the second season Eos and Mondial gave a lower total P-uptake per plant (Table 3.5). However, Soratto (2015) reported that Mondial is more efficient in total P-uptake per plant. In both seasons, there were differences in total P-uptake per plant by the different genotypes. These observed differences may necessarily mean that the other cultivars which had significantly lower total P-uptake per plant are incapable in taking up P. This is mainly because P is relatively immobile in the soil. Since potato roots are capable of taking up and using P applied through irrigation water (Westermann 1984, 2005; Mackay et al. 1988; Hopkins et al. 2010).

Torres-Dorante et al. (2006) conducted research and found P-uptake values between 0.03 and 0.06 mg P (m root\textsuperscript{-1}). Torres-Dorante et al. (2006), also found that P uptake differs amongst soil types (silty-loam soil and sandy soils). A study conducted by Soratto (2015) found total P-uptake per plant values between 22.6 mg plant\textsuperscript{-1} and 31.4 mg plant\textsuperscript{-1} under low P and between 41.1 mg plant\textsuperscript{-1} and 54.3 mg plant\textsuperscript{-1} under high levels of P applications. Phosphorus uptake may vary depending on difference in climate, P sources/rates, cultivars and soil type used as verified by Torres-Dorante et al. (2006).
**Table 3.5** Differences in total P-uptake per plant for four potato cultivars after being cultivated with different P application combinations. Cultivars with different letters within the same season differed significantly (P<0.1) in season 1 (2015) and season 2 (2016) (P<0.05).

<table>
<thead>
<tr>
<th>Cultivars</th>
<th>P uptake (g mg plant(^{-1}))</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2015</td>
<td>2016</td>
<td></td>
</tr>
<tr>
<td>Mondial</td>
<td>104.27(^{ab})</td>
<td>Mondial</td>
<td>59.49(^{b})</td>
</tr>
<tr>
<td>Sifra</td>
<td>94.20(^{b})</td>
<td>Destiny</td>
<td>78.38(^{a})</td>
</tr>
<tr>
<td>Lanorma</td>
<td>116.34(^{a})</td>
<td>Lanorma</td>
<td>67.90(^{ab})</td>
</tr>
<tr>
<td>Innovator</td>
<td>103.70(^{ab})</td>
<td>Eos</td>
<td>64.31(^{b})</td>
</tr>
</tbody>
</table>

**Significant F test at p<0.05(*) and at p<0.1(**).**

**Table 3.6** ANOVA table for total P-uptake per plant in the first season (2015) and second season (2016), testing different P sources on four potato cultivars.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F-value</td>
<td>P&gt;F Significance</td>
<td></td>
<td>F-value</td>
</tr>
<tr>
<td>Treatment</td>
<td>4.32</td>
<td>0.56</td>
<td>ns</td>
<td>0.09</td>
</tr>
<tr>
<td>Cultivar</td>
<td>2.38</td>
<td>0.07</td>
<td>**</td>
<td>5.26</td>
</tr>
<tr>
<td>Treatment*Cultivar</td>
<td>1.25</td>
<td>0.42</td>
<td>ns</td>
<td>1.03</td>
</tr>
</tbody>
</table>

Any significant interactions between main effects that emerged for parameters measured are presented in tables * p < 0.05; **p < 0.1; ns, not significant at p > 0.05

**Nutrient value of tubers**

According to Walworth and Muniz (1983), application of the different P sources had no negative impact on the potato crop. All the nutrient levels recorded in the present study were within the acceptable ranges for the potato crop, as indicated by the tuber chemical analysis results (Table 3.7).

According to Walworth and Muniz (1983) the tuber nutrient levels recorded in the present study were within acceptable ranges for the different cultivars (Table 3.8). The different P sources were able to provide all the cultivars with sufficient nutrient concentrations.
Table 3.7 Chemical compositions of potato tubers after being cultivated with four different P sources during summer and winter season 1 (2015) and season 2 (2016). Treatments with different letters within the same season differed significantly (P<0.05).

<table>
<thead>
<tr>
<th>Treatments</th>
<th>N%</th>
<th>P%</th>
<th>K%</th>
<th>Ca%</th>
<th>Mg%</th>
</tr>
</thead>
<tbody>
<tr>
<td>100%Ortho:P(Control)</td>
<td>2.06c</td>
<td>0.48b</td>
<td>2.58a</td>
<td>0.08a</td>
<td>0.19a</td>
</tr>
<tr>
<td>25%(Poly-P)</td>
<td>2.19b</td>
<td>0.51b</td>
<td>2.57a</td>
<td>0.08a</td>
<td>0.19a</td>
</tr>
<tr>
<td>50%(Poly-P)</td>
<td>2.31a</td>
<td>0.55a</td>
<td>2.57a</td>
<td>0.09a</td>
<td>0.19a</td>
</tr>
<tr>
<td>100%(Poly-P)</td>
<td>2.19b</td>
<td>0.53a</td>
<td>2.45b</td>
<td>0.09a</td>
<td>0.17a</td>
</tr>
<tr>
<td>*</td>
<td>*</td>
<td></td>
<td>ns</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Significant F test at p<0.05 (*) and non-significant (ns) at p >0.05.

Table 3.8 Chemical compositions of potato tubers from four potato cultivars in season 1 (2015) and season 2 (2016). Cultivars with different letters within the same season differed significantly (P<0.05).

<table>
<thead>
<tr>
<th>Cultivars</th>
<th>N%</th>
<th>P%</th>
<th>K%</th>
<th>Ca%</th>
<th>Mg%</th>
<th>Zn(mg/kg)</th>
<th>B(mg/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mondial</td>
<td>2.26b</td>
<td>0.50b</td>
<td>2.73a</td>
<td>0.07c</td>
<td>0.18b</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sifra</td>
<td>2.10c</td>
<td>0.52ab</td>
<td>2.52b</td>
<td>0.06c</td>
<td>0.20a</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lanorma</td>
<td>2.41a</td>
<td>0.52ab</td>
<td>2.71a</td>
<td>0.09b</td>
<td>0.17b</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Innovator</td>
<td>1.97d</td>
<td>0.54a</td>
<td>2.22c</td>
<td>0.11a</td>
<td>0.18b</td>
<td></td>
<td></td>
</tr>
<tr>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Significant F test at p<0.05 (*), ns at (p>0.05). Norms according to Walworth and Muniz (1993).
Table 3.9 ANOVA table for composition of tuber essential nutrient elements of four potato cultivars fertilised with different orthophosphate and polyphosphate ratios in season 1 (2015) and season 2 (2016)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F-value</td>
<td>P&gt;F</td>
<td>Significance</td>
</tr>
<tr>
<td>Treatment</td>
<td>7.99</td>
<td>0.00</td>
<td>*</td>
</tr>
<tr>
<td>Cultivar</td>
<td>27.92</td>
<td>0.00</td>
<td>*</td>
</tr>
<tr>
<td>Treatment*Cultivar</td>
<td>0.76</td>
<td>0.85</td>
<td>ns</td>
</tr>
</tbody>
</table>

Any significant interactions between main effects that emerged for parameters measured are presented in tables * p < 0.05; ns, not significant at p > 0.05

Leaf analysis

According to Bennett (1993) the nutrient levels recorded in the present study were within acceptable ranges for potato leaves. This implies that both the orthophosphates and polyphosphates supplied sufficient nutrients to the leaves of the different potato cultivars (Table 3.11). In addition, there were no deficiency symptoms on the leaves. Therefore, it appears as if the different P sources did not to suppress the uptake of other essential nutrients (Table 3.10).

Table 3.10 Means of different leaf essential nutrient elements of potato after being cultivated with two different P sources and four application levels season 1 (2015) and season 2 (2016). Treatments with different letters within the same season differed significantly (P<0.05).

### Leaf analysis 2015

<table>
<thead>
<tr>
<th>Treatment</th>
<th>N%</th>
<th>P%</th>
<th>K%</th>
<th>Ca%</th>
<th>Mg%</th>
</tr>
</thead>
<tbody>
<tr>
<td>100%Ortho:P(MKP)</td>
<td>4.12ab</td>
<td>0.70b</td>
<td>5.38a</td>
<td>0.86b</td>
<td>0.33b</td>
</tr>
<tr>
<td>25%(Poly-P)</td>
<td>4.41a</td>
<td>0.77b</td>
<td>5.40a</td>
<td>0.90ab</td>
<td>0.35ab</td>
</tr>
<tr>
<td>50%(Poly-P)</td>
<td>4.59a</td>
<td>0.84a</td>
<td>5.33a</td>
<td>1.04a</td>
<td>0.37a</td>
</tr>
<tr>
<td>100%(Poly-P)</td>
<td>4.36ab</td>
<td>0.80a</td>
<td>5.10b</td>
<td>0.99ab</td>
<td>0.35ab</td>
</tr>
</tbody>
</table>

### Leaf analysis 2016

<table>
<thead>
<tr>
<th>Treatment</th>
<th>N%</th>
<th>P%</th>
<th>K%</th>
<th>Ca%</th>
<th>Mg%</th>
<th>Zn(mg/kg)</th>
<th>B(mg/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100%_OrthoP</td>
<td>4.17a</td>
<td>0.41b</td>
<td>11.00a</td>
<td>2.24a</td>
<td>0.39a</td>
<td>17.83b</td>
<td>21.28c</td>
</tr>
<tr>
<td>25%_PolyP</td>
<td>4.35a</td>
<td>0.53b</td>
<td>9.60a</td>
<td>1.81a</td>
<td>0.43a</td>
<td>22.96ab</td>
<td>31.00bc</td>
</tr>
<tr>
<td>50%_PolyP</td>
<td>4.90a</td>
<td>0.68a</td>
<td>9.42a</td>
<td>2.23a</td>
<td>0.50a</td>
<td>30.00a</td>
<td>54.54a</td>
</tr>
<tr>
<td>100%_PolyP</td>
<td>4.76a</td>
<td>0.69a</td>
<td>10.00a</td>
<td>1.80a</td>
<td>0.40a</td>
<td>27.63ab</td>
<td>48.82ab</td>
</tr>
</tbody>
</table>

Significant F test at p<0.05(*). Treatments means followed by different letters within the same season differed significantly (p<0.05).
Table 3.11 Differences in composition of leaf essential nutrient elements for four potato cultivars after being cultivated with different P application combinations. Cultivars with different letters within the same season differed significantly (P<0.05) season 1 (2015) and season 2 (2016).

<table>
<thead>
<tr>
<th>Cultivars</th>
<th>N%</th>
<th>P%</th>
<th>K%</th>
<th>Ca%</th>
<th>Mg%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mondial</td>
<td>4.48b</td>
<td>0.73b</td>
<td>5.74a</td>
<td>0.79d</td>
<td>0.32b</td>
</tr>
<tr>
<td>Sifra</td>
<td>4.23c</td>
<td>0.74b</td>
<td>5.28b</td>
<td>0.71c</td>
<td>0.39a</td>
</tr>
<tr>
<td>Lanorma</td>
<td>4.80a</td>
<td>0.75b</td>
<td>5.51c</td>
<td>1.04b</td>
<td>0.33b</td>
</tr>
<tr>
<td>Innovator</td>
<td>3.97d</td>
<td>0.89a</td>
<td>4.63d</td>
<td>1.25a</td>
<td>0.35ab</td>
</tr>
</tbody>
</table>

* Significant F test at p<0.05(*). Cultivars means followed by different letters differ significantly (p<0.05).

Norms according to Bennet (1993)

Table 3.12 ANOVA table for composition of essential nutrient elements for leaves for four potato cultivars fertilised with different P levels and sources season 1 (2015) and season 2 (2016)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F-value</td>
<td>P&gt;F Significance</td>
</tr>
<tr>
<td>Treatment</td>
<td>7.05</td>
<td>*</td>
</tr>
<tr>
<td>Cultivar</td>
<td>29.83</td>
<td>*</td>
</tr>
<tr>
<td>Treatment*Cultivar</td>
<td>0.64</td>
<td>0.95</td>
</tr>
</tbody>
</table>

* Significant F test at p<0.05 (*) and non-significant (ns). Treatment means followed by different letters differ significantly (p<0.05).
Conclusions

Interaction effects between treatments and cultivars did not significantly influence quality parameters. Treatments did not influence any quality parameters, with the exception of tuber and leaf nutrient elements. Cultivars significantly influenced dry matter content, total P-uptake per plant and tuber and leaf analysis. In the first season (2015), Lanorma and Innovator gave higher tuber dry matter content in comparison to Sifra. Destiny showed higher tuber dry matter content in the second season (2016) than all the other cultivars. It appears as if Destiny was more successful in portioning dry matter to the tubers. Specific gravity (SG) and defects were not significantly influenced by the cultivars. Phosphorus-utilization efficiency was not affected by the cultivars, although total P-uptake per plant was significantly influenced by the cultivars in both seasons. Lanorma gave higher total P-uptake per plant than Sifra. Similarly, Lanorma gave highest root dry mass than all the other cultivars. In the winter trial Destiny gave highest total P-uptake per plant in comparison to Eos. Similarly, Destiny gave higher root dry mass than Eos. It might be that root dry mass is related to increased P-uptake. Balemi and Schenk (2009) observed that longer, denser roots with a higher root yield increase P-uptake as well as the extension of the depletion zone from the root surface into the soil.

All the nutrient levels recorded in the present study were within the acceptable ranges for the potato crop, as indicated by the tuber and leaf chemical analysis results. Application of the different P sources had no negative impact on potato quality.
References


Coetzee PE. 2013. Response of maize to phosphorus and nitrogen fertilisers on a soil with low phosphorus status. MSc Thesis University of the Free State.


Chapter 4

The effect of orthophosphates and polyphosphates on potato (Solanum tuberosum L.) growth, yield and quality under different pH levels.

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*Corresponding author, e-mail: nvhuthu@gmail.com

Abstract

Polyphosphate fertilisers are becoming popular in the agricultural sector due to easy application and reported high yields related to the application of this fertiliser. A study was initiated to determine the effects of pH on growth, yield and quality of potatoes using orthophosphate and polyphosphate as phosphorus source. Potato plantlets of the cultivar Mondial was grown using two different P sources (100% orthophosphate and 100% polyphosphate) and three pH levels. The pH levels in the different treatments were maintained at 5.5, 6.5 and 7.5. Each treatment combination was repeated six times (2X3X6) and treatments were laid out as a completely randomised design (CRD). The interaction between P application and pH levels significantly influenced total yield. Applying P as polyphosphate resulted in significantly lower tuber fresh yield at solution pH of 6.5 and 7.5. Phosphate application treatments and pH levels had no significant effects on quality parameters. Phosphorus-utilization efficiency (PUE) and total P-uptake per plant was not influenced by phosphate treatments nor the pH levels. The overall results showed that the two P sources did not differ in most of the measured parameters.

Keywords: Mondial, orthophosphate, pH, polyphosphate, potato
Introduction
The problem of having to increase yield per hectare on diminishing agricultural land to meet the needs of an ever rising population cannot be neglected (Ngezimana and Agenbag 2013). Potatoes are one of the most commonly grown crops which account for more than 80% of human calorie intake globally; potatoes are also the primary source of starch in many countries (Leff et al. 2004; Nabors 2004). Proper management of soil fertility has been identified as one of the major management practices that can improve growth, yield and development of plants (Tisdale et al. 1995). Inorganic fertilisers have been used in recent years to increase crop yield per hectare and to address food insecurity (Woldgiorgis 2014). Phosphorus is an essential macronutrient required in large amounts by most plants where it plays a major role in the growth and development processes of plants (Sultenfuss et al. 1999). Potatoes require relatively more nutrients than other crops (Stark et al. 2004; Munoz et al. 2005). Phosphorus availability is however problematic since most soils have a low P status and in those soils which do have sufficient P in the soil, the P may be in unavailable forms. The average total P available in land which is suitable for growing crops is 0.05% (400 to 2000 kg ha\(^{-1}\)) of which only a microscopic part of the P is available to the plant (Miller 1995).

Phosphate can be applied to crops in different forms. The use of polyphosphates is becoming popular in the world (Torres-Dorante et al. 2006) but polyphosphates are still a relatively new technology in South Africa and extensive research is still needed to determine if polyphosphates (liquid phosphorus fertilisers) have significant yield benefits in comparison to the conventional orthophosphate (granular/solid fertilisers) when applied to crops (Holloway et al. 2004). In fertiliser programs where part of the fertiliser is applied through fertigation throughout the season, liquid fertilisers such as polyphosphate may be beneficial since the polyphosphates are not only highly water soluble but also will become available for plant uptake over a longer time period. Several studies have reported that potatoes respond well to the application of both orthophosphates and polyphosphates (Dobson et al. 1970; Jung and Jugens-Gschwind 1975; Terman 1975; Engelstad and Terman 1980; Dick and Tabatabi 1987). Higher yields related to polyphosphate applications have been reported for several crops Torres-Dorante et al. (2006), such as soybean (Billore and Bargale 1991), rice (Rao et al. 1991), chickpea and wheat (Verugopalan and Prasad 1989). However, polyphosphate hydrolysis depends on a number of factors such as ionic environment, temperature and pH (Van Wazer et al. 1952; Rashchi and Finch 2000; Ahmad and Kelso 2001). In addition, Haverkort et al. (1993) noted that the potato crop can grow on a wide range of soil pH levels (5.0-8.3), but they also noted that a slightly acidic pH (5.5-6.3) is more suitable. However, Horneck et al (2007) reported that pH should not
be too acidic as this will inhibit nutrient availability. They concluded that pH affects tuber quality and yield. Van Wazer et al. (1955) showed that pH is one of the most important factors when studying hydrolysis of polyphosphates. They showed that hydrolysis of polyphosphates constantly increased when pH was reduced from 13 to 1. Thus, the objective of this study was to determine the ideal pH level for highest yield by potato plants when applying P as orthophosphate or polyphosphate.

**Materials and Methods**

*Location and crop details*

The research was carried out in a glasshouse at Welgevallen experimental farm, Stellenbosch University in the Western Cape of South Africa. Potato (*Solanum tuberosum* L.) seedlings of the cultivar Mondial were used for this experiment. Mondial is a medium maturing cultivar which generally takes 90 to 110 days before maturing, with a short dormancy period of about 50 to 60 days. Mondial is a strong, tall grower with semi-erect to slightly spreading stems (Visser 2012).

*Preparation of planting material*

Homogenous sprouts were cut from the tubers and planted into seedling trays in a glasshouse on the 6th of April 2016 (Plate 4.1). A seedling mix containing coco-peat, vermiculite and perlite was used as growing medium for the 36 potato seedlings. The seedlings were irrigated every other day with Municipal water before being transplanted 3 weeks later (at 3 leaf stage) into growing bags. Upon transplanting seedlings were irrigated manually every second day with 250 ml of the different solutions. Solutions consisted of either 100% orthophosphate or 100% polyphosphate, each prepared at a pH of 5.5, 6.5 and 7.5 (Table 4.1). The irrigation frequency was increased at 4 weeks after planting to 500 ml daily (250 ml at 09:30 and 250 ml at 14:00). Water drained from the growing bags were monitored; initially at 50% and later in the season up to 10% drained of the applied nutrient solution.
Table 4.1 Composition of the nutrient solutions containing the two P sources and 3 pH levels used to fertigate potato plants.

<table>
<thead>
<tr>
<th>Fertiliser application rate (g/1000L)</th>
<th>100% Poly-P</th>
<th>100% Ortho-P</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH levels</td>
<td>5.5</td>
<td>6.5</td>
</tr>
<tr>
<td>Polyphosphate (ml)</td>
<td>317.5</td>
<td>317.5</td>
</tr>
<tr>
<td>KNO$_3$</td>
<td>282.8</td>
<td>282.8</td>
</tr>
<tr>
<td>K$_2$SO$_4$</td>
<td>226.2</td>
<td>226.2</td>
</tr>
<tr>
<td>KH$_2$PO$_4$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ca(NO$_3$)$_2$·2H$_2$O</td>
<td>650.0</td>
<td>650.0</td>
</tr>
<tr>
<td>MgSO$_4$·7H$_2$O</td>
<td>369.0</td>
<td>369.0</td>
</tr>
<tr>
<td>CaSO$_4$·2H$_2$O</td>
<td>56.0</td>
<td>56.0</td>
</tr>
</tbody>
</table>

The pH was monitored and controlled manually using either sodium hydroxide to raise the pH or nitric acid to lower the pH. A portable hand pH meter was used to monitor the pH (Milwaukee instruments). Solutions were made up in six 20 litre buckets and replenished every three weeks. Temperature and relative humidity inside the glasshouse was measured throughout the entire growing season (Figure 4.1).
Figure 4.1 Measurement of temperature and relative humidity inside the glasshouse throughout the growing season.

**Measurements and analysis**

At harvesting the shoot, tuber and root fresh and dry mass were measured. Specific gravity (SG) was also measured as an indication of tuber starch content and quality. Tuber number per plant was determined and the harvest index (HI) was determined as the ratio of dry yield of tubers to the total dry biomass at harvest (Woldgiorgis 2014). Tubers were grouped into small (<20 g), medium (20-80 g) and large (>80 g) tubers.

The dry matter percentages was calculated according to Williams (1968) using the following formulas.

\[
\text{Tuber dry matter content (\%)} = \frac{\text{tuber dry mass (g)}}{\text{tuber fresh mass (g)}} \times 100
\]

The P concentration in the plants was determined as stated below in order to calculate total P uptake per plant and P-utilization efficiency (PUE) as follows:
Total P uptake per plant (mg plant⁻¹) = Total P concentration (tubers + leaves) (mg/g) × dry matter (g/plant) (Akhtar et al. 2008)

\[
PUE = \frac{\text{Tuber dry matter (g plant}^{-1})}{P (mg plant}^{-1})
\] (Elloitt and White 1994)

Specific gravity as a measure of processing quality was measured by dividing tuber mass by the total volume of water displaced by the tubers when they were lowered in a beaker. The mass of the tuber was then divided with the volume of water displaced to obtain SG using the equation:

\[
SG = \frac{\text{tuber mass (g)}}{\text{volume of water displaced (mL)}}
\] (Tabatabaeefar 2002)

Tubers were also visually inspected for defects, both on the tuber’s external surface for growth cracks and also by cutting tubers in half and checking for internal physiological disorders such as internal brown spot, hollow heart and brown centres. For macro element determinations, skin and medullary tissue samples were taken and processed according to the procedures described by Kratzke and Palta (1986) and Soltanpour et al. (1996). Samples were washed and dried in an oven at 49°C for 5 days, grounded to pass a 40-mesh of (0.635 mm) screen, weighed, burnt at 450°C for 8 hours, dissolved in 2 N HCl, and diluted with a Lanthanum chloride (LaCl₃×H₂O) solution and distilled in deionized water to obtain samples in 0.2 HCl and in Lanthanum (La) at 2000 μg/mL. Samples were replicated 4 times by reading on the inductively coupled plasma atomic emission spectrophotometry wave-length table. Macro element concentrations were determined by atomic absorption spectrophotometry as described by Karlsson and Palta (2006).
Plate 4.1 Homogenous sprouts cut from potato cultivar Mondial, then planted in seedling trays.

Treatments and experimental design

Only one potato cultivar (Mondial) was used for this trial and two different P sources, orthophosphate and polyphosphate, were applied to the potato plants. Treatment factors consisted of: T1: Control – 100% of P applied as orthophosphate (mono-potassium phosphate) at pH levels 5.5, 6.5 and 7.5 and T2: P applied as polyphosphate at of pH levels 5.5, 6.5 and 7.5 (Table 4.1). Each treatment combination was repeated six times (2X3X6) and treatments were laid out as a completely randomised design (CRD) with one plant per repetition. Data was analysed using two-way analysis of variance (ANOVA), data was checked for normality, homogeneity was also tested and means compared (P<0.05) using the general linear model of Statistica 12 software (Statistica 2012).

Results and Discussion

Morphology and vegetative growth

The P application treatments and solution pH significantly influenced shoot dry mass (Table 4.2). Orthophosphate gave a higher shoot dry mass (10.31 g plant⁻¹) in comparison to polyphosphates (7.82 g plant⁻¹) (Table 4.2). Tshisola (2014) also found a significant effect of fertilisers on shoot dry mass. They noted minimum and maximum values of 5.28 and 7.01 g plant⁻¹ for shoot dry mass in response to fertilisation. The results by Tshisola (2014) are similar.
to the results of the current study. De Ruijter (1999) noted that shoot dry mass was highly affected by P fertilisation; in the study orthophosphates were used as a source of P. Some studies have corroborated the above findings in the present study. Coetzee (2013) found that mono-ammonium phosphate (MAP) gave a higher shoot dry mass in comparison to the polyphosphates. They noted dry mass values of 39 and 43 g for orthophosphate and polyphosphate respectively. Ahmad and Kelso (2001) reported that regardless of polyphosphate water solubility, polyphosphates are not considered to be as efficient as orthophosphates in terms of plant nutrition. On the contrary, Woldgiorgis (2014) noted that the main effect of P did not significantly affect shoot biomass (Table 4.2).

Low pH levels of 5.5 and 6.5 gave higher shoots dry mass in comparison to high pH of 7.5 (Table 4.2). High pH thus appears to inhibit hydrolysis, thus reducing available P and thus, reduced leaf development. Furthermore, De Ruijter (1999) also reported that high pH reduces shoot mass. High pH levels reduce potato growth by reducing P availability. On the contrary, Britto and Kronzucker (2002) reported that a low-medium soil pH has been found to greatly suppress dry mass as a result of increased ammonium sensitivity and/or toxicity by the plants roots and metabolism.

Several studies by Dobson et al. (1970) and Jung and Jugens-Gschwind (1975) and Terman (1975) and Engelstad and Terman (1980) and Dick and Tabatabi (1987) reported that the two P sources (orthophosphate and polyphosphate) do not differ. The high pH could have caused the reduced observed shoot dry mass at pH=7.5 (Table 4.2) since pH has an effect on P availability. De Ruijter (1999) noted significant interaction between fertilisation and pH on shoot mass. This was not apparent in the present study (Table 4.3). In addition to those studies, Lugt et al. (1964) observed no significant difference in plant establishment as a result of N, P and K fertiliser applications.
Table 4.2: The means of shoot dry mass measured on potato cultivar Mondial grown with two different P sources at three pH levels under glasshouse conditions.

<table>
<thead>
<tr>
<th>Phosphate treatment</th>
<th>Shoot dry mass (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orthophosphate</td>
<td>10.31&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Polyphosphate</td>
<td>7.82&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>pH levels</th>
<th>Shoot dry mass (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH=5.5</td>
<td>9.56&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>pH=6.5</td>
<td>10.35&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>pH=7.5</td>
<td>7.30&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

* Treatments with different letters differed significantly (P<0.05) or (P<0.1). Non-significant (ns) at P>0.05

Table 4.3 ANOVA table: treatment, pH and interaction between treatment and pH for shoot dry mass

<table>
<thead>
<tr>
<th>ANOVA</th>
<th>F-value</th>
<th>Pr&gt;F</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment</td>
<td>0.64</td>
<td>0.01</td>
<td>*</td>
</tr>
<tr>
<td>pH</td>
<td>1.09</td>
<td>0.02</td>
<td>*</td>
</tr>
<tr>
<td><em>Treatment</em>pH</td>
<td>2.30</td>
<td>0.53</td>
<td>ns</td>
</tr>
</tbody>
</table>

Any significant interactions between main effects that emerged for parameters measured are presented in graphs * *p < 0.1; ns, not significant at p > 0.05

Root yield

There were no significant differences in root fresh and dry yield as influenced by the P treatments and the pH levels (Table 4.4 and Table 4.5). A study conducted by Tshisola (2014) found that the average root dry mass of potatoes at harvest maturity fertilised with a well-balanced nutrient solution ranged from 4 to 20 g. Woldgiorgis (2014) found that root dry mass of potatoes after N and P fertilisation ranged between 31.3 to 90.5 g. The root dry mass was generally low in the current study (Table 4.4) in comparison to the aforementioned studies, which was not expected since optimum supply of P is associated with increased root growth and in the present study a well-balanced nutrient solution was used to irrigate the plants. The low root dry yield values could have been caused by the relatively low temperatures in the glasshouse (Figure 4.1).
Application of orthophosphates such as mono-ammonium phosphate (MAP) and mono-potassium phosphate (MKP), which are readily available after application, were reported to have a significant effect on root dry yield (Lynch and Brown 2001). In the current study those significant orthophosphate effects were not observed in comparison to polyphosphates. For polyphosphates to be taken up by the roots they have to be broken down into orthophosphates. Orthophosphates have an added advantage since they are already in the form in which P is absorbed through the root system (Coetzee 2013). In the present study orthophosphates were expected to have yielded a higher root yield since the orthophosphate (MKP) is readily available after P fertilisation. The increased P availability by the orthophosphate was expected to have increased root growth due to greater absorption by the roots since a slight increase in P can intensify root growth and morphology (Qu et al. 2003; Zhang et al. 2012).

The non-significant differences in root yield due to the pH levels in the present study were also not expected. Root yield at high pH of 7.5 was expected to be lower in comparison to root yield at lower pH levels of 5.5 and 6.5 (Table 4.4). Tang et al. (1996) noted that a high pH causes a reduction in root number, which consequently affects root yield due to decreased root elongation.

**Table 4.4** The means of root fresh and dry yield measured on potato cultivar Mondial grown with two different P sources and at different pH levels under glasshouse conditions.

<table>
<thead>
<tr>
<th>Phosphate treatment</th>
<th>Root fresh yield (g plant(^{-1}))</th>
<th>Root dry yield (g plant(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orthophosphate</td>
<td>10.41(^{a})</td>
<td>1.61(^{a})</td>
</tr>
<tr>
<td>Polyphosphate</td>
<td>11.31(^{a})</td>
<td>1.51(^{a})</td>
</tr>
<tr>
<td>ns</td>
<td>ns</td>
<td>ns</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>pH levels</th>
<th>Root fresh yield (g plant(^{-1}))</th>
<th>Root dry yield (g plant(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH=5.5</td>
<td>10.88(^{a})</td>
<td>1.62(^{a})</td>
</tr>
<tr>
<td>pH=6.5</td>
<td>10.03(^{a})</td>
<td>1.32(^{a})</td>
</tr>
<tr>
<td>pH=7.5</td>
<td>11.67(^{a})</td>
<td>1.74(^{a})</td>
</tr>
<tr>
<td>ns</td>
<td>ns</td>
<td>ns</td>
</tr>
</tbody>
</table>

*Treatments with different letters differed significantly (P<0.05). Non-significant (ns) at P>0.05*
Table 4.5 ANOVA table: phosphate treatment, pH and interaction between main effects for root fresh mass and root dry mass.

<table>
<thead>
<tr>
<th></th>
<th>ANOVA</th>
<th>F-value</th>
<th>Pr&gt;F</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Root fresh mass</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Treatment</td>
<td>0.17</td>
<td>0.68</td>
<td>ns</td>
<td></td>
</tr>
<tr>
<td>pH</td>
<td>0.18</td>
<td>0.83</td>
<td>ns</td>
<td></td>
</tr>
<tr>
<td>Treatment*pH</td>
<td>1.23</td>
<td>0.31</td>
<td>ns</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>ANOVA</th>
<th>F-value</th>
<th>Pr&gt;F</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Root dry mass</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Treatment</td>
<td>0.03</td>
<td>0.86</td>
<td>ns</td>
<td></td>
</tr>
<tr>
<td>pH</td>
<td>0.19</td>
<td>0.83</td>
<td>ns</td>
<td></td>
</tr>
<tr>
<td>Treatment*pH</td>
<td>1.19</td>
<td>0.32</td>
<td>ns</td>
<td></td>
</tr>
</tbody>
</table>

Any significant interactions between main effects that emerged for parameters measured are presented in tables ns, not significant at p >0.05.

Total tuber fresh yield

Interaction effects between P treatments and pH levels on the fresh tuber yield were noted (Table 4.6). Total fresh tuber yield was not affected by the pH of the solution when P was applied as orthophosphate (Figure 4.2). However, when applying the P as polyphosphate, tuber yield was significantly lower at solution pH of 6.5 and 7.5. Haverkort et al. (1993) noted that the potato crop can grow on a wide range of pH levels of 5.0-8.3. They also noted that acidic pH (5.5-6.3) is more suitable, as is evident in the current study for polyphosphate, where tuber yield was significantly lower at solution pH of 6.5 and 7.5. These results indicate that pH may have an effect on P availability when polyphosphate is used but not orthophosphates. The reduction in crop yields showed by the polyphosphate at pH 6.5 and pH 7.5 (Figure 4.2), could also be due to reduced hydrolysis at high pH. Sutton and Larsen (1964) reported that polyphosphates are ineffective source of P before hydrolysis to orthophosphate form. Hydrolysis of polyphosphate to orthophosphate is dependent on pH and other environmental factors. High pH may have inhibited polyphosphate hydrolysis since orthophosphate ions are readily available for plant uptake as either a primary orthophosphate ion ($H_2PO_4^-$ at a soil pH < 7.0) or a secondary orthophosphate ion ($HPO_4^{2-}$ with a soil pH > 7.0) (Noack 2010). Van Wazer et al (1955) also noted that hydrolysis of polyphosphates constantly increased when pH was reduced from 13 to 1. The aforementioned was apparent as the polyphosphate decreased tuber yield as pH increased from 5.5 to 7.5. In addition the growing medium (sandy soil) used in the present study may have also inhibited polyphosphate hydrolysis. Torres-Dorante et al. (2006) reported that after one to three days of polyphosphate application to sandy soils, breakdown of
polyphosphate to orthophosphate in the soil solution is low. Torres-Dorante et al. (2006) also reported that with time the amount of P in the polyphosphate will increase and reach the same P concentration as the orthophosphate. In the present study the high pH may have inhibited hydrolysis over time, resulting in reduced P availability, thus lower yields in the polyphosphate treatment.

Soratto (2015) conducted research and found minimum and maximum average values of 444.4 and 740.2 g plant\(^{-1}\) potato yields after P fertilisation. The average tuber fresh yield values as reported by Soratto (2015) were higher in comparison to the results of the present study (Figure 4.2). This could be because the light intensity and the temperature used by Soratto (2015) were favourable. Temperature was maintained at 27/14 °C (day/night temperature) with a 12-hour photoperiod. The light intensity maximum value was 1500 \(\mu\)mol m\(^{-2}\) s\(^{-1}\). This is in contrast to the relatively low temperatures in the glasshouse in the present study (Figure 4.1).

Mulder (1994) and Maier et al. (2002) reported that there is a decline in P availability as pH increases and this may have caused a significant impact on yield since P is important for plant growth. The high pH resulting in reduced tuber yield (Figure 4.2) is in agreement with the findings of De Ruijter (1999), who reported that high pH reduced final tuber yield. However, De Ruijter (1999) also observed that yield loss was greater at high pH compared to lower acidic pH of 5.5 and this was due to decreased concentrations of P and K. However, Horneck et al. (2007) reported that pH should not be too acidic (<3) since extremely low pH inhibits P availability and pH affects polyphosphate hydrolysis. They concluded that pH affects tuber quality and yield.
Figure 4.2 The interaction means of tuber fresh yield measured on potato cultivar Mondial grown with two different P sources and three pH levels under glasshouse conditions. Treatments with different letters within the same P source differed significantly (P<0.05).

Table 4.6 ANOVA table: treatment, pH and interaction between treatment and pH for total tuber yield per plant.

<table>
<thead>
<tr>
<th>ANOVA</th>
<th>F-value</th>
<th>Pr&gt;F</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment</td>
<td>6.94</td>
<td>0.01</td>
<td>*</td>
</tr>
<tr>
<td>pH</td>
<td>4.10</td>
<td>0.03</td>
<td>*</td>
</tr>
<tr>
<td>Treatment*pH</td>
<td>3.50</td>
<td>0.04</td>
<td>*</td>
</tr>
</tbody>
</table>

Any significant interactions between main effects that emerged for parameters measured are presented in graphs * p < 0.05.

Total number of tubers

There were no significant differences in total number of tubers as influenced by the two P sources and pH levels (Table 4.7 and Table 4.9). Tshisola (2014) found a significant effect of fertilisation on total number of tubers and found average tuber numbers of 14.10 and 52.05 g plant$^{-1}$. Phosphorus affects total number of tubers since application of P increases the number of tubers set (Sommerfeld and Knutson 1965; Maier et al. 1994). This is because P is important for tuber initiation, starch synthesis, transport and storage (Brink 2016). Rosen and Bierman (2008), however, noted an indirectly proportional relationship between tuber yield and total number of tubers, thus more tubers formed had a reduced yield; this can be noted especially with P fertilisation (Seome 2013). Brink (2016) reported that this is because low tuber number
provides less competition per unit area and allows the crops’ energy and resources to be used in producing larger tubers/bulking instead of initiating new tubers. Yibekal (1998) reported that higher P levels significantly increased total tuber number per plant. On the contrary Sharma and Arora (1987) reported no significant differences in the total number of tubers per square meter of land area as a result of N, P and K fertiliser application. Seome (2013) noted no significant effect of pH on tuber number. Lower pH was expected to have higher total number of tubers since high pH is believed to inhibit P availability, thus reduced potato growth and consequently lower tuber numbers (Seome 2013).

**Tuber size distribution**

There were no significant differences in tuber yield per size as influenced by the two P sources and the three pH levels (Table 4.7 and Table 4.8). According to Mulubrhan (2004) and Sharma and Arora (1987) the interaction effect of different macro elements in the soil during crop growth including that P increased medium and large size tuber but significantly decreased small sized tubers of potato. Tsegaye et al. (2014) reported that medium sized tubers correlated positively with marketable tuber yield (r = 0.57**) and correlated negatively(r = -0.56**) with unmarketable tubers. This means that factors such as fertilisation with P which increase marketable tubers, also reduces unmarketable tubers.

**Table 4.7** The means of tuber yield per size and total number of tubers measured on potato cultivar Mondial grown with two different P sources and three pH levels under glasshouse conditions.

<table>
<thead>
<tr>
<th>Phosphate treatment</th>
<th>Tuber yield (g plant⁻¹)</th>
<th>Tuber number plant⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Small</td>
<td>Medium</td>
</tr>
<tr>
<td>Orthophosphate</td>
<td>33.43⁺</td>
<td>155.95⁺</td>
</tr>
<tr>
<td>Polyphosphate</td>
<td>46.39⁺</td>
<td>138.48⁺</td>
</tr>
<tr>
<td></td>
<td>ns</td>
<td>ns</td>
</tr>
</tbody>
</table>

**pH levels**

<table>
<thead>
<tr>
<th>pH</th>
<th>Tuber yield (g plant⁻¹)</th>
<th>Tuber number plant⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Small</td>
<td>Medium</td>
</tr>
<tr>
<td>pH=5.5</td>
<td>38.13⁺</td>
<td>180.61⁺</td>
</tr>
<tr>
<td>pH=6.5</td>
<td>37.10⁺</td>
<td>143.75⁺</td>
</tr>
<tr>
<td>pH=7.5</td>
<td>44.51⁺</td>
<td>117.30⁺</td>
</tr>
<tr>
<td></td>
<td>ns</td>
<td>ns</td>
</tr>
</tbody>
</table>

*Non-significant (ns) at P>0.05*
Table 4.8 ANOVA table: treatment, pH and interaction between treatment and pH for total small, medium and large tuber yield per size.

<table>
<thead>
<tr>
<th></th>
<th>Small tubers</th>
<th></th>
<th>Medium tubers</th>
<th></th>
<th>Large tubers</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ANOVA</td>
<td>F-value</td>
<td>Pr&gt;F</td>
<td>Significance</td>
<td>ANOVA</td>
<td>F-value</td>
</tr>
<tr>
<td>Treatment</td>
<td></td>
<td>2.22</td>
<td>0.15</td>
<td>ns</td>
<td>Treatment</td>
<td>0.50</td>
</tr>
<tr>
<td>pH</td>
<td></td>
<td>2.28</td>
<td>0.75</td>
<td>ns</td>
<td>pH</td>
<td>2.15</td>
</tr>
<tr>
<td>Treatment*pH</td>
<td></td>
<td>2.07</td>
<td>0.14</td>
<td>ns</td>
<td>Treatment*pH</td>
<td>1.13</td>
</tr>
</tbody>
</table>

Any significant interactions between main effects that emerged for parameters measured are presented in table ns, not significant at p > 0.05

Table 4.9 ANOVA table: treatment, pH and interaction between treatment and pH for small, medium, large and total tuber number per plant.

<table>
<thead>
<tr>
<th></th>
<th>Small tubers</th>
<th></th>
<th>Medium tubers</th>
<th></th>
<th>Large tubers</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ANOVA</td>
<td>F-value</td>
<td>Pr&gt;F</td>
<td>Significance</td>
<td>ANOVA</td>
<td>F-value</td>
</tr>
<tr>
<td>Treatment</td>
<td></td>
<td>0.45</td>
<td>0.51</td>
<td>ns</td>
<td>Treatment</td>
<td>0.99</td>
</tr>
<tr>
<td>pH</td>
<td></td>
<td>0.25</td>
<td>0.78</td>
<td>ns</td>
<td>pH</td>
<td>1.56</td>
</tr>
<tr>
<td>Treatment*pH</td>
<td></td>
<td>1.94</td>
<td>0.16</td>
<td>ns</td>
<td>Treatment*pH</td>
<td>0.60</td>
</tr>
<tr>
<td>ANOVA</td>
<td>F-value</td>
<td>Pr&gt;F</td>
<td>Significance</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-------------</td>
<td>---------</td>
<td>------</td>
<td>--------------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Treatment</td>
<td>0.99</td>
<td>0.33</td>
<td>ns</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pH</td>
<td>0.26</td>
<td>0.77</td>
<td>ns</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Treatment*pH</td>
<td>1.91</td>
<td>0.17</td>
<td>ns</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Any significant interactions between main effects that emerged for parameters measured are presented in tables ns, not significant at p = 0.05

Tuber dry mass yield

Tuber dry mass yield was not statistically different as influenced by the P treatments and the pH levels (Table 4.10 and Table 4.11).

Quality parameters

There were no significant differences in tuber dry matter content as influenced by the two P sources (orthophosphate and polyphosphate) and the three pH levels (Table 4.10 and Table 4.11). These results are in agreement with those of Storey and Davies (1992), who reported that no significant effects of P fertilisation on potato tuber dry matter content have been observed. Sparrow et al. (1992) also reported non-significant differences in dry matter content due to P fertilisation. Storey and Davies (1992) also reported that tuber dry matter content is influenced by different factors such as soil water and cultural practices. According to Brink (2016), 20-25% is appropriate for tuber dry matter content. Optimal P concentrations encourage higher dry matter contents and starch (Mulder and Turkensteen 2005).

There was no interaction between treatments and pH levels with regards to defects. There were also non-significant differences in defects as influenced by the two P sources and pH levels, (Table 4.10 and Table 4.11). It appears as if the different P sources and the pH levels did not cause any defects to tubers. Woldgiorgis et al. (2014) reported that when P levels where increased, defected tubers were reduced. However, Boral and Milthorpe (1962) noted that re-absorption and net assimilation processes in the potato tubers result in increased tuber yield and tuber size, which results in more marketable tubers instead of defected tubers.

The treatments, pH and interaction between treatment and pH levels were non-significant with regards to specific gravity (SG) (Table 4.10 and Table 4.11). However, results regarding the effect of P fertilisation on SG are contradictory (Woldgiorgis et al. 2014). The results in the present study are in agreement with Lujan and Smith (1964), who reported no significant effect of P on the SG of tubers. This is in contrast with Zandstra et al. (1969) and Dubetz (1975), who
noted an indirectly proportional relationship between P fertilisation and SG. Human (1961) on the other hand reported increase in SG with increase in P application. Munro et al. (1977) also noted the same results as stated above by Zandstra et al. (1969) and Dubetz (1975). Although Munro et al. (1977) noted this using N instead of P they noted higher SG with N (50 kg/ha) applications. Woldgiorgis (2014) conducted research and found SG values between 1.03 and 1.066 in response to increasing P fertiliser rates. Modisane (2007) found SG values for mature tubers ranging from 1.085 to 1.090 with an average value of 1.087. The SG values in the current study as influenced by pH=6.5 and 7.5 were extremely low (Table 4.9), in comparison to findings by Modisane (2007). This can be attributed to the method used to determine SG (4.4), which tends to underestimate SG values.

Table 4.10 The means of quality characteristics and tuber dry mass measured on potato cultivar Mondial grown with different P sources and pH levels under glasshouse conditions.

<table>
<thead>
<tr>
<th>Phosphate treatments</th>
<th>Dry matter content (%)</th>
<th>Tuber dry mass (g plant⁻¹)</th>
<th>Defects for (medium/marketable tubers) %</th>
<th>Specific gravity (medium/marketable tubers)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orthophosphate</td>
<td>15.73a</td>
<td>49.13a</td>
<td>5.00a</td>
<td>1.06a</td>
</tr>
<tr>
<td>Polyphosphate</td>
<td>16.58a</td>
<td>41.67a</td>
<td>4.88a</td>
<td>1.07a</td>
</tr>
<tr>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
</tr>
<tr>
<td>pH levels</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pH=5.5</td>
<td>15.56a</td>
<td>50.62a</td>
<td>5.00a</td>
<td>1.05a</td>
</tr>
<tr>
<td>pH=6.5</td>
<td>16.26a</td>
<td>46.37a</td>
<td>5.00a</td>
<td>1.02a</td>
</tr>
<tr>
<td>pH=7.5</td>
<td>16.23a</td>
<td>39.24a</td>
<td>4.83a</td>
<td>1.03a</td>
</tr>
<tr>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
</tr>
</tbody>
</table>

*Significant F test at P<0.05 (*) and non-significant (ns) P > 0.05.*
Table 4.11 ANOVA table: treatment, pH and interaction between treatment and pH for tuber post-harvest quality parameters and tuber dry mass.

<table>
<thead>
<tr>
<th></th>
<th>ANOVA</th>
<th>F-value</th>
<th>Pr&gt;F</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tuber dry yield</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Treatment</td>
<td>3.12</td>
<td>0.87</td>
<td>ns</td>
<td></td>
</tr>
<tr>
<td>pH</td>
<td>2.47</td>
<td>0.10</td>
<td>ns</td>
<td></td>
</tr>
<tr>
<td>Treatment*pH</td>
<td>1.77</td>
<td>0.19</td>
<td>ns</td>
<td></td>
</tr>
<tr>
<td><strong>Tuber dry matter content</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Treatment</td>
<td>0.72</td>
<td>0.40</td>
<td>ns</td>
<td></td>
</tr>
<tr>
<td>pH</td>
<td>0.40</td>
<td>0.67</td>
<td>ns</td>
<td></td>
</tr>
<tr>
<td>Treatment*pH</td>
<td>0.30</td>
<td>0.77</td>
<td>ns</td>
<td></td>
</tr>
<tr>
<td><strong>Tuber defects</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Treatment</td>
<td>0.94</td>
<td>0.34</td>
<td>ns</td>
<td></td>
</tr>
<tr>
<td>pH</td>
<td>0.95</td>
<td>0.40</td>
<td>ns</td>
<td></td>
</tr>
<tr>
<td>Treatment*pH</td>
<td>0.95</td>
<td>0.40</td>
<td>ns</td>
<td></td>
</tr>
<tr>
<td><strong>Tuber specific gravity (SG)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Treatment</td>
<td>0.02</td>
<td>0.87</td>
<td>ns</td>
<td></td>
</tr>
<tr>
<td>pH</td>
<td>0.58</td>
<td>0.57</td>
<td>Ns</td>
<td></td>
</tr>
<tr>
<td>Treatment*pH</td>
<td>0.29</td>
<td>0.75</td>
<td>ns</td>
<td></td>
</tr>
</tbody>
</table>

Any significant interactions between main effects that emerged for parameters measured are presented in table ns, not significant at p > 0.05

Harvest index

Interaction between treatment and pH level was non-significant. Treatments and pH levels had no effect on harvest index (Table 4.12). Mulubrhan (2004) also noted that harvest index (HI) was undesirably affected by P. In contrast, Woldgiorgis et al. (2014) revealed that P treatments significantly affected (P < 0.01) HI. Woldgiorgis et al. (2014) noted that high HI was obtained at high P application. They concluded that this may be due to the effect of P which increased tuber production of the potato instead of the vegetative part of the potato plants. The HI values in the present study were 82% and 84% as influenced by the orthophosphate and the polyphosphate respectively. The HI values as influenced the pH levels were found to be 84%, 85% and 82%. The results in the current study are in corroboration with Jefferies and MacKerron (1989),
Beukema and Van der Zaag (1990), Vos (1997) and Belanger et al. (2001), who reported that under optimal potato growing conditions harvest index values range from 70% to 85%.

Table 4.12 ANOVA table: treatment, pH and interaction between treatment and pH for harvest index.

<table>
<thead>
<tr>
<th>ANOVA</th>
<th>F-value</th>
<th>Pr&gt;F</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment</td>
<td>1.02</td>
<td>0.32</td>
<td>ns</td>
</tr>
<tr>
<td>pH</td>
<td>1.43</td>
<td>0.25</td>
<td>ns</td>
</tr>
<tr>
<td>Treatment*pH</td>
<td>0.03</td>
<td>0.96</td>
<td>ns</td>
</tr>
</tbody>
</table>

Any significant interactions between main effects that emerged for parameters measured are presented in graphs *p < 0.05, ns, not significant at p > 0.05

**Phosphorus utilization efficiency and total P-uptake per plant**

Phosphorus-utilization efficiency (PUE) was not significantly influenced by the P treatments nor the pH levels. Total P-uptake per plant was also not significantly influenced by the P treatments or the pH levels. Although not significantly different PUE and total P-uptake per plant as influenced by the orthophosphate and polyphosphate was 36.00 and 39.00 mg plant\(^{-1}\) and 51.34 and 65.25 mg plant\(^{-1}\) respectively. Hussein (2009) conducted research and found (minimum and maximum) PUE and total P-uptake per plant values between 44.0 and 164.67 kg kg\(^{-1}\) P\(_2\)O\(_5\) and 10.32 and 35.71 kg ha\(^{-1}\) respectively. Bell (2009) found P-uptake values between 0.171 and 0.956 mg per pot. Phosphorus-utilization efficiency and total P-uptake per plant values will differ across different climates and environmental conditions. Havlin et al. (1999), reported that P concentration in the soil solution varies widely depending on soil type, plant species, cultivation and history of fertilisation (Basu 2011).

Torres-Dorante et al. (2006) found that when silty-loam soil was used instead of sand polyphosphate increased P-uptake by 20% compared to orthophosphate. They also found that PUE with orthophosphate was efficient and polyphosphate was inefficient. It was observed that in sandy soil, all P sources increased P uptake per unit root length to a similar degree in comparison to silty-loam soil (Torres-Dorante et al. 2006).

**Tuber nutrient analysis**

According Walworth and Muniz (1983), tuber nutrient levels recorded in the present study were within acceptable ranges, except for N under pH = 7.5 using orthophosphates and under pH = 6.5 using polyphosphates. Also, polyphosphate at all pH ranges and orthophosphate at pH=7.5 had lower Mg content than the acceptable ranges for the potato cultivar Mondial (Table 4.13). The different pH levels might have caused reduction in uptake of these elements, since pH
influences nutrient availability. The different pH levels might have caused suppression of these elements.

Uchida (2000) reported that Ca is immobile and is difficult for Ca to move from the stems to the tubers. This is evident since the Ca content varies within the leaf and tubers. In the present study the Ca content was higher in the leaf analysis than in tuber analysis as observed in Table 4.13 and Table 4.14. In the present study Ca ranged from 0.03-0.04 % in the tubers and 1.81 to 2.55 % in the leaves, thus tuber Ca deficiency may not necessarily be noted in the leaf analysis or in the young leaves, but deficiencies may exist within the tubers.

Leaf nutrient analysis

According to Bennet (1993) the nutrient levels recorded in the present study were within acceptable ranges for potato leaves (Table 4.14). Unlike in the tubers analysis, the two P sources at the different pH levels were able to provide the leaves with sufficient nutrients.

Table 4.13 Interaction effects between treatments and pH levels on tuber nutrient content for potato cultivar Mondial after being cultivated with two different P sources and three different pH levels.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>pH levels</th>
<th>N%</th>
<th>P%</th>
<th>K%</th>
<th>Ca%</th>
<th>Mg%</th>
<th>Zn(mg/kg)</th>
<th>B(mg/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OrthoP</td>
<td>5.5</td>
<td>1.40&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>0.34&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>2.13&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.03&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.14&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>27.44&lt;sup&gt;b&lt;/sup&gt;</td>
<td>7.39&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>OrthoP</td>
<td>6.5</td>
<td>1.39&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>0.39&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>2.44&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.04&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.15&lt;sup&gt;a&lt;/sup&gt;</td>
<td>33.34&lt;sup&gt;b&lt;/sup&gt;</td>
<td>9.44&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>OrthoP</td>
<td>7.5</td>
<td>1.03&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.30&lt;sup&gt;c&lt;/sup&gt;</td>
<td>2.03&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.03&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.13&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>27.48&lt;sup&gt;b&lt;/sup&gt;</td>
<td>6.59&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>PolyP</td>
<td>5.5</td>
<td>1.50&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.36&lt;sup&gt;abc&lt;/sup&gt;</td>
<td>1.80&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.03&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.11&lt;sup&gt;c&lt;/sup&gt;</td>
<td>35.99&lt;sup&gt;b&lt;/sup&gt;</td>
<td>6.27&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>PolyP</td>
<td>6.5</td>
<td>1.23&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>0.34&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>2.06&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.03&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.11&lt;sup&gt;c&lt;/sup&gt;</td>
<td>33.05&lt;sup&gt;b&lt;/sup&gt;</td>
<td>6.07&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>PolyP</td>
<td>7.5</td>
<td>1.97&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.43&lt;sup&gt;a&lt;/sup&gt;</td>
<td>2.14&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.04&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.12&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>48.55&lt;sup&gt;a&lt;/sup&gt;</td>
<td>6.67&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

| Norms     | >1.38     | >0.14 | >1.41 | 0.02-0.04 | >0.14 |
| LSD       | 0.21      | 0.04  | 0.21  | 0.00      | 0.01  | 5.51  | 0.77     |
| p-value   | 0.00      | 0.02  | 0.22  | 0.16      | 0.09  | 0.06  | 0.03     |

Different letters differ significantly (P<0.05). *p < 0.05, **p < 0.1, ns not significant at p > 0.05. Norms according to Walworth and Muniz 1993.
Table 4.14 Interaction effects between treatments and pH levels on leaf essential nutrient element content for potato cultivar Mondial after being cultivated with two different P sources and three different pH levels.

<table>
<thead>
<tr>
<th>Leaf analysis</th>
<th>Treatment</th>
<th>pH levels</th>
<th>N%</th>
<th>P%</th>
<th>K%</th>
<th>Ca%</th>
<th>Mg%</th>
<th>Zn(mg/kg)</th>
<th>B(mg/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>OrthoP</td>
<td>5.5</td>
<td>3.60&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>0.42&lt;sup&gt;b&lt;/sup&gt;</td>
<td>9.73&lt;sup&gt;a&lt;/sup&gt;</td>
<td>2.55&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.69&lt;sup&gt;a&lt;/sup&gt;</td>
<td>82.33&lt;sup&gt;b&lt;/sup&gt;</td>
<td>46.72&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>OrthoP</td>
<td>6.5</td>
<td>3.83&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>0.59&lt;sup&gt;a&lt;/sup&gt;</td>
<td>9.19&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.89&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.52&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>63.49&lt;sup&gt;b&lt;/sup&gt;</td>
<td>69.12&lt;sup&gt;ab&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>OrthoP</td>
<td>7.5</td>
<td>4.16&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>0.48&lt;sup&gt;a&lt;/sup&gt;</td>
<td>10.18&lt;sup&gt;a&lt;/sup&gt;</td>
<td>2.09&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.61&lt;sup&gt;ab&lt;/sup&gt;</td>
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<td>54.68&lt;sup&gt;cd&lt;/sup&gt;</td>
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<tr>
<td></td>
<td>PolyP</td>
<td>5.5</td>
<td>4.22&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>0.96&lt;sup&gt;a&lt;/sup&gt;</td>
<td>9.24&lt;sup&gt;a&lt;/sup&gt;</td>
<td>2.09&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.43&lt;sup&gt;b&lt;/sup&gt;</td>
<td>226.69&lt;sup&gt;a&lt;/sup&gt;</td>
<td>62.25&lt;sup&gt;bc&lt;/sup&gt;</td>
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<tr>
<td></td>
<td>PolyP</td>
<td>6.5</td>
<td>3.14&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.97&lt;sup&gt;a&lt;/sup&gt;</td>
<td>9.13&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.81&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.53&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>129.56&lt;sup&gt;b&lt;/sup&gt;</td>
<td>47.38&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>PolyP</td>
<td>7.5</td>
<td>4.41&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.75&lt;sup&gt;a&lt;/sup&gt;</td>
<td>8.26&lt;sup&gt;a&lt;/sup&gt;</td>
<td>2.20&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.70&lt;sup&gt;a&lt;/sup&gt;</td>
<td>126.57&lt;sup&gt;b&lt;/sup&gt;</td>
<td>81.17&lt;sup&gt;a&lt;/sup&gt;</td>
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<td></td>
<td></td>
<td></td>
<td>**</td>
<td>ns</td>
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<td>**</td>
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</tr>
<tr>
<td>Norms</td>
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<td>&gt;3</td>
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<td>&gt;1.5</td>
<td>&gt;0.15</td>
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<td>&gt;0.1</td>
<td>&gt;0.1</td>
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</tr>
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<td>LSD</td>
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<td>0.52</td>
<td>0.09</td>
<td>0.99</td>
<td>0.29</td>
<td>0.11</td>
<td>32.31</td>
<td>6.51</td>
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</tr>
<tr>
<td>p-value</td>
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<td>0.07</td>
<td>0.20</td>
<td>0.41</td>
<td>0.38</td>
<td>0.1</td>
<td>0.1</td>
<td>0.00</td>
<td></td>
</tr>
</tbody>
</table>

Different letters differ significantly (P<0.05). *p < 0.05, **p < 0.1, ns not significant at p > 0.05. Norms according to Bennet (1993)
**Conclusion**

A number of researchers have concluded that orthophosphates and polyphosphates do not differ in terms of yield. As verified by Rhue et al. (1981) who reported that orthophosphates and polyphosphates do not differ with regards to crop yields. Similarly, in the present study there was no difference in most measured parameters amongst the P sources. The parameters that did differ were the shoot dry mass and fresh yield. Shoot dry mass was lower at pH=7.5. Tuber fresh yield was also lower at pH=6.5 and pH=7.5, when P was applied as polyphosphate instead of orthophosphate. This may be due to the effect of pH, which may have caused the observed differences. Since pH is known to have an effect on P availability when polyphosphate is used but not orthophosphates. In addition, the availability of P in the soil solution is highly dependent on the pH of the soil solution. The growing medium may have also inhibited hydrolysis of polyphosphates at high pH of 6.5 and 7.5. Furthermore, Torres-Dorante et al. (2006) reported that the rate of polyphosphate hydrolysis seemed to be faster in the silty-loam soil than in the sandy soil used in the current study. Applying P as polyphosphate gave lower tuber yield at high pH of 6.5 and 7.5. Thus, the results may imply that the optimal pH level for polyphosphates is lower acidic pH for optimum yields.

Treatment and pH as well as their interaction did not affect tuber size distribution (small, medium, large), total number of tubers, root fresh and dry mass. Phosphorus utilization efficiency (PUE) and total P-uptake per plant was not affected by the different pH levels. In the present study higher pH was expected to have a lower total P-uptake per plant in comparison to pH=5.5, since pH influences nutrient availability (Horneck et al. 2007). Horneck et al. (2007) reported that pH inhibits nutrient availability and ultimately P-uptake.

The other interaction effects which were noted between treatment and pH were on nutrient content. The tuber nutrient levels were within acceptable ranges, except for N and Mg at certain pH levels. With regards to leaf analysis, unlike the tubers the two P sources at the different pH levels were able to support the leaves with sufficient nutrient
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Chapter 5

Summary and General Conclusions

Understanding the chemical reactions of P, both in the soil as well as in the plant, is unquestionably an important requirement for optimum potato production. Phosphorus occurs in different forms (liquid or solid granules) and in chemical composition or form (orthophosphate or polyphosphate), with varying soil and crop reactions. The aim of this study was to evaluate the growth, yield, quality and nutrient concentration of potatoes in response to different P sources orthophosphate (mono-potassium phosphate – MKP) and polyphosphate with varying pH levels. Previous studies have been conducted in different countries and satisfactory results were achieved using polyphosphates. According to those studies, polyphosphates particularly had shown higher productivity in comparison to orthophosphates. Some studies found that the two P sources do not differ. Polyphosphate have a ring structure and contain more P compounds which diffuse slowly, thus more P becomes available for plant uptake, which is a major factor that reportedly leads to yield increase.

Three experiments were performed at Welgevallen experimental farm of Stellenbosch University from 2015-2016 to investigate the use of polyphosphates for potato production, since little is known about applying this P source under South African conditions. Although the efficacy of polyphosphate has once been tested on maize in the Free State, it has never been tested on potatoes under South African conditions.

Tuber productivity is a product of different factors during potato plant growth and tuber initiation processes. Results in the current study indicated that different P sources and ratios used influenced the morphological development of plants. Yield of potato tubers was influenced by different P treatments and cultivars, while interactions between treatment and cultivar did not influence yield in both seasons (2015 and 2016). The results of the pH experiment showed that the interaction between treatment and pH influenced tuber fresh yield.

Phosphorus treatments

The 100% orthophosphate was compared with three different polyphosphate proportions of total P, namely 25, 50 and 100% polyphosphate. In both seasons the P treatments significantly influenced the shoot dry mass. With regards to yield, in both seasons the P treatments highly significantly influenced tuber fresh and dry mass and total number of tubers. This study indicated that 100% orthophosphate was successful to induce more tubers. Regarding quality
parameters, the P treatments did not influence any of the measured quality parameters, with the exception of the tuber and leaf essential elements. It appears that P fertiliser application is important in order to produce high yield, but may not have any effect on potato quality.

In most of the measured parameters the 100% orthophosphate outperformed the polyphosphate treatments. In both trials, in terms of yield the 100% orthophosphate performed far better than the polyphosphates treatments (25, 50 and 100%), implying that orthophosphate is a better source of P under the specific experimental conditions. Polyphosphate may perform differently under other local conditions.

Future research should be focused on evaluating the use of 100% orthophosphate by Mondial cultivar since this cultivar produced higher yields in both seasons and maybe increasing the polyphosphate concentration in the nutrient solution should be explored.

In the present study polyphosphates were expected to give higher yields in comparison to the orthophosphates, it is comforting to know that the orthophosphates commonly used by farmers outperformed polyphosphates.

_Tuber and leaf analysis as influenced by the P sources._

The nutrients were in sufficient ranges in the two season study (2015 and 2016). These show that the P sources were able to provide sufficient nutrients to the plants. The P sources did not supress uptake of other nutrients.

_Potato cultivars_

The role of P in the plant is important for plant growth. Therefore, potato plantlets of cultivars of Mondial, Sifra Lanorma and Innovator were used as test crops in season 1 (2015). In the second season instead of Sifra and Innovator, cultivars Destiny and Eos were used (2016), together with the four different P levels and ratios (100% orthophosphate, 25, 50 and 100% polyphosphate). For the pH experiment only cultivar Mondial was used.

In both seasons cultivars influenced all the vegetative and yield parameters, with the exception of shoot dry mass in the first season (2015). Quality parameters were not influenced by the different cultivars, with the exception of tuber dry matter content and tuber and leaf essential element content. It appears as if Mondial is a high yielding cultivar, which is confirmed by several other studies that have also shown that Mondial is a high yielding cultivar. More South African potato cultivars can be used to determine if there is a variation in response to polyphosphate application.
**Tuber and leaf analysis as influenced by the cultivars**

All the nutrients were within the sufficiency ranges in the two season study (2015 and 2016). This is a clear indication that the P sources were able to provide the potato cultivars with sufficient nutrients.

**pH experiment**

Generally there were no significant differences between the orthophosphates and polyphosphates in most measured parameters. Treatment and pH as well as their interaction did not affect tuber size distribution (small, medium, large) and total number of tubers. Phosphorus-utilization efficiency (PUE) and total P-uptake per plant were not significantly influenced by the P treatments and the pH levels. The tuber nutrient levels were within acceptable ranges, except for N and Mg at certain pH levels. With regards to leaf analysis, unlike the tuber analysis, the two P sources at the different pH levels were able to support the leaves with sufficient nutrients.

Interaction between phosphate treatment and pH influenced tuber fresh yield. The results showed that the optimal pH level for polyphosphates is lower acidic pH (5.5) for optimum yields.

**Phosphorus efficiency**

Phosphorus-utilization efficiency (PUE) was not significantly different in both seasons (2015 and 2016). Treatments did not differ with regards to total P-uptake per plant. However, in both seasons the cultivars differed with regards to total P-uptake per plant. Results of the two season study show that cultivars (Lanorma and Destiny) which had a higher root yield ultimately had a high total P-uptake per plant.

In both seasons (2015 and 2016) best yield in terms of total tuber fresh yield was realised when potato plants were fertilised with 100% orthophosphate (mono-potassium phosphate – MKP) (2338.65 g plant⁻¹ and 612.20 g plant⁻¹). Yields were slightly lower in the second season due to climatic factors. Primarily the reason why orthophosphates gave higher yields could be due to immediate availability of orthophosphates after application. Thus, easy uptake since orthophosphates are readily available and are in the form in which plants easily take up P, in contrast to polyphosphates, which need to be hydrolysed before take up. Some external factors could have prevented hydrolysis of polyphosphates.
For future research it is recommended that:

i) The trial be repeated on a soil with a low soil pH (KCl) of ≤4.5 in order to determine the economic viability of polyphosphate in the general South African environment and if hydrolysis will be favoured under low pH.

ii) The experiment is performed in the field to determine how P sources (orthophosphate and polyphosphate) compare when environmental conditions are not controlled.

iii) A different crop like sugarcane or cassava, which takes longer to mature, should be considered, since the extended growth period may help to determine whether polyphosphate availability increases if the hydrolysis period is extended.

iv) Another source of P such as mono-ammonium phosphate (MAP) should be compared to the polyphosphate.

v) The study should be repeated on another soil type, which may be more conducive to the hydrolysis of polyphosphates.
## Appendix

**Table A1** Interaction between treatment and pH levels on the total small tuber numbers of Mondial potato cultivar grown in the glasshouse. Significant F test at P<0.05 (**) and P<0.01 (***), and non-significant (ns). Treatment means followed by different letters differ significantly (P<0.05).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>pH level</th>
<th>Small tubers (total number of tubers)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% OrthoP</td>
<td>5.5</td>
<td>2.83&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>100% OrthoP</td>
<td>6.5</td>
<td>4.33&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>100% OrthoP</td>
<td>7.5</td>
<td>4.20&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>100% PolyP</td>
<td>5.5</td>
<td>5.00&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>100% PolyP</td>
<td>6.5</td>
<td>3.20&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>100% PolyP</td>
<td>7.5</td>
<td>4.50&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

Table A1 Interaction between treatment and pH levels on the total small tuber numbers of Mondial potato cultivar grown in the glasshouse. Significant F test at P<0.05 (**) and P<0.01 (***), and non-significant (ns). Treatment means followed by different letters differ significantly (P<0.05).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>pH level</th>
<th>Medium tubers (total number of tubers)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% OrthoP</td>
<td>5.5</td>
<td>4.20&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>100% OrthoP</td>
<td>6.5</td>
<td>3.83&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>100% OrthoP</td>
<td>7.5</td>
<td>3.66&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>100% PolyP</td>
<td>5.5</td>
<td>4.40&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>100% PolyP</td>
<td>6.5</td>
<td>3.20&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>100% PolyP</td>
<td>7.5</td>
<td>2.33&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
</tbody>
</table>
Table A3 Interaction between treatment and pH levels on the total large tuber numbers of Mondial potato cultivar grown in the glasshouse. Significant F test at P<0.05 (*) and P<0.01 (**) and non-significant (ns). Treatment means followed by different letters differ significantly (P<0.05).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>pH level</th>
<th>Large tubers (average total number)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% OrthoP</td>
<td>5.5</td>
<td>1.20&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>100% OrthoP</td>
<td>6.5</td>
<td>1.60&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>100% OrthoP</td>
<td>7.5</td>
<td>1.40&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>100% PolyP</td>
<td>5.5</td>
<td>1.50&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>100% PolyP</td>
<td>6.5</td>
<td>1.33&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>100% PolyP</td>
<td>7.5</td>
<td>1.50&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

Table C2 Interaction between treatment and pH levels on the root fresh yield of tubers grown in glasshouse under different pH levels. Significant F test at P<0.05 (*) and P<0.01 (**) and non-significant (ns). Treatment means followed by different letters differ significantly (P<0.05).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>pH levels</th>
<th>roots(fresh yield)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% OrthoP</td>
<td>5.5</td>
<td>8,67&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>100% OrthoP</td>
<td>6.5</td>
<td>11,93&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>100% OrthoP</td>
<td>7.5</td>
<td>10,62&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>100% PolyP</td>
<td>5.5</td>
<td>13,1&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>100% PolyP</td>
<td>6.5</td>
<td>8,13&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>100% PolyP</td>
<td>7.5</td>
<td>12,72&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

Stellenbosch University  https://scholar.sun.ac.za
Plate A1 Seedlings transplanted 4 weeks in the greenhouse season 1 (2015).

Plate A2 Seedlings 14 weeks after planting in the greenhouse season1 (2015).
Plate B1 Seedlings transplanted 1 week in the greenhouse season 2 (2016).

Plate B2 Seedlings transplanted 14 weeks in the greenhouse season (2016).
Plate C1 pH experiment, Mondial seedlings first week after transplanting in the glasshouse.

Plate C2 pH experiment, Mondial Potato plants 14 weeks after planting in the glasshouse.
Plate A3 Potato plants fertilised with 100% orthophosphate at harvest season 1 (2015).

Plate A4 Potato plants fertilised with 25% Polyphosphate at harvest season 1 (2015).
Plate A5 Potato plants fertilised with 50% Polyphosphate at harvest season 1 (2015).

Plate A6 Potato plants fertilised with 100% polyphosphate at harvest season 1 (2015).
Plate B3 Potato plants fertilised with 100% orthophosphate at harvest season 2 (2016).

Plate B4 Potato plants fertilised with 25% polyphosphate at harvest Season 2 (2016).
Plate B5 Potato plants fertilised with 50% polyphosphate, at harvest season 2 (2016).

Plate B6 Potato plants fertilised with 100% polyphosphate, at harvest season 2 (2016).