INCREASE THE CROP WATER USE EFFICIENCY USING SUPER ABSOREBNT POLYMERS

by

Rahul Suresh

Department of Bioresource Engineering

Macdonald Campus, McGill University

Montreal, Quebec

A thesis submitted to McGill University

in partial fulfillment of the requirements of the degree of Master of Science

August 2015

This thesis is dedicated to my lovely parents, Mr. and Mrs. Suresh, my dear sibling, Rohit Suresh and to all my friends who accompanied me in this journey.

ABSTRACT

Freshwater plays an important role in supporting life on the planet. Agriculture uses 70% of the total accessible freshwater (0.03% of the total global water resources) which makes it important to increase irrigation efficiency so that we can produce more with less freshwater use. SAPs or hydrogels are cross-linked polymeric three-dimensional structures which have the ability to absorb and retain large amounts of water relative to their own mass. The objective of this study was to investigate the gain in water use efficiency and physiological growth of cherry tomatoes (*Solanum lycopersicum var. cerasiforme*) under different levels of SAP and irrigation treatments. The experiment was laid out in a completely randomised block design with three levels of SAP treatments which include 0% (control), 0.1% and 0.5% and three levels of plant watering application treatments which included everyday watering (control), once in two days watering and once in three days watering from the day of transplant up to four months; all treatments were replicated five times. Trials were carried out in a greenhouse at Macdonald Campus of McGill University in Sainte-Anne-de-Bellevue, Quebec, Canada. The results of the study indicate that 0.5% SAP performed significantly better than control (0% SAP) in terms of yield (P=0.0056) and water use efficiency (P=0.050), whereas, no significant difference was found within the SAP treatments for photosynthetic activity (P=0.5039), stomatal conductance (P=0.5344), transpiration rate (P=0.4907), normalised differential vegetative index (NDVI) (P=0.3901) and plant height (P=0.8967). However, the trends in each of the measurement confirm positive effect of SAP on cherry tomatoes. A microtox toxicology analysis revealed that the SAPs were

not toxic to the agro-mix and is safe to use in the fields. Thus, the application of 0.5% SAP can significantly increase the yield and the water use efficiency.

RÉSUMÉ

L'eau douce joue un rôle prépondérant dans le maintien de la vie sur notre planète. Puisque l'agriculture utilise 70% des eaux douces accessibles (0.03% des ressources en eaux globales) il est important d'améliorer l'efficacité de l'irrigation afin de produire plus avec moins d'eau douce. Les polymères superabsorbants (PSAs) ou hydrogels sont des structures polymères réticulés tridimensionnelles capables d'absorber et retenir de grandes quantités d'eau par rapport à leur propre masse. Cette étude visa à évaluer le gain en efficacité d'utilisation de l'eau et en progression physiologique de tomates cerise (*Solanum lycopersicum var. cerasiforme*) cultivées pour quatre mois sous différents niveaux d'irrigation et d'amendement du sol avec des PSAs, dans un dispositif aléatoire par blocs. Trois niveaux d'amendement du sol en PSAs, soit 0% (étalon), 0.1% et 0.5%, furent combinés en un plan factoriel complet à cinq répétitions, avec trois niveaux d'irrigation, soit quotidiennement, aux deux jours, et aux trois jours. Les essais ont été menés dans une serre au campus Macdonald de l'université McGill, à Sainte-Anne-de-Bellevue, Québec, Canada. Le rendement (P=0.0056) et l'efficacité d'utilisation de l'eau (P=0.050) furent améliorés de façon significative par un amendement de 0.5% en SAP, par rapport à l'étalon, mais le taux d'amendement en SAP n'eut aucun effet sur l'activité photosynthétique (P=0.5039), la conductance stomatique (P=0.5344), le taux de transpiration (P=0.4907), indice de différence normalisée de végétation (NDVI) (P=0.3901) et la hauteur du plant (P=0.8967). Cependant, des tendances dans chacune des mesures confirment un effet positif d'un amendement avec SAP sur les tomates cerises. Une analyse Microtox démontra que les amendements en SAP n'étaient pas toxiques au sol, et donc que leur utilisation au

champ est sans danger. Un amendement du sol avec 0.5% de SAP peut donc augmenter le rendement et l’efficacité d'utilisation de l'eau de façon significative.

ACKNOWLEDGEMENT

Firstly, I would like to take this opportunity to express my utmost appreciation and sincere gratitude to my supervisor, Dr. Shiv O. Prasher whose expertise, understanding, and patience, added considerably to my graduate experience. I thank him for being an excellent supervisor and a dedicated researcher who was always approachable and available throughout my graduate studies including his sabbatical leave. I would also like to thank him for providing me with sufficient funding.

Secondly, I would like to thank Dr. Hashemi and Dr. Abdul Mannan Ehsan for their insightful ideas and support throughout the study which kept me motivated and focused.

My gratitude is conveyed to Dr. Sedigheh Zarayan who supported me technically and emotionally throughout my experiment. I would like to thank Dr. Timothy Swinghammer for his expertise in statistics and Dr. George T Dodd for editing and translating the abstract to French.

Additionally, I would like to thank McGill for giving me this opportunity to network with some of the bright minds around the world and the Department of Bioresource Engineering for providing me with scholarships and a positive environment to improve my professional career.

Finally, I would like to express my hearty appreciation to my family, friends and colleagues around the world for their unconditional support and love.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 Problem statement

An essential and key component to life on this planet, global water resources include a small fresh water fraction (≈3%), of which only a third is readily available. Of that global 1% of water resources — some 0.7–0.8% exists as groundwater and <0.01% as surface water in lakes, swamps and rivers (Postel et al., 1996). Given these limited water resources it is essential to use water efficiently.

Population and economic growth in the 19th and 20th centuries has led to tremendous increases in fresh water consumption on both the national and global scale (Brown, 2000; Gleick, 2003). The world's population has increased from 1.7 billion in 1910 to 7.2 billion in 2014 and is forecasted to reach 9.7 billion in 2050 (PRB, 2014). According to the UN Comprehensive Assessment of the Freshwater Resources of the World, it is estimated that in 2025 up to two-thirds of the world's population will be living in water-stressed countries (Arnell, 2004).

While 20% of cultivated land is irrigated, it accounts for 40% of global food production (UNESCO-WWAP, 2014). Irrigated agriculture represents the largest instance of human-driven water consumption and accounts for 67% of current global water withdrawal and 87% of consumptive water use (Döll, 2002; Fereres and Soriano, 2007). The United Nations' Food and Agricultural Organization projects that food and feed production will need to increase by 70% by 2050 to meet a doubling of world food demand (FAO, 2007).

Given the increasing demands that will be placed on water resources by a rising population, climatic changes and environmental factors related to irrigation, it is imperative to reduce water consumption. This can be achieved through a combination of good management practices and environmental friendly and efficient technologies. Best management practices (BMPs) include the use of drought-resistant crops (Parry et al., 1998), crop rotation (Huang et al., 2003; Tennakoon and Hulugalle, 2006), better water management practices in urban areas (Gleick, 2003b) and efficient water delivery systems for irrigated agriculture (Clothier and Green, 1994; Wallace, 2000; Howell, 2001; Fereres and Soriano, 2007).

A sustainable alternative to current agricultural water management practices could be achieved by altering soils' water holding capacity, thereby allowing irrigation water use efficiency to be optimized for both agricultural and recreational activities (*e.g.,* golf courses). Increasing water retention in sandy soils has been shown to increase crop yield (Ahmed et al., 2000). However, altering soils' water retention properties could have an effect on their saturated hydraulic conductivity (k_{sat}), and therefore on the infiltration rate and surface run-off (Van Genuchten, 1980). Super absorbent polymers (SAPs) have the ability to retain 400- to 1600-fold their own weight in water. By mixing SAPs into the soil, k_{sat} and water retention can be altered (Buchholz and Graham, 1998; Kazanskii and Dubrovskii, 1992) in such a manner as to improve crop yield, reduce ground water infiltration and save water.

1.2 Objectives

The overall objective of this study was to quantify and substantiate the role of SAPs in improving water use efficiency and crop plants' overall physiological state when grown in an agro-mix media. Greenhouse studies were developed to investigate the ability of SAPs, employed as an amendment to a conventional agro-mix used in greenhouse tomato (*Solanum lycopersicon* L.) production, to capture, store and release water according to crop requirements.

The specific objective of the study was to understand the water use efficiency and physiological characteristics of a greenhouse cherry tomato crop at different water stress levels (irrigation scheduling) in combination with different levels of SAP amendment in the growth medium.

1.3 Scope

The use of SAP soil amendments will help the agricultural community by minimizing water losses during irrigation, thereby reducing the stress on water resources, as well as improving crop yield, thereby increase the food supply. The results obtained in this study, however, are applicable only for cherry tomatoes grown in greenhouses on agro-mix media. Caution and professional judgment should be used in extrapolating the results of this study to other crops and different growing conditions.

CHAPTER 2

Review of literature

2.1 Background Information

In our day-to-day life, sponges and paper towels are most commonly used to absorb water, however, these materials absorb relatively little, given their poor water retention properties (Liu and Rempel, 1997). Superabsorbent polymers, on the other hand, are polymers that have the ability to hold large amounts of a liquid relative to their own mass (Horie et al., 2004). In the 1960s, the United States Department of Agriculture (USDA) developed a resin by grafting an acrylonitrile polymer onto a starch backbone. Hydrolysis of the starch-acrylonitrile co-polymer allowed the material, termed “Super slurper,” to absorb 400 times its own weight in water. It was only in the 1970s that a SAP was first used commercially in disposable hygienic products. Later, as the technology progressed, it was introduced as a soil amendment to improve the soil’s water holding capacity and promote seed germination and plant growth.

Composed of cross-linked polymeric chains, SAPs are produced by either inverse suspension polymerisation or solution polymerisation (Zohuriaan-Mehr and Kabiri, 2008). The ability of a SAP to hold water and swell arises from the electrostatic repulsion between charges on the polymer backbone and the osmotic imbalance between the interior and exterior of the SAP particle (Ono et al., 2007). While acrylic acid and its sodium or potassium salts are the most common raw materials used in standard SAP production (Zohuriaan-Mehr and Kabiri, 2008), in the case of SAPs designed for agricultural use, acrylamide is the main raw material (Ahmed, 2013). The absorptive and swelling properties of SAPs as well as their lack of solubility are generally controlled through the type and level of polymer cross-linking (Buchholz and Graham, 1998; Liu and Rempel, 1997; Liu and Guo, 2001; Xie et al., 2009), as well as the morphology of individual SAP particles (Isık and Kıs, 2004; Turan and Caykara, 2007). SAPs also undergo considerable changes due to environmental conditions such as temperature, pH and ionic strength (Beltran et al., 1991; Gudeman and Peppas, 1995; Liu et al., 1995).

Given their water absorbing characteristics and attendant ability to alter a soil's water holding capacity, SAPs have found numerous applications in the agricultural field, where they can serve to optimize irrigation water use efficiency (WUE) and contribute to maintaining a sustainable use of available water resources. This thesis focuses on the water holding properties SAP-amended agro-mix media used in greenhouse tomato production with respect to WUE and physiological characteristics of the tomato crop. Additionally, crop spectral reflectance was measured and assessed with respect to water stress and SAP-amendment level.

2.2 Overview of existing technologies

2.2.1 Advanced Irrigation technologies

While irrigation has been practised for over 6000 years, it is mostly in the last hundred years that advancements such as diversion works, pumping, filtration, conveyance, distribution, application methods, drainage, power resources, scheduling, fertigation, chemigation, erosion control, land grading, soil water conservation and management have occurred (Evans and Sadler, 2008).

Initially, modern irrigation was done by distributing water through gravity-feed methods in which an elevated reservoir with an outlet at the bottom fed water into a basic furrow irrigation system which was controlled either manually or by a timer. This is one of the most cost-effective irrigation methods if precipitation is consistent and sufficient to keep the reservoir filled.

With the development of low cost aluminium pipes, later replaced by PVC pipes, sprinkler technology emerged, by which water could be applied uniformly regardless of topography, soil type and variety of crops in the field. Such a system is best suited for low-growing crops which include alfalfa (*Medicago sativa* L.), small grains, rice (*Oryza sativa* L.), and soybean [Glycine max (L.) Merr.], and some taller crops such as corn (*Zea mays* L.) and sugarcane (*Saccharum officinarum* L). Currently, more agricultural land in the Americas are irrigated by this method.

A modification of such sprinkler irrigation systems in terms of being self-propelled has been found to be very efficient under field conditions, allowing low-energy precision applications (LEPA) (Evans and Sadler, 2008). LEPA systems are generally used in large fields suffering from a water shortage (i.e., shallow water aquifer).

Under certain conditions, surface irrigation techniques can also be efficient, but this requires high levels of automation and management, besides precise grading of the topography and high instantaneous flow rates.

Micro-irrigation represents irrigation water application at a slow rate, low pressures and discrete locations. Including surface drip, subsurface drip, bubblers and micro-sprinkler systems, it has become a common and efficient irrigation practice for water conservation and achieving desired plant responses. Such systems are widely used for high value vegetable crops and widely-spaced trees. Subsurface drip systems, when carefully maintained, provides the greatest potential for water conservation.

Low-cost energy and water efficient irrigation management systems present an ideal solution to agricultural water stress. A well-designed micro-irrigation system, along with an effective soil water monitoring program and appropriate management practice, can allow such a system to achieve an application efficiency of 95% or more, and thereby eliminate any drought stress. Reduced evaporation from the soil surface and greater WUE can be achieved by combining micro-irrigation with the use of biodegradable plastic mulches.

Improving irrigation efficiency may require not only considerable investment from the farmers in terms of equipment and infrastructure but also in terms of higher operating and energy costs and the need for greater management skills. Achieving such high WUE will require growers to manage the rate and frequency of water applications to optimize allocation of limited water among crops, reduce soil erosion, as well as minimize evaporation and seepage losses. Modification in water policies are essential to enable and foster emerging technologies in irrigation.

Irrigated agriculture can reduce water use while maintaining reasonable production levels; however, the challenges are very considerable. In an era when research on cropping systems is declining, it is essential to work towards sustainability through innovation and cost-effective remedies.

2.2.2 Bio-char

At varying temperatures, under controlled conditions of oxygen-limited or oxygen-free incomplete combustion, a biomass feedstock (e.g., wood, plant waste, manure) is converted through pyrolysis into a carbon-rich form of charcoal, termed biochar (Lehmann, 2007). Biochar is usually used as a soil amendment to improve soil quality, store carbon or filter water percolating through the soil (Lehmann and Joseph, 2009). Biochar used as a soil amendment has been found to have a mean residence time of over 1000 years, which makes it a permanent carbon sink (Spokas, 2010).

Though an excellent soil amendment which aids in retaining nutrients, water and organic matter, biochar has yet to achieve its true potential. The effect of biochar amendment on soil quality and crop productivity has been observed to vary, but is generally positive. Of the handful of published studies on field-scale soil amendment with biochar, the majority were carried out in low fertility soils, particularly acidic tropical soils. Compared to non-amended soils, large yield improvements (up to 3-fold) were generally obtained when such soils were amended with biochar (Lehmann and Rondon, 2006). Long-term positive effects of biochar applications were observed in a few studies which monitored soil fertility over several years (Steiner et al., 2007). More recently, the effects of biochar amendment have been tested in the higher fertility soils of temperate climes, resulting in more modest (4-20%) improvements in biomass production (Husk and Major, 2010; Laird et al., 2010). The positive effects on crop yield of biochar amendments to agricultural soils are, in part, attributable to an elevation of the pH of acidic soils (Peng et al., 2011), the direct addition of nutrients (Novak et al., 2009), the retention of nutrients in soil (Lehmann et al., 2003) and positive interactions with beneficial soil microbes (Solaiman et al., 2010).

Biochar is highly porous and has a large surface area (up to 400 m^2 g^{-1}); thus, over time, its impact on the soil's cation exchange capacity (CEC) can be significant (Liang et al., 2006). Biochar's resulting ability to retain nutrients in the rooting zone also results in it reducing nutrient leaching through the soil profile.

Application of biochar to soil is beneficial in terms of carbon sequestration and soil fertility improvement (Peng et al., 2011). Mohan et al. (2007) evaluated biochar made from pine (*Pinus* sp.) wood, pine bark, oak (*Quercus* sp.) wood and oak bark for their capacity to remove arsenic, cadmium, and lead from water/wastewater. They found all these forms of biochar to effectively remove heavy metals. Biochar has also been reported to be a good sorbent of organic contaminants (Beesley and Marmiroli, 2011; Brändli et al., 2008).

2.2.2.1 Limitations of Biochar

Recognizing that biochar technology is in its infancy, there are many concerns about the applicability of the technology in the United States. The three main issues are feedstock availability, biochar handling, and biochar system deployment. Successful implementation of biochar technology depends on the capacity of the agricultural community to afford and operate a system that is complementary to current farming and forestry practices.

While existing biochar technologies may prove to be successful, investment and management aspects may prove to be a stumbling block. Therefore, other possible soil amendment materials with similar properties (e.g., SAPs) should be evaluated, particularly with regard to their ability to improve the soil' water holding capacity.

2.3 Superabsorbent polymers (SAPs)

Superabsorbent polymers (SAPs) are cross-linked polymers, which can absorb and retain large volumes of liquid within them (Figure 2.1). This is realized by an increase in volume of the polymer (Figure 2.2) (Buchholz and Graham, 1998; Kazanskii and Dubrovskii, 1992).

First developed in 1970s by the USDA for applications in agriculture, SAPs were initially designed to serve in improving agricultural soils' water holding capacity, thereby promoting better seed germination and plant growth. However, such materials now find extensive application in disposable pads, sheets and towels used in surgery, as well as products for adult incontinence and female hygiene products (Liu and Guo, 2001)

SAPs are generally classified into two types, based on charge (*e.g.,* non-ionic or ionic SAP; Buchholz and Graham, 1998) or their affinity towards water (*e.g.,* hydrophobic or hydrophilic; Atta et al., 2005). Furthermore, ionic SAPs are classified into cationic and anionic (Buchholz and Graham, 1998).

In general, two types of hydrogels exist: natural and synthetic. However, as expected, synthetic hydrogels have gradually replaced the natural ones due to their higher water absorption capacity, long service life, and wide varieties of raw chemical resources (Ahmed, 2013).

Figure 2.1: SAPs in crystalline form without swelling.

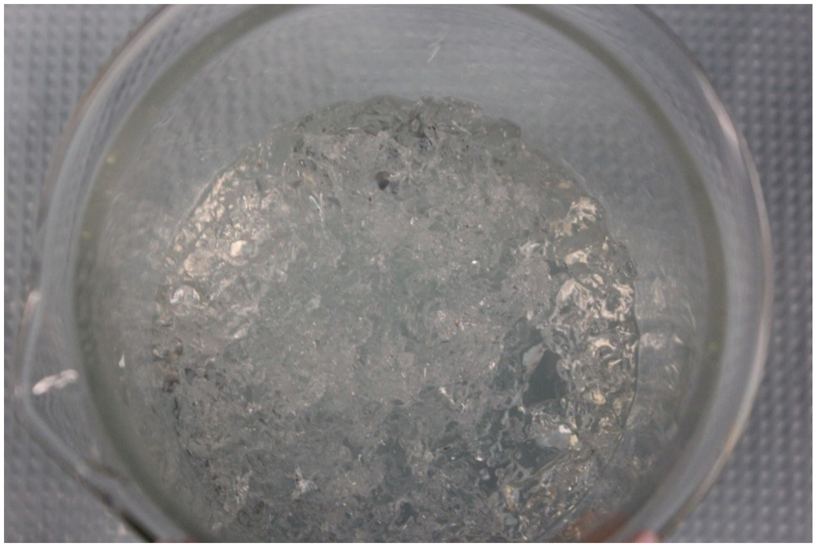

Figure 2.2: Swollen SAPs with the addition of water.

2.3.1 Principle

Superabsorbent polymers are usually categorized into two main classes based on the water absorption mechanism: physical and chemical absorption. Chemical absorbers (*e.g.*, metal hydrides) hold water via chemical reactions converting their entire nature. Physical absorbers, on the other hand, imbibe water in four different ways:

1. Reversible changes of their crystal structure (*e.g.*, silica gel and anhydrous inorganic salts)
2. Physical entrapment of water via capillary forces in their macro-porous structure (*e.g.*, soft polyurethane sponge)
3. A combination of the physical entrapment mechanism and hydration of functional groups (*e.g.*, tissue paper); and
4. A combination of mechanisms of physical entrapment and hydration and essentially dissolution and thermodynamically-favoured expansion of the

macromolecular chains limited by cross-linkages. SAPs make use of this mechanism.

SAPs take water in through a diffusion driven mechanism which depends on a gradient, *i.e.*, presence of a moisture gradient between inside the SAP and water outside the SAP (Zohuriaan-mehr and Kabiri, 2008).

2.3.2 Chemical structure of SAPs

Consisting of long polymeric chains with cross-linkers (Liu and Guo, 2001), SAPs achieve their water absorbing properties from electrostatic repulsion between charges on the polymer chain and the osmotic imbalance between the interior and exterior of the polymer (Ono et al., 2007). Additionally, certain functional groups in the polymeric change form hydrogen bonds with water molecules (Xie et al., 2007). The swelling of the polymer chain is generally limited since it is cross-linked (Liu and Guo, 2001), making it insoluble in water (Buchholz and Graham, 1998).

There are two types of polymerization processes involved in the production of SAPs namely, solution and inverse suspension polymerization (Buchholz and Graham, 1998). SAP properties can be quantified through measures of water absorption capacity, swelling rate, swollen gel strength, wicking capacity, sol fraction, residual monomer and ionic sensitivity (Zohuriaan-Mehr and Kabiri, 2008)

The water absorbing capacity of the polymer depends on the type and degree of cross-linking between the polymeric chains and the SAP's morphology. Xie et al. (2009)

discusses the effect of cross-linking agent on the water absorbing property of SAPs. The length of the polymeric chain affects water absorption capacity, with shorter chains having more polymer ends which do not contribute to water absorption (Liu and Rempel, 1997).

Morphological properties such as porosity and particle size affect water absorption of SAPs (Isık and Kıs, 2004; Turan and Caykara, 2007; Zohuriaan-Mehr and Kabiri, 2008). Bhardwaj et al. (2007) noted that water absorption was greater when the SAP's average grain size was smaller. Furthermore, SAPs undergo minor controllable volume changes in response to temperature, pH and ionic strength (Beltran et al., 1991; Gudeman and Peppas, 1995; Liu et al., 1995).

2.3.3 Production of SAP

The most frequently used monomers for industrial SAP production are acrylic acid and acrylamide, along with potassium or sodium salts (Ahmed, 2013). Zohuriaan-Mehr and Kabiri (2008) discuss the use of acrylic acid in the production of SAP and review the use of other additional treatments such as surface cross linking (Buchholz and Graham, 1998), modified gel drying methods (Buchholz and Graham, 1998; Kabiri et al., 2003a, 2003b) and porosity generating techniques (Buchholz and Graham, 1998; Kabiri et al., 2003b).

Materials with SAP properties are often synthesized through free-radical-initiated polymerization of acrylic monomers. A hydrocarbon or aqueous medium is chosen to prepare the resin.(Zohuriaan-Mehr and Kabiri, 2008). There are two types of polymerization processes involved in the production of SAPs: solution and inverse suspension polymerization.

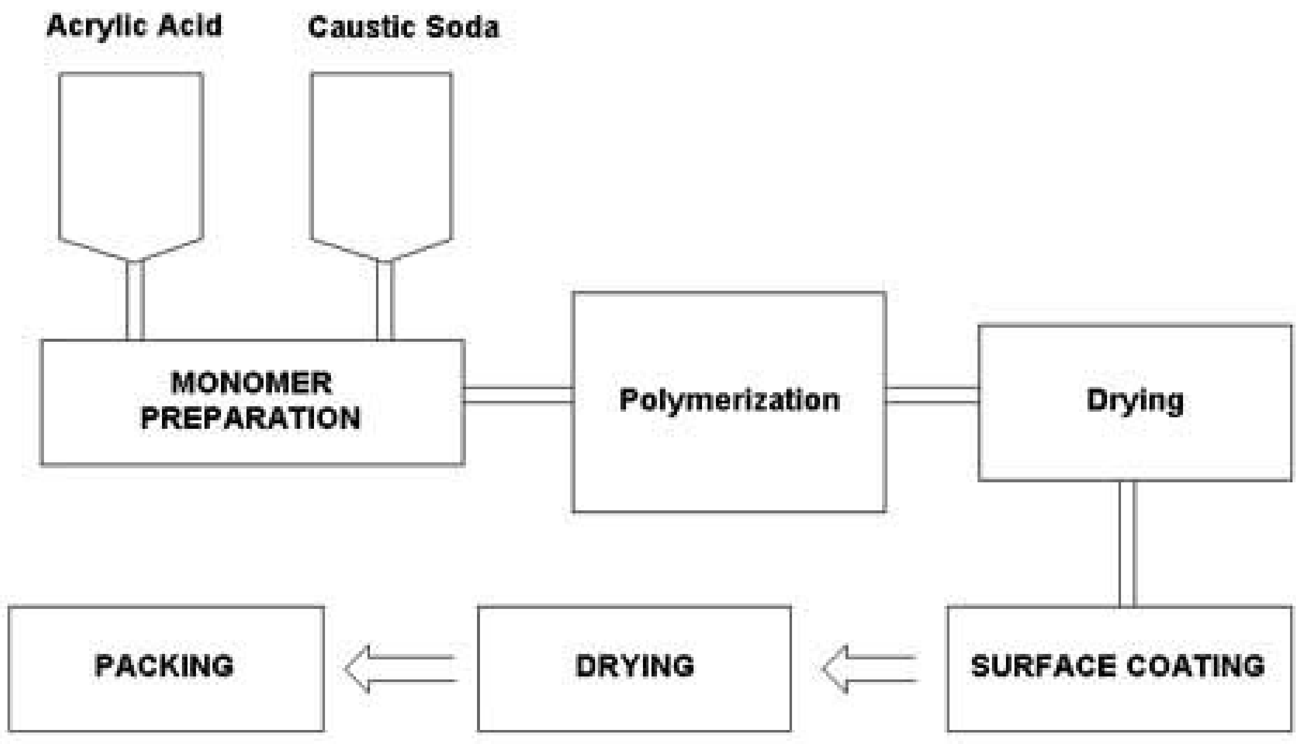

Figure 2.3: Process diagram for the production of SAPs.

2.3.3.1 Solution polymerization:

This process involves a free-radical-initiated polymerization of acrylic acid and its salt (and acrylamide), along with cross linking with a suitable crosslinking agent (Zohuriaan-mehr and Kabiri, 2008). The carboxylic acid groups of the products are neutralised, before or after polymerisation. Initiation is generally carried out chemically with free radical azo species, peroxide thermal dissociative species or by a reaction between a reducing agent and an oxidising agent (redox system) (Buchholz, 1994; Po, 1994). Alternatively, radiation can also be used to initiate the polymerisation process (Buchholz and Graham, 1998; Doelker et al., 1990; Po, 1994; Russell et al., 1976).

In the solution polymerization process, reactants are dissolved in water at desired concentrations (usually 10-70%) yielding a gel-like elastic product due to a fast exothermic reaction. The dried macroporous mass is then pulverized and sieved to obtain the required particle size. The limitations of this process includes lack of a sufficient reaction control, non-exact particle size distribution (Omidian et al., 1994a, 1994b) and undesirable effects of hydrolytic and thermal cleavage (Kabiri et al., 2008). However, solution polymerisation is used in general production due to its low cost, acceptable swelling properties and most importantly speed of production.

2.3.3.2 Inverse Solution polymerization

In this process, the monomers are dispersed in the hydrocarbon phase along with the initiator as a homogenous mixture. The main factors that govern the resin particle size and shape include, viscosity of the monomer solution, agitation speed, rotor design and dispersant type (Buchholz and Peppas, 1994; Buchholz, 1994; Doelker et al., 1990; Po, 1994; Russell et al., 1976). Since the dispersion is thermodynamically unstable it requires both continuous agitation and addition of a low hydrophilic-lipophilic-balance (HLB) suspending agent. This technique produces SAPs with high swelling ability and fast absorption kinetics (Trijasson et al., 1990). A water soluble initiator is preferred over an oil soluble type due to better efficiency. When the initiator dissolves in the dispersed phase it behaves like an isolated micro-batch polymerization reactor since each particle contains all the reactive species (Askari et al., 1993). Upon filtration or centrifugation, the resulting micro spherical particles are easily separated from the continuous organic phase. The products are obtained as powders or microspheres and thus grinding is not required.

The various advantages of inverse-suspension polymerization over solution polymerization are: better control of the reaction, *ab initio* regulation of the particle-size distribution, as well as particle structure adjustment or morphology alteration (Trijasson et al., 1990).

2.3.4 Different types of SAP

Depending on the hydrogel family, the SAPs can be classified into four groups based on the presence and absence of electrical charge located on the cross-linked chain (Zohuriaan-Mehr, 2006) :

1. Ionic
2. Non-ionic includes anionic and cationic groups
3. Amphoteric electrolyte, containing acidic and basic groups
4. Zwitter-ionic, containing both anionic and cationic groups in each repeating unit

SAPs can also be categorized based on monomeric units which include (Po, 1994; Zohuriaan-Mehr, 2006) :

1. Cross-linked polyacrylates and polyacrylamides
2. Hydrolyzed cellulose-polyacrylonitrile (PAN) or starch-PAN graft copolymers
3. Cross-linked copolymers of maleic anhydride

However, most SAPs are divided in to two main classes: Natural and Synthetic

Natural SAPs are further divided into hydrogels based on polysaccharides and hydrogels based on polypeptides.

2.3.5 Properties of SAP

Different features of an ideal SAP include (Zohuriaan-Mehr, 2006)

- The highest absorption capacity occurs in a saline environment (maximum equilibrium swelling)
- Desired rate of absorption (based on particle size and porosity)
- Highest absorbency under load (AUL)

- Lowest soluble content and residual monomer
- Lowest price
- Highest durability and stability in the swelling environment and during storage
- Highest biodegradability without formation of toxic species following degradation
- pH neutrality after swelling in water
- Colourlessness, odourlessness and absolute non-toxicity
- Photo-stability

It is impossible for a SAP to fulfil all the above features, since achieving a maximum rating for some features would lead to an inefficiency in the rest. Hence, in practice, it is recommended to strike an appropriate balance between the different properties in order to get an efficient SAP.

2.3.6 Uses of SAPs in agriculture

The ability of SAPs to absorb large volumes of water and retain them has many practical applications in agriculture. The saturated hydraulic conductivity of soil (k_{sat}) decreases significantly with an increase in mixing ratio and swelling properties of the SAP (Andry et al., 2009). Abedi-Koupai et al. (2008) concluded that when SAPs swell in soil, it reduces large pores, especially in sandy soils. However, Bhardwaj et al. (2007) found that while k_{sat} initially increased after soil amendment with an SAP, it eventually decreased. Also, Andry et al. (2009) states that the expansion of soil-SAP mixture increased with an increase in mixing ratio and swelling property of the SAP.

Additionally, the application of SAPs to the soil increases saturated and residual water content ($\theta_{\mathrm{sat}}$and θ_{r}, respectively) also, water holding capacity and available water content, *i.e.*, $\theta_{\mathrm{sat}} - \theta_{\mathrm{pwp}}$, where θ_{pwp} is the soil moisture at permanent wilting point (Abedi-Koupai et al., 2008; Andry et al., 2009; Dorraji et al., 2010; Sivapalan, 2006). Furthermore, Buchholz and Graham (1998) reported that SAPs could also be used in the same way as mulch to help soil retain more moisture for longer periods.

Soil amendment with SAPs affects soil properties such as infiltration rate, bulk density (ρ), soil structure, compaction, soil texture, aggregate stability, crust hardness and evaporation rates (Abedi-Koupai and Asadkazemi, 2006). Bai et al. (2010) reported that soil ρ decreases with increasing SAP amendment rates.

Amendment of soil with SAPs reduces infiltration, thus, avoids potential loss to deep percolation. Furthermore, this reduction in infiltration does not decline with a decreasing thickness of soil layer (Hüttermann et al., 2009; Lentz, 2007). Buchholz and Graham (1998) found that the expansion and contraction of SAPs in soil during the cycle of absorption and evaporation helps improve air content in soils, especially soils with high clay content.

An advantage of SAPs is that they are biodegradable and do not harm the soil's microbial community (Hüttermann et al., 2009). Additionally, it greatly reduces the need and frequency of irrigation, a property which could be best utilized for water management in arid and semi-arid regions (Sivapalan, 2006; Abedi-Koupai et al., 2008). Furthermore, SAP soil amendments greatly reduce irrigation-induced erosion and also increases uniformity of furrow water applications (Dorraji et al., 2010; Geesing and Schmidhalter, 2004; Ingram and Yeager, 1987; Lentz and Sojka, 2009, 1994; Lentz et al., 1992).

In more than one instance, corn grown in soils amended with SAP has outstipped that in the absence of SAP (El-Rehim et al., 2004); Lentz and Sojka, 2009). A number of studies have shown an increase in crop WUE with the application of SAP to soil (Dorraji et al., 2010; Hüttermann et al., 2009; Islam et al., 2011; Karimi and Naderi, 2007; Mahalleh et al., 2011; Nazarli et al., 2010; Sivapalan, 2006; Wanas, 2006). Burke et al. (2010) found that there was a significant increase of biomass in rye grass (*Lolium perenne* L.) in SAP-amended (*vs.* non-amended) soil, which concurred with the work of Dorraji et al. (2010), who reported that SAP amendment increased crop WUE and biomass.

Soil amendment with SAPs not only helps in plant growth by increasing the plant available water in soil but also prolongs the survival of plants under water deficit conditions (Beniwal et al., 2010; Buchholz and Graham, 1998; Hüttermann et al., 2009).

Certain other soil properties which promote plant growth can also be influenced by SAP amendment. For example, SAPs reduce the negative effect of soil salinity on plant growth (Dorraji et al., 2010). SAPs also help in binding some heavy metals, thereby reducing their bioavailability to plants (Hüttermann et al., 2009). Additionally, SAPs can also help in the slow release of nutrients (Liu et al., 2006; Teodorescu et al., 2009). Furthermore, they have been used in soil for the restoration of grass in regions where regular irrigation is a constraint (Lucero et al., 2010). Another study revealed that under water deficit conditions, plant survival rates doubled when the soil was amended with an SAP (Abedi-Koupai et al., 2008). Indeed, SAPs soil amendments have been used in Africa and Australia to increase plant survival (Abedi-Koupai and Asadkazemi, 2006). Rowe et al. (2005) found the survival of trees in wastelands was higher in SAP amended soils.

Although, the cost of SAP amendment is high, it can be recovered through lowered irrigation rates and greater crop yields (Hüttermann et al., 2009; Lentz and Sojka, 2009).

2.3.7 Limitations to SAP use in agriculture

While soil amendment with SAPs is useful in many ways, there are limitations to their use in soil. SAPs are quite fragile and could lose their water retention capacity once they come apart. Additionally, SAPs when added in soil can come under pressure and their water absorption activity be decreased due to their inability to swell (Bhardwaj et al., 2009). Furthermore, the formation of additional crosslinks with ions like Al^{3+} and Ca^{2+} present in soil, their water absorption capacity could be reduced (Chatzoudis and Rigas, 1999).

Several studies have suggested that SAPs increase the salinity of irrigation water (Lentz and Sojka, 2009; Taban and Naeini, 2006). Additionally, studies by Geesing and Schmidhalter (2004) reported that at high SAP amendment rates, their effectiveness was decreased on rewetting, which, in turn, affected the hydraulic properties of soil. Al-Harbi et al. (1999) reported that the efficiency of SAP reduced greatly over time and hence, higher application rates were required. These factors affect the economic value of crops grown in the presence of SAP amendments to the soil.

In some cases, SAP amendment to soil can have negative effect on plant growth. Studies by Chatzoudis and Rigas (1999) and Sarvaš et al. (2007) suggest that SAP does not have much effect on the soil's θ_{pwp} and that high application rates could cause plant mortality. In studies conducted by Oraee and Moghadam (2013), stem height decreased upon soil amendment with SAPs and decreased further with as the SAP application rate increased. In a certain study with wheat [*Triticum æstivum* L.], the height of the wheat plant grown in an SAP-amended soil was lower than that of a wheat plant grown in a soil without SAP (Ingram and Yeager, 1987).

Soil amendment with SAP also affects crop fertilizer use in the soil. Chatzoudis and Rigas (1998) reported that soil amendment with SAP increased water content which in turn increases the dissolution of fertilizers, which were thus leached to deeper depths. For water soluble fertilizers, the quantity of potassium leached increased with an increase in water absorption capacity of polymers. Therefore, SAPs also play a role of increased dissolution of controlled-released fertilizer (Chatzoudis and Rigas, 1998).

Most of the studies reviewed indicate that the application of SAPs in soil have a very positive effect on plants in the early stages, however, there are either little or no later in production or post-production (Frantz et al., 2005). However, since SAPs with different properties were used in the different studies no clear overall inferences could be drawn.

The goal of this thesis was to study the physiological properties of greenhouse-grown cherry tomatoes (*Solanum lycopersicum* var. *cerasiforme*) upon the addition of SAP to a soil-based growth mix at different concentrations of SAP and under different irrigation initiation conditions.

2.3.8 Environmental fate of SAPs in soil

In the last decade, one of the most important problems affecting the environment is the increased use of plastics and their subsequent disposal (Curcio and Picci, 2008). Conventional polymers, such as polyethylene and polypropylene persist for many years after disposal and are inappropriate for short time periods. Amongst the various possible routes to eliminate polymeric wastes, bio assimilation via biodegradation and bio recycling is considered as an attractive solution for environmental protection (Curcio and Picci, 2008).

The environmental fate of SAPs is becoming an increasingly important factor because of their use in various products (such as diapers, agriculture, adult incontinence etc.). In depth ecotoxicological testing has provided no evidence for significant adverse effects of polymers to marker organisms in water or plants and birds because of the chemical inertness of polymers (Sutherland et al., 1997); however, bacteria are unable to degrade these polymers due to the stability of the carbon-carbon backbone of polymers and high molecular mass due to cross-linking (Stahl et al., 2000).

Research by Sutherland et al. (1997) reported that, white-rot fungi extensively degrade polymers in water. Further research conducted by Stahl et al. (2000) reported that, white-rot fungi such as *Phanerochaete chrysosporium*, could degrade polymers extensively and sometimes could degrade many compounds completely to CO_2, a process called mineralization. White-rot fungi have the ability to degrade a wide variety of pollutants (including lignin, DDT, dioxin etc.) (Bumpus and Aust, 1995; Higson, 1991). Stahl et al., (2000) also reported that addition of sawdust as a nutrient source increased the degradation process significantly because sawdust acted as a reservoir, absorbing and storing water thus supplementing moisture to the microorganisms when needed.

CHAPTER 3

Materials and Methods

3.1 Materials

Super ABA 200 (Iramont Inc., Laval, QC), a SAP consisting of a polyacrylamide chain with potassium cations, was applied directly to the experimental soil without prior swelling in water.

3.2 Experimental site

All the studies were carried out in a greenhouse located on the Macdonald Campus of McGill University, Sainte-Anne-de-Bellevue, Canada. Daytime temperature averaged 25°C and night-time temperature, 16°C. The tomato plants were grown for four months from 25th March to 10th July. The seedlings were grown in the greenhouse and transplanted after two weeks. All the measurements were recorded during the day around 1:00 PM to 2:30 PM. The hours of daytime temperature was set for 16 hours and night time temperature was set for 8 hours.

3.3 Experimental design

A randomized complete block design with five replicates was employed. Two different SAP treatments were tested, one with 0.5% (w/w) Super ABA 200 and another with 0.1% Super ABA 200 in 1:1 Agro-Mix and water. A control with no SAP was also included. Three different plant watering applications were selected with an aim of inducing drought-like conditions: everyday watering (no stress), once in two days (moderate stress) and once in three days (severe stress). Watering was done on the basis of crop growth needs. However, watering volume was increased on days with hot temperature due to higher evaporative losses from evaporation. For an irrigation cycle, the amount of water to be applied was estimated by adding water to the pot without SAP and measuring the weight of the pot until the point where the water comes out freely at the bottom of the pot. Therefore, the irrigation amount for that cycle equalled the amount of water added to the pot. In an Irrigation cycle, the irrigation amounts were maintained uniform, for instance, if the no stress pot received 300 ml of water then the moderate stress and severe stress would also receive the same amount of water in two and three days respectively.

A3B2	A1B1	A2B3	
A2B2	A3B1	A2B1	Block 4
A1B3	A3B3	A1B2	
A3B1	A1B2	A3B2	
A2B1	A1B1	A2B2	Block 1
A1B3	A3B3	A2B3	
A3B3	A2B1	A1B3	
A1B1	A3B1	A2B3	Block 5
A2B2	A3B2	A2B3	
A3B3	A3B1	A2B3	
A1B3	A2B1	A2B2	Block 2
A3B2	A1B1	A2B3	
A1B1	A3B3	A2B3	
A2B2	A3B1	A2B3	Block 3
A2B1	A1B3	A3B2	

Figure 3.1: Randomised complete block design layout used in the study (A and B signify SAP concentrations and plant watering application; 1, 2 and 3 represent SAP concentration levels or water application treatments).

Given its superior drainage and gas diffusion properties, Agro-mix G6 (Fafard & Frères, ltée. Saint-Bonaventure, QC) was used as the substrate. Two gallon (US) plastic pots (8.5 inches wide and 8 inches deep) were filled with a mixture of agro-mix and water in a ratio of 1 (agromix):1(water). The SAP was randomly mixed into the soil in the middle of the pots to a depth of 15 cm from the top of the pots. A total of 45 experimental units were tested (3 irrigation treatments x 3 SAP treatments x 5 replicate). Miracle grow fertilizer for tomatoes were used as fertilizer in our study and was applied once in 14 days.

Figure 3.2: Random layout of experiments in the Greenhouse with different treatments and control.

3.4 Plant height

Plant height (cm) was measured once in three days by measuring the length of the stem from the soil surface to the tip of the tomato plant using a measuring tape. The plants were not pruned throughout the experiment; however, the suckers did not grow longer than the stem and the height was measured using the main stem.

3.5 Spectral reflectance

The Crop Circle ACS-470 (Holland Scientific Inc., Lincoln, Nebraska) active crop canopy sensor provides classic vegetation index data, including the normalised difference vegetative index (NDVI) as well as basic reflectance information from plant canopies and soil. NDVI was measured by mounting the sensor over a support and placing it at a distance of 5 cm above the crop so that the light emitted covered the entire canopy. The sensor was connected to a computer where the data was stored.

NDVI is measured by calculating the ratio of difference in the reflectance of near infrared wavelength (760 nm) and red wavelength (550 nm) by the plant to the sum of the reflectance of near infrared wavelength (760 nm) and red wavelength (550 nm) by the same plant.

$$\text{NDVI} = \frac{\text{Reflectace (NIR)} - \text{Reflectance (Red)}}{\text{Reflectance (NIR)} + \text{Reflectance (Red)}}$$

Where

NDVI = Normalised differential vegetative Index

Reflectance (NIR) = Reflectance of near Infra-red wavelength by the plant (760 nm)

Reflectance (Red) = Reflectance of red wavelength by the plant (550 nm)

3.6 Photosynthetic activity, stomatal conductance and transpiration

Photosynthetic rate, stomatal conductance and transpiration were measured using a Li-cor 6400 device (LI-COR, Lincoln, Nebraska). One leaf was randomly chosen from the top three leaves and tested and the results recorded. All the measurements were recorded weekly and done in the afternoon and the system was calibrated before recording the values.

3.7 Plant yield

Plant yield was measured by counting the number of fruits at the end of the study. Full sized mature fruits were monitored thoroughly for quality as only 1% or lower showed symptoms of catfacing, cracking, and blossom end rot. Counting was done thrice to minimise errors.

3.8 Water use efficiency

Water-use efficiency (WUE) refers to the ratio of water used in plant metabolism to water lost by the plant through transpiration(Bacon, 2009). Consequently, biomass production per unit evapotranspiration has been used extensively as a representative measure of water use efficiency (Singh et al., 2014). In our study, ET was defined as the total amount of water applied to the crop during its growth which includes both soil evaporation and transpiration losses.

$$WUE = \frac{Y}{ET} \quad (1)$$

Where,

Y is the marketable yield in tomatoes (kg)

ET is the quantity of water applied to the crop during its growth (mm)

In the present case, the WUE was measured by calculating the total weight of the fruits (fresh weight) at the end of study and the total amount of water applied to the plants. Ripe fruits were counted and weighed to get the total amount of biomass and the total amount of water was found by weighing the pots before and after irrigation. The difference in weight between the pots after water was applied in the previous day and the weight of the pots before the water was applied on the present day gave an estimate of the amount of water taken up by the plant and evaporated from the soil surface (evapotranspiration). The summation of the water applied on each day gives the total amount of water applied.

Figure 3.3: Weighing the pots before and after the application of water.

3.9 Micro-tox toxicology test

Thirty five soil leachate samples were analysed using the 15-min Microtox luminescent assay. The samples were first extracted using EPA method 1312 (synthetic precipitation leaching method) (Montour et al., 1998). The extraction was done in the soil and water quality lab of the Department of Bioresource Engineering, McGill University and the Micro-tox assessment was done in the analytical lab of the National Research Council Centre located in Montreal, Canada.

3.10 Statistical analysis

The statistical analysis was done using SAS (SAS 9.3, SAS Institute Inc., Cary, NC, USA). The F-tests, conducted by SAS PROC GLIMMIX, determined whether or not the treatment had an effect on height, NDVI, photosynthesis rate, transpiration, stomatal conductance and fruit yield. To test for significance and the differences between the control and the treatments, adjustments for multiple comparisons were made using the Bonferroni method. The WUE variable did not conform to the assumptions of conventional parametric statistics, and so it was analysed using the Scheirer-Ray-Hare extension of the Kruskal-Wallis test and the Bonferroni adjustment for multiple comparisons. The interaction of plant watering condition and SAP concentration was removed from the model due to its insignificance for any of the data sets. The null hypothesis for Kolmogorov-Smirnov test is that the variables are normally distributed.

Outcome variable	Kolmogorov-Smirnov (D)	p value
NDVI	0.14	<0.0100
Water use efficiency	0.26	<0.0100
photosynthesis activity	0.18	<0.0100
Stomatal conductance	0.12	<0.0100
Transpiration	0.08	0.0934

Table 3.1: Test for normal distribution using Kolmogorov-Smirnov test

The low p-values indicate that the NDVI, water use efficiency, photosynthetic activity and stomatal conductance were not normally distributed. Table 3.1 suggests that transpiration rate was the only parameter which was normally distributed; however, fit statistics (Akaike's Information criterion and Bayesian Information criterion) for PROC

GLIMMIX suggested that gamma distribution or lognormal distribution was more plausible than the normal distribution. A total of 45 samples were tested for normal distribution using Kolmogorov-Smirnov's test for every parameter.

Plant height and fruit yield data sets did not conform to normal distribution because; the data sets in plant height are positively auto-correlated (i.e. over time the values increase) and in fruit yield the data sets were positively skewed because the values were not negative and hence, it was not normally distributed and the variance was equivalent to the mean.

The interaction of plant watering condition and SAP concentration was removed from the model due to its insignificance for any of the data sets. However, the interaction in fruit yield data sets were suggestive of significance but inconclusive.

CHAPTER 4

Results and Discussion

4.1 Plant height

General trends

Trends indicate that amendment of soil with 0.5% SAP increased the height considerably as compared to the control (Fig 4.1). Additionally, amendment of agro-mix with 0.1% SAP decreased the height of the tomatoes for once in two days and once in three days plant watering condition and a possible reason for decrease in growth through height could be drought stress since it leads to a decrease in water potential to a lower level than needed for cell elongation which eventually results in decrease in cell growth (Oraee and Moghadam, 2013).

Another possible reason for decrease in shoot length could be due to blocking up of xylem and phloem vessels, thus hindering the process of translocation (Lovisolo and Schubert, 1998). The results of our study for plant height are in line with various other studies which recorded higher plant height values against the control (Yazdani et al., 2007)(Awad et al., 1995)(Singh et al., 2007) (Fernando et al., 2013)(Abedi-koupai and Asadkazemi, 2006). However, a study on *Ficus benjamina* (starlight) by Ghehsareh et al. (2010) contradicted the results obtained in our study.

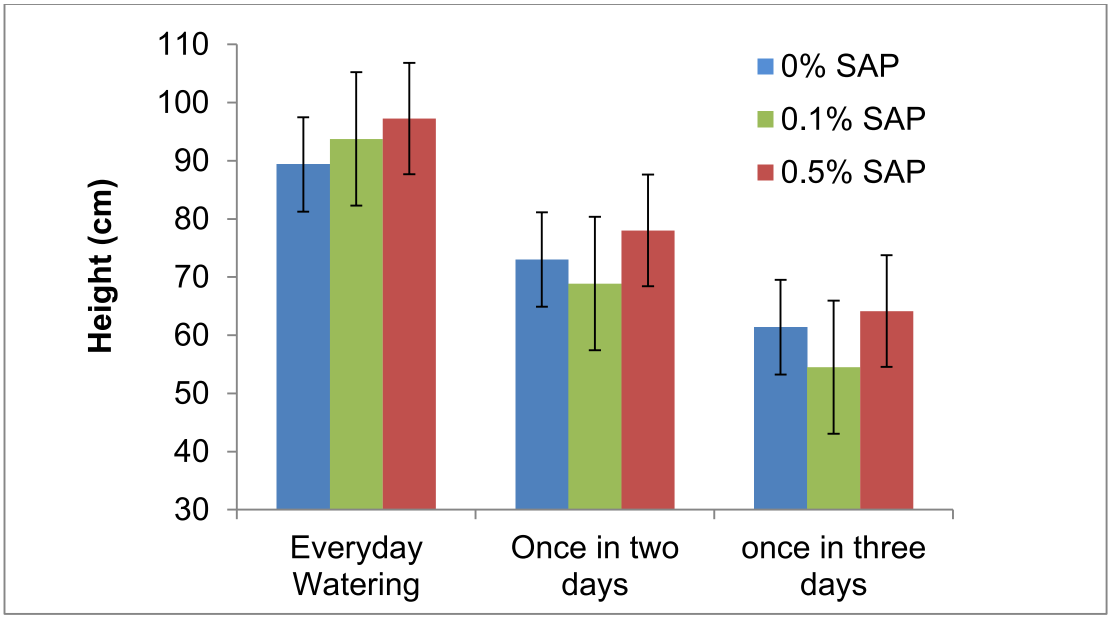

Fig 4.1: Average plant height values with different plant watering applications and SAP concentrations

Figure 4.2: Height comparison between 0%, 0.5% and 0.1% respectively and everyday plant watering application.

Outcome variable	Plant watering application		SAP concentration		Interaction	
	F value	Pr > F	F value	Pr > F	F value	Pr > F
Plant height	83.42	<.0001	0.11	0.8967	.	.
NDVI	1.41	0.2495	0.95	0.3901	.	.
Photosynthesis activity	0.4	0.6727	0.71	0.5039	.	.
Stomatal conductance	33	<.0001	0.63	0.5344	.	.
Transpiration rate	24.87	<.0001	0.72	0.4907	.	.
fruit count	495.28	<.0001	6.31	0.0056	2.18	0.099

Table 4.1: Type III test for fixed effects for different outcome variables

Statistical analysis

Statistical analysis presented in Table 4.1 indicated that the plant watering application (P<0.0001) was highly significant and also the SAP concentration (P=0.8967) did not have a significant effect on the plant height. This confirms the null hypothesis.

Least square means adjustments for multiple comparisons: Bonferroni				
Irrigation frequency	**Irrigation frequency**	**Adj P**	**Adj Lower**	**Adj Upper**
1	2	<0.001	0.1617	0.2714
1	3	<0.001	0.2219	0.3446
2	3	0.0664	-0.00311	0.1366

Table 4.2: Differences of Plant watering application (Irrigation frequency) least square means adjustments for multiple comparisons: Bonferroni

Table 4.2 suggests that there was convincing evidence for significance in the differences between everyday watering and, once in two days and once in three days watering for plant height at 95% confidence limits. However, the differences between once in two days plant watering application and once in three day plant watering application was suggestive of significance but inconclusive for plant height.

4.2 Spectral Reflectance

Trends

In all three plant watering applications, 0.5% SAP amendment recorded the highest values for NDVI compared to the no SAP condition (Fig 4.3). Additionally, the lowest values for NDVI for once in two days and once in three days watering application were recorded by 0.1% SAP. Amendment of agro-mix with 0.5% SAP gave better results and the trends were similar in all the plant watering conditions and a possible reason for such a trend could be the working of a SAP, which usually stores water and nutrients and the plants can use it during water deficit conditions.

Spectral reflectance of vegetation canopy in wavelength categories such as infrared is related to the health of plants (Serrano et al., 2000; Yang et al., 2008). The contrast between vegetation and soil is at a maximum in the red and near infrared region; therefore, spectral reflectance data can be used to compute a variety of vegetative indices that are well-correlated with agronomic and biophysical plant parameters related to photosynthetic activity and plant productivity (Adamsen et al., 1999; Ma et al., 2001).

Several combinations of bands such as red and NIR have been developed to relate the spectral reflectance of vegetation canopy to their biological features (Curran et al., 2001; Jago et al., 1999; Uno et al., 2005). It is one of the most commonly used Vis (Vegetative Indices), with wide range of applications and accuracy in the determining plant nitrogen status (Vouillot et al., 1998).

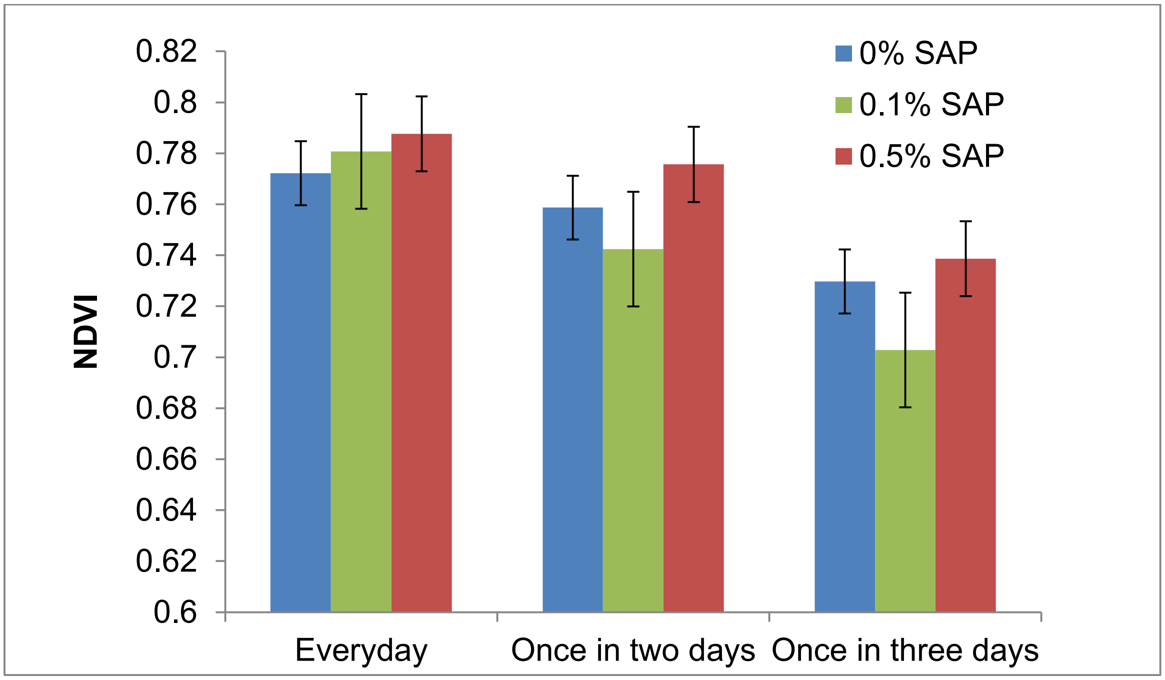

Figure 4.3: Average NDVI values for different plant watering applications and SAP concentrations

Statistical analysis

The NDVI variable was *T* – distributed based on fit statistics for the general linear mixed model. The plant watering condition had no significant effect on the plant NDVI, (P = 0.2495). The SAP concentration also, did not have a significant effect on the plant NDVI (P = 0.3901). Plant tissue readily absorbs light in the visible portion of the spectrum (and reflects a small amount typically 2% to 10%) and reflects NIR light (35% to 60%) due to discontinuity in the refractive indexes between cell walls and intercellular air gaps. These anatomical characteristics are affected by environmental factors such as soil moisture, nutrient status, soil salinity, and leaf stage (Ma et al., 2001).

4.3 Photosynthetic activity, stomatal conductance and transpiration rate

4.3.1 Photosynthetic activity

Trends

Amendment of agro-mix with SAP recorded highest values for photosynthetic activity for all the watering conditions against the control (Fig 4.4). Trends show that the effect of SAP amendment on photosynthesis rate was highest for 0.5% SAP, compared to 0.1% SAP in all the watering conditions. The lowest value for photosynthesis activity was the control in everyday and once in three days plant watering condition and 0.1% SAP concentration in two day plant watering application.

Significant effect of plant watering application ($P<0.0001$) was found on the photosynthesis rate, however, no significant effect of SAP concentration ($P=0.5344$) was found on the photosynthesis rate. 0.5% SAP and everyday watering produced the highest value for photosynthesis rate (2.515 µmol CO2 m^{-2} s^{-1}).

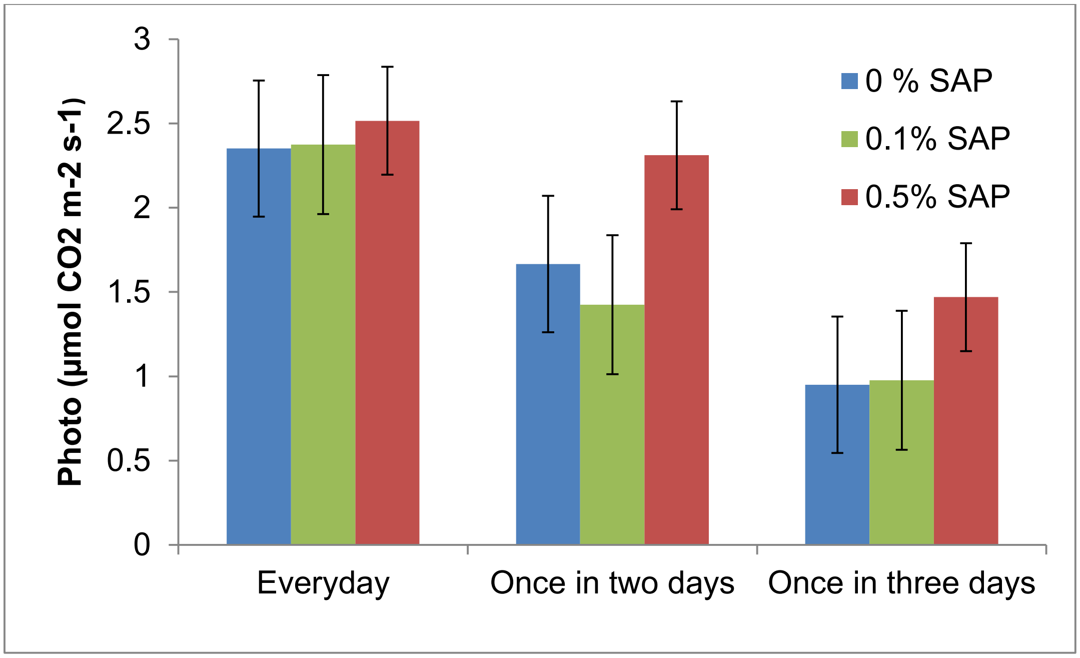

Figure 4.4: Average Photosynthesis activity values for different plant watering applications and SAP concentrations

Statistical analysis

The photosynthetic rate was not normally distributed but the natural logarithms were normally distributed, it was therefore lognormal distributed.

The plant watering condition had no significant effect on the photosynthetic rate (P = 0.6727). There was no effect of SAP concentration on the photosynthesis rate (P = 0.5039). The experimental data confirms the null hypothesis. It is well known that under water deficit conditions, growth gets restricted (Ismail and Davies, 1998), however, the objective was to measure the effectiveness of SAP under water deficit conditions and although trends show that 0.5% SAP had overall better development but statistical significance was not achieved.

4.3.2 Stomatal conductance

Trends

Amendment of agro-mix with SAP recorded highest values for stomatal conductance for all the watering conditions against the control (Fig 4.5). Trends show that the effect of SAP amendment on stomatal conductance was highest for 0.5% SAP, compared to 0.1% SAP, in all the watering conditions. The lowest value for stomatal conductance was the control in everyday and once in three days plant watering condition. However, amendment of agro-mix with 0.1% SAP recorded the lowest value for once in two days plant watering application.

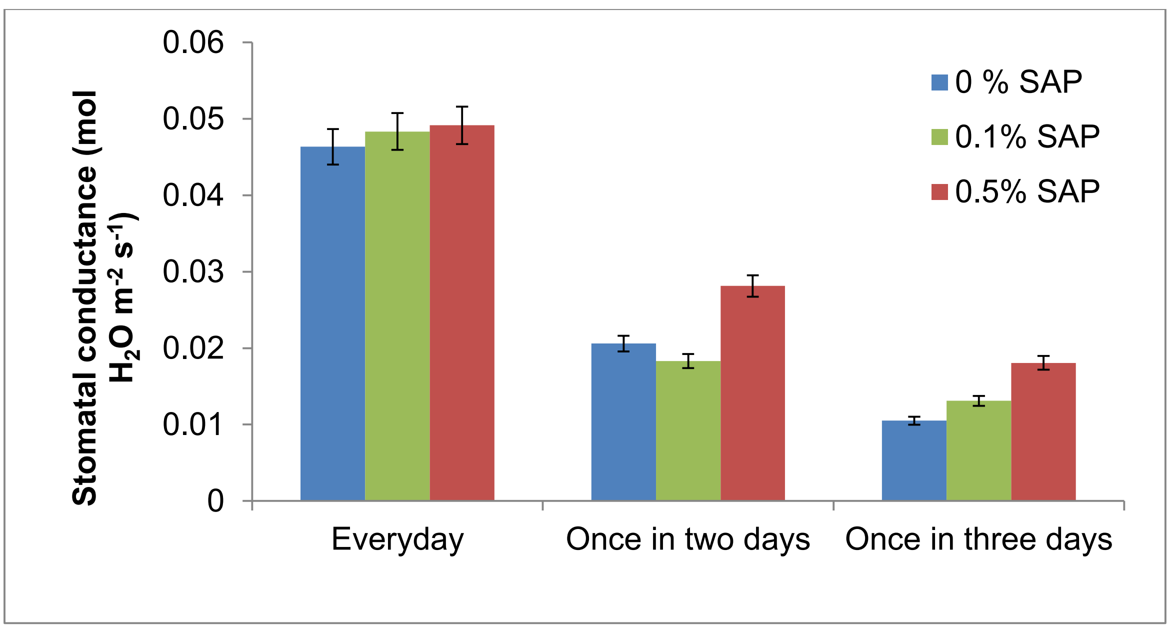

Figure 4.5: Average stomatal conductance values for different plant watering applications and SAP concentrations

Statistical analysis

The data for stomatal conductance was gamma distributed. Gamma distribution is common for variables with variance dependent on the means in biological variables. The effect of plant watering application on stomatal conductance was significant ($P < 0.0001$) therefore rejecting the null hypothesis. The effect of SAP concentration was not significant on the stomatal conductance ($P = 0.5344$).

Least square means adjustments for multiple comparisons: Bonferroni				
Irrigation frequency	**Irrigation frequency**	**Adj P**	**Adj Lower**	**Adj Upper**
1	2	0.0018	0.1907	1.0139
1	3	<0.001	0.9538	1.7815
2	3	<0.001	0.3514	1.1792

Table 4.3: Differences of plant water application least square means adjustments for multiple comparisons: Bonferroni

According to the Bonferroni adjusted limits at 95% confidence, everyday plant watering application would increase stomatal conductance from 21% to 175% compared to once in two days plant watering application and 159% to 493% compared to once in three days plant watering application. Once in two days plant watering application would increase stomatal conductance from 42% to 225% compared to once in three days plant watering application.

4.3.3 Transpiration rate

Trends

In all three plant watering applications, 0.5% SAP recorded the highest value for transpiration. The control recorded the lowest value in everyday and once in three days plant watering application and 0.1% recorded the lowest value in once in two days plant watering application.

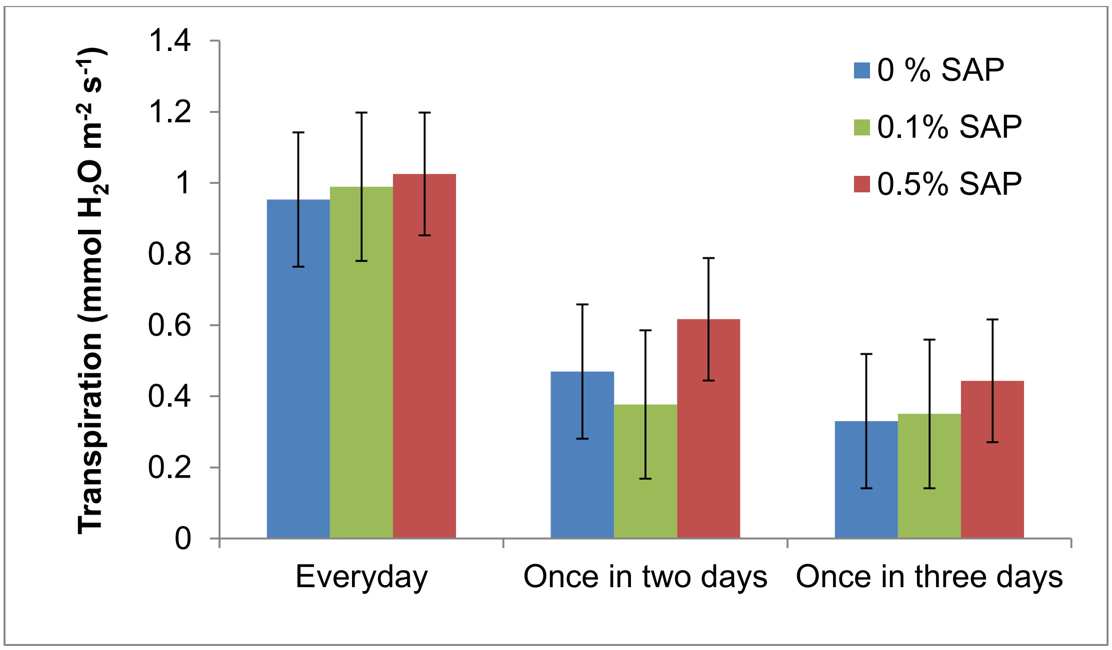

Figure 4.6: Average Transpiration values for different plant watering applications and SAP concentrations

The application of SAP also may favor different physiological activities (photosynthesis, transpiration and intracellular CO_2) in tomatoes. The increase in photosynthesis rate (P_N) enhances growth and ameliorates drought stress and also under stomatal and non-stomatal limitations reduces P_N (Shangguan et al., 1999). In our study, there is an increase in P_N for treatments with 0.5% SAP in all the plant watering applications. Stomatal conductance depends on the relative leaf water content which is also responsible for the transpiration efficiency in crops (Jarvis and Davies, 1998).

The trend in our study was in line with the trends obtained in the study by Islam et al. (2011), however, statistical significance was not achieved.

Statistical Analysis

Significant effect of plant watering application was found on the transpiration rate ($P<0.0001$). Transpiration rate increased with higher plant watering. However, no significant effect of SAP concentration ($P=0.4907$) was found on transpiration rate.

Least square means adjustments for multiple comparisons: Bonferroni				
Irrigation frequency	**Irrigation frequency**	**Adj P**	**Adj Lower**	**Adj Upper**
1	2	0.0007	0.1761	0.9694
1	3	<0.001	0.7474	1.545
2	3	0.0007	0.1747	0.9722

Table 4.4: Differences of plant water application least square means adjustments for multiple comparisons: Bonferroni

According to the Bonferroni adjusted limits at 95% confidence, everyday plant watering application would increase transpiration rate from 19% to 163% compared to once in two day plant watering application and 111% to 368% compared to once in three day plant watering application. Once in two day plant watering application would increase transpiration rate from 19% to 164% compared to once in three days plant watering application.

4.4 Fruit count

Trends

The yield was found at the end of the study by counting the number of fruits. In everyday watering, 0.5% SAP (230) recorded the highest value whereas the control (200) recorded the lowest. In once in two days watering application, 0.5% SAP (145) recorded the highest value for yield whereas 0.1% SAP (135) had the lowest. Once in three days watering application, 0.5% SAP (62) recorded the highest yield whereas 0% SAP (45) had the lowest.

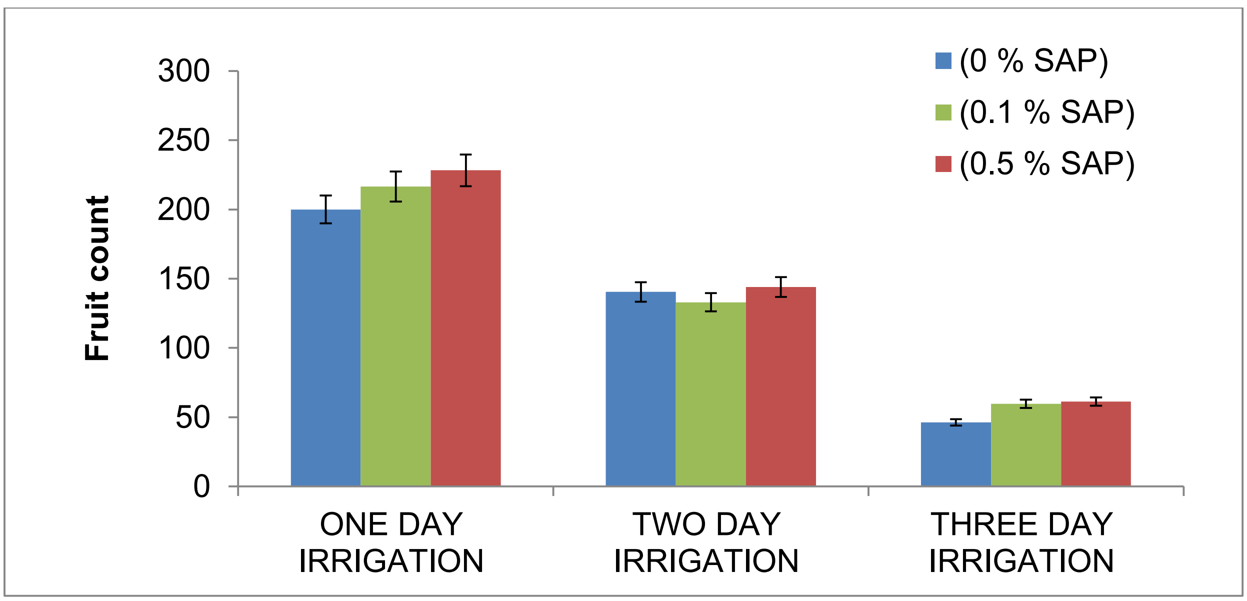

Figure 4.7: Average fruit count values per treatment for different plant watering applications and SAP concentrations

The effect of SAP has a significant impact in reducing drought stress effects and to improve plant yield (Khadem et al., 2010). Hayat and Ali (2004) also found that SAP has a significant effect on the yield of tomatoes and a reason could be because of the reduced impact of water stress during the growing cycle (Johnson and Piper, 1997).

The results of our study are in line with various other studies where the yield was significantly higher than the control (Yazdani et al., 2007)(Khadem et al., 2010)(Hayat and Ali, 2004)(Moslemi et al., 2011).

Statistical analysis

The effect of plant watering condition on fruit yield was significant ($P < 0.0001$). Both the SAP concentrations were found to be significant on the fruit yield, compared to the control ($P < 0.0056$). The interaction between the two treatments, SAP concentration and plant watering application, was not significant on the fruit yield ($P = 0.0986$). Also, from Table 4.5, we can see that 0.1% and 0.5% SAP concentrations were not different from each other ($P = 0.1974$).

SAP conc	**SAP conc**	**Pr > t**	**Adj P**
0	0.1	0.0334	0.0839
0	0.5	0.015	0.004
0.1	0.5	0.1974	0.3991

Table 4.5: Differences of SAP concentration least square means adjustments for multiple comparisons simulated.

Plant watering condition	F value	Pr>F
1	3.74	0.0367
2	0.91	0.4155
3	4.87	0.0157

Table 4.6: Tests of effect slices for plant watering condition x SAP concentration sliced by plant watering condition.

The SAP concentration had a significant effect on the plants watered everyday $F(2, 27) = 3.74$, $p=0.0367$; and, plants watered once in three days $F(2,27) = 4.87$, $p=0.0157$.

According to 95% confidence limits, within the everyday watering application, the pots grown with 0.5% SAP amendment produced 20% to 28% higher fruits than the control ($p=0.0111$, $k=3$, $Padj = k*p = 0.0333$).

Within once in three days plant watering application, plants with 0.1% SAP produced 36% to 42% higher fruits than the plants grown with 0% SAP amendment ($p=0.0144$, $k=3$, $Padj = k*p = 0.0432$) and also, 0.5% SAP produced 38% to 55% higher fruits than the plants grown with 0% SAP amendment ($p= 0.0076$, $k=3$, $Padj = k*p = 0.0228$).

In short, the total number of fruits harvested increased with the amendment of SAP in agro-mix.

4.5 Water use efficiency

General trends

Compared to the non-amended control, the two treatments amended with SAP were successful in increasing the water use efficiency in everyday and once in three days plant watering condition (Fig 4.1). However, in once in two days only 0.5% SAP amendment showed better water use efficiency. 0.5% SAP is observed to have a better water use efficiency overall given the similar trends for different plant watering conditions.

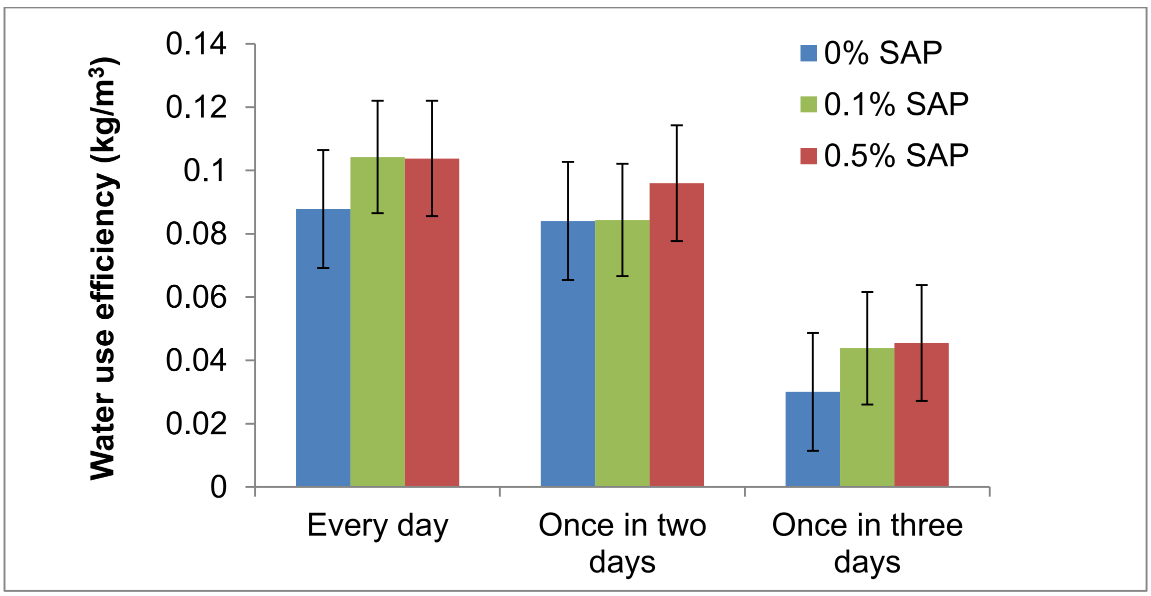

Figure 4.8: Water use efficiency for different rates of plant watering applications with different SAP concentrations

SAPs have been used extensively as water retaining materials in agricultural and horticultural fields because they can retain large quantities of water and nutrients. The results suggest that the SAP helps in storing water and releasing it based on requirement thus increasing the water holding capacity of the rooting medium and consequently, the availability of the nutrients (Boatright et al., 1995, Van Cottem, 1999, El-Rehim et al., 2004). Another reason could be the release of potassium from the SAP (El-Hady and AbdEl-Hady, 2003). The study was in accordance with Nazarli et al. (2010) and Islam et al. (2011) who had tested the effectiveness of SAP on different species and yielded similar results which is associated with higher water retention capacity and available water. El-Hady and AbdEl-Hady (2003) tested the effects of compost or/and hydrogels on water use efficiency of tomatoes and yielded similar results as in our study.

Statistical analysis

Since the WUE data did not conform to conventions of conventional and parametric statistics, the analysis of variance procedure was performed using Scheirer-Ray-Hare extension of the Kruskal-Wallis test (non-parametric two way ANOVA) and it was found that the effect of SAP concentration (P=0.050) was significant on water use efficiency. With the interaction included, the data is suggestive with respect to the effect of SAP concentration, $P(\chi_2^2 \geq H) = 0.05$. After adjustment for multiple comparisons, however, no difference in WUE could be detected at the $p < 0.05$ level between the groups of plants grown at differing SAP concentrations at levels 0.1% and 0.5%.

4.6 Micro-tox toxicology test

Thirty five soil leachate samples were analysed using the 15-min Micro-tox luminescent assay. Twenty samples out of thirty five significantly inhibited the luminescence of the bacteria compared to the Blank control (agro-mix). However, two samples (control) had high inhibition effect (> 50% compared to the negative control). Analysis of variance followed by Post Hoc test using least significant means showed that ten out of the 35 samples were not toxic to *Vibrio fischeri* and had p-values > 0.05 compared to Blank control. The sample with 0.5% SAP and 0.1% showed lower toxicity towards the bacteria compared to the control.

Sample	% Inhibition	Standard deviation
Blank	6.6	3.11
0% 1 day	53.4	0.58
0% 1 day	58.2	0.96
0% 1 day	23.9	0.26
0% 1 day	8.7	1.87
0% 2 day	41.2	2.86
0% 2 day	20.8	1.38
0% 2 day	13.5	1.62
0% 3 day	11.5	5.55
0% 3 day	9.7	4.37
0% 3 day	18.2	0.33
0.1% 1 day	13.3	2.21
0.1% 1 day	48.4	1.12
0.1% 1 day	15.2	4.67
0.1% 2 day	45	1.33
0.1% 2 day	39	2.71
0.1% 2 day	19.9	2.25
0.1% 2 day	30.4	3.04
0.1% 2 day	16.7	3.08
0.1% 3 day	1.3	1.51

0.1% 3 day	7.7	2.69
0.1% 3 day	5.1	2.38
0.5% 1 day	29	1.67
0.5% 1 day	37.3	0.94
0.5% 1 day	6.5	1.84
0.5% 2 day	11.1	3.23
0.5% 2 day	15	3.28
0.5% 2 day	19	2.36
0.5% 2 day	16.4	1.85
0.5% 2 day	13.1	3.02
0.5% 3 day	43.8	2.67
0.5% 3 day	26.2	2.12
0.5% 3 day	10.2	2.45
0.5% 3 day	1.8	2.46
0.5% 3 day	12.2	8.34

Table 4.7: The values of percent inhibition and standard deviation for the thirty-five samples used in micro-tox assessment procedure

The Micro-tox procedure was done to understand the toxicity of the agro-mix with the addition of SAP against the blank (agro-mix) and from the inhibition test by using a bio-luminescent bacterium (*Vibrio fischeri*), it was found that the treatments with SAP did not have any toxic effect on the media (agro-mix) and it is safe to use in the fields. However, two samples, with 0% SAP and everyday plant watering application were reported of having higher percent of inhibition to the bacteria as compared to the blank.

CHAPTER 5

Summary, Conclusion and Recommendation for Future Work

5.1 Summary

The effectiveness of two different concentrations of SAP (based on soil dry weight) in the production of cherry tomatoes were studied and analysed. The result from discussion and statistical analysis can be summarized as follows:

1. The water use efficiency was calculated by finding the ratio between the total amount of biomass produced and the total amount of water used and was compared between the control and two different concentrations of SAP (0.1% and 0.5%). The statistical analysis showed that the amendment of soil with SAP ($P=0.050$) showed higher water use efficiency compared to that of the control.

2. The yield was calculated by counting the number of fruits and was compared between the control (0% SAP) and different concentrations of SAP (0.1% and 0.5%). The statistical analysis showed that the amendment of soil with SAP ($P=0.0056$) produced higher yields compared to the control.

3. The overall trends of the result obtained from Li-Cor for photosynthesis rate, stomatal conductance and transpiration rate show that there is an increasing effect of SAP amendment in agro-mix compared to control. However, the statistical analysis showed that SAP amendment in agro-mix was not significant.

4. The overall trends of the results obtained from height show that amendment of agro-mix with 0.5% SAP proved to be really effective, compared to control and 0.1% SAP. However, the statistical analysis showed that SAP amendment in soil was not significant.

5. The overall trends of the results obtained from the spectral reflectance data obtained from crop circle show that the amendment of agro-mix with 0.5% SAP yielded higher NDVI values compared to the control. However, the statistical analysis showed that the amendment of agro-mix with SAP was not significant.

6. The SAP amendment in agro-mix was tested for any toxic effects through a microtox analysis. It was found that the amendment of SAP in agro-mix was not toxic, compared to the blank, and is therefore safe to use from an ecological viewpoint.

5.2 Conclusions

As a conclusion, SAP as a soil amendment is effective in increasing the water use efficiency and yield of cherry tomatoes. It could be widely used in the field by farmers to increase the yield and improve the water holding capacity of soil. SAPs do not appear to be environmentally toxic and are easily usable. It is also known for other benefits such as better fertilizer use efficiency. However, care must be taken to choose the right amount of SAP concentration in soil. Selection should be based on the following parameters; swelling capacity, cross linker used, starting materials, and swelling rate.

5.3 Future recommendations

Although the study revealed some important findings, the following areas must further be explored:

1. Economic analysis on the use of SAPs as a soil amendment in agricultural fields
2. Study the fertilizer use efficiency in detail
3. Perform field trials and to understand the physiological characteristics compared to the greenhouse trials
4. Conduct studies with other crops
5. Understand the life cycle of SAPs in soil.

6. References

Abedi-Koupai, J., Asadkazemi, J., 2006. Effects of a hydrophilic polymer on the field performance of an ornamental plant (Cupressus arizonica) under reduced irrigation regimes. Iran. Polym. J. 15, 715.

Abedi-koupai, J., Asadkazemi, J., 2006. ch Ar ch ive 15, 715–725.

Abedi-Koupai, J., Sohrab, F., Swarbrick, G., 2008. Evaluation of Hydrogel Application on Soil Water Retention Characteristics. J. Plant Nutr. 31, 317–331. doi:10.1080/01904160701853928

Adamsen, F.G., Pinter, P.J., Barnes, E.M., LaMorte, R.L., Wall, G.W., Leavitt, S.W., Kimball, B.A., 1999. Measuring wheat senescence with a digital camera. Crop Sci. 39, 719–724.

Ahmed, E.M., 2013. Hydrogel: Preparation, characterization, and applications. J. Adv. Res. doi:10.1016/j.jare.2013.07.006

Ahmed, M.M., Sanders, J.H., Nell, W.T., 2000. New sorghum and millet cultivar introduction in Sub-Saharan Africa: impacts and research agenda. Agric. Syst. 64, 55–65.

Al-Harbi, A.R., Al-Omran, A.M., Shalaby, A.A., Choudhary, M.I., 1999. Efficacy of a hydrophilic polymer declines with time in greenhouse experiments. HortScience 34, 223–224.

Andry, H., Yamamoto, T., Irie, T., Moritani, S., Inoue, M., Fujiyama, H., 2009. Water retention, hydraulic conductivity of hydrophilic polymers in sandy soil as affected by temperature and water quality. J. Hydrol. 373, 177–183.

Arnell, N.W., 2004. Climate change and global water resources: SRES emissions and socio-economic scenarios. Glob. Environ. Chang. 14, 31–52.

Askari, F., Nafisi, S., Omidian, H., Hashemi, S.A., 1993. Synthesis and characterization of acrylic-based superabsorbents. J. Appl. Polym. Sci. 50, 1851–1855.

Atta, A.M., El-Ghazawy, R.A.M., Farag, R.K., El-Kafrawy, A.F., Abdel-Azim, A.A., 2005. Crosslinked cinnamoyloxyethyl methacrylate and isooctyl acrylate copolymers as oil sorbers. Polym. Int. 54, 1088–1096.

Awad, F., Kah, L., Kluge, R., 1995. Environmental aspects of sewage sludge and evaluation of super absorbent hydrogel under Egyptian conditions 91–97.

Bacon, M., 2009. Water use efficiency in plant biology. John Wiley & Sons.

Bai, W., Zhang, H., Liu, B., Wu, Y., Song, J., 2010. Effects of super-absorbent polymers on the physical and chemical properties of soil following different wetting and drying cycles. Soil Use Manag. 26, 253–260. doi:10.1111/j.1475-2743.2010.00271.x

Beesley, L., Marmiroli, M., 2011. The immobilisation and retention of soluble arsenic, cadmium and zinc by biochar. Environ. Pollut. 159, 474–480.

Beltran, S., Baker, J.P., Hooper, H.H., Blanch, H.W., Prausnitz, J.M., 1991. Swelling equilibria for weakly ionizable, temperature-sensitive hydrogels. Macromolecules 24, 549–551.

Beniwal, R.S., Langenfeld-Heyser, R., Polle, A., 2010. Ectomycorrhiza and hydrogel protect hybrid poplar from water deficit and unravel plastic responses of xylem anatomy. Environ. Exp. Bot. 69, 189–197.

Bhardwaj, A.K., McLaughlin, R.A., Shainberg, I., Levy, G.J., 2009. Hydraulic characteristics of depositional seals as affected by exchangeable cations, clay mineralogy, and polyacrylamide. Soil Sci. Soc. Am. J. 73, 910–918.

Bhardwaj, A.K., Shainberg, I., Goldstein, D., Warrington, D.N., J Levy, G., 2007. Water retention and hydraulic conductivity of cross-linked polyacrylamides in sandy soils. Soil Sci. Soc. Am. J. 71, 406–412.

Boatright, J.L., Zajicek, J.M., Mackay, W.A., 1995. WATER AND NITROGEN RETENTION IN ANNUAL LANDSCAPE BEDS AMENDED WITH A HYDROPHILIC POLYMER. HortScience 30, 440.

Brändli, R.C., Hartnik, T., Henriksen, T., Cornelissen, G., 2008. Sorption of native polyaromatic hydrocarbons (PAH) to black carbon and amended activated carbon in soil. Chemosphere 73, 1805–1810.

Brown, T.C., 2000. Projecting US freshwater withdrawals. Water Resour. Res. 36, 769–780.

Buchholz, F.L., 1994. Recent advances in superabsorbent polyacrylates. Trends Polym. Sci. 2, 277–281.

Buchholz, F.L., Graham, A.T., 1998. Modern superabsorbent polymer technology. John! Wiley Sons, Inc, 605 Third Ave, New York, NY 10016, USA, 1998. 279.

Buchholz, F.L., Peppas, N.A., 1994. Superabsorbent polymers: science and technology. American Chemical Society.

Bumpus, J.A., Aust, S.D., 1995. Biodegradation of environmental pollutants by the white-rot fungus–P. chrysosporium. Bio Essays 6, 166–170.

Burke, D.R., Akay, G., Bilsborrow, P.E., 2010. Development of novel polymeric materials for agroprocess intensification. J. Appl. Polym. Sci. 118, 3292–3299.

Chatzoudis, G.K., Rigas, F., 1998. Macroreticular hydrogel effects on dissolution rate of controlled-release fertilizers. J. Agric. Food Chem. 46, 2830–2833.

Chatzoudis, G.K., Rigas, F., 1999. Soil salts reduce hydration of polymeric gels and affect moisture characteristics of soil. Commun. Soil Sci. Plant Anal. 30, 2465–2474.

Clothier, B.E., Green, S.R., 1994. Rootzone processes and the efficient use of irrigation water. Agric. Water Manag. 25, 1–12.

Curcio, M., Picci, N., 2008. Polymer in agriculture: a review. Am. J. Agric. Biol. Sci. 3, 299–314.

Curran, P.J., Dungan, J.L., Peterson, D.L., 2001. Estimating the foliar biochemical concentration of leaves with reflectance spectrometry: testing the Kokaly and Clark methodologies. Remote Sens. Environ. 76, 349–359.

Doelker, E., Brannon-Peppas, L., Harland, R.S., 1990. Absorbent Polymer Technology.

Döll, P., 2002. Impact of climate change and variability on irrigation requirements: a global perspective. Clim. Change 54, 269–293.

Dorraji, S.S., Golchin, A., Ahmadi, S., 2010. The effects of hydrophilic polymer and soil salinity on corn growth in sandy and loamy soils. Clean–Soil, Air, Water 38, 584–591.

El-Hady, O., AbdEl-Hady, N.A., 2003. Rizk and ES El-Saify, 2003. The potentiality for improving plant-soil-water relations in sandy soil using some synthesized Am Na (or K) ATEA hydrogels. Egypt. J. Soil Sci 43, 547–566.

El-Rehim, H. a. A., Hegazy, E.-S. a., El-Mohdy, H.L.A., 2004. Radiation synthesis of hydrogels to enhance sandy soils water retention and increase plant performance. J. Appl. Polym. Sci. 93, 1360–1371. doi:10.1002/app.20571

El-Rehim, H.A., Hegazy, E.A., El-Mohdy, H.L., 2004. Radiation synthesis of hydrogels to enhance sandy soils water retention and increase plant performance. J. Appl. Polym. Sci. 93, 1360–1371.

Evans, R.G., Sadler, E.J., 2008. Methods and technologies to improve efficiency of water use. Water Resour. Res. 44, 1–15. doi:10.1029/2007WR006200

Fereres, E., Soriano, M.A., 2007. Deficit irrigation for reducing agricultural water use. J. Exp. Bot. 58, 147–159.

Fernando, T.N., Disanayaka, C.K., Kulathunge, S., Forty, P., Storied, T., Project, B., Senarath, I.C., Pasqual, H., Jamil, S.F., Ariadurai, S.A., 2013. effect of super water absorbent polymer and water capacity on growth of tomato. J. Eng. Technol. open Univ. srilanka.

Frantz, J.M., Locke, J.C., Pitchay, D.S., Krause, C.R., 2005. Actual performance versus theoretical advantages of polyacrylamide hydrogel throughout bedding plant production. HortScience 40, 2040–2046.

Geesing, D., Schmidhalter, U., 2004. Influence of sodium polyacrylate on the water-holding capacity of three different soils and effects on growth of wheat. Soil use Manag. 20, 207–209.

Ghehsareh, M.G., Khosh-Khui, M., Abedi-Koupai, J., 2010. Effects of Superabsorbent Polymer on Water Requirement and Growth Indices of Ficus Benjamina L. "Starlight." J. Plant Nutr. 33, 785–795. doi:10.1080/01904161003654030

Gleick, P.H., 2003a. Water use. Annu. Rev. Environ. Resour. 28, 275–314.

Gleick, P.H., 2003b. Global freshwater resources: soft-path solutions for the 21st century. Science (80-.). 302, 1524–1528.

Gudeman, L.F., Peppas, N.A., 1995. pH-sensitive membranes from poly (vinyl alcohol)/poly (acrylic acid) interpenetrating networks. J. Memb. Sci. 107, 239–248.

Hayat, R., Ali, S., 2004. Water absorption by synthetic polymer (Aquasorb) and its effect on soil properties and tomato yield. Int. J. Agric. Biol. 6, 998–1200.

Higson, F.K., 1991. Degradation of xenobiotics by white rot fungi, in: Reviews of Environmental Contamination and Toxicology. Springer, pp. 111–152.

Horie, K., Báron, M., Fox, R.B., He, J., Hess, M., Kahovec, J., Kitayama, T., Kubisa, P., Maréchal, E., Mormann, W., Stepto, R.F.T., Tabak, D., Vohlídal, J., Wilks, E.S., Work, W.J., 2004. Definitions of terms relating to reactions of polymers and to functional polymeric materials (IUPAC Recommendations 2003). Pure Appl. Chem. 76, 889–906. doi:10.1351/pac200476040889

Howell, T.A., 2001. Enhancing water use efficiency in irrigated agriculture. Agron. J. 93, 281–289.

Huang, M., Shao, M., Zhang, L., Li, Y., 2003. Water use efficiency and sustainability of different long-term crop rotation systems in the Loess Plateau of China. Soil Tillage Res. 72, 95–104.

Husk, B., Major, J., 2010. Commercial scale agricultural biochar field trial in Québec, Canada over two years: effects of biochar on soil fertility, biology and crop productivity and quality. Dynamotive Energy Syst. Febr.

Hüttermann, A., Orikiriza, L.J.B., Agaba, H., 2009. Application of Superabsorbent Polymers for Improving the Ecological Chemistry of Degraded or Polluted Lands. CLEAN - Soil, Air, Water 37, 517–526. doi:10.1002/clen.200900048

Ingram, D.L., Yeager, T.H., 1987. Effects of irrigation frequency and a water absorbing polymer amendment on Ligustrum growth and moisture retention by a container medium. J. Environ. Hort 5, 19–21.

Isık, B., Kıs, M., 2004. Preparation and determination of swelling behavior of poly (acrylamide-co-acrylic acid) hydrogels in water. J. Appl. Polym. Sci. 94, 1526–1531.

Islam, M.R., Xue, X., Li, S., Ren, C., Eneji, a. E., Hu, Y., 2011. Effectiveness of Water-Saving Superabsorbent Polymer in Soil Water Conservation for Oat Based on Ecophysiological Parameters. Commun. Soil Sci. Plant Anal. 42, 2322–2333. doi:10.1080/00103624.2011.605490

Ismail, M.R., Davies, W.J., 1998. Root restriction affects leaf growth and stomatal response: the role of xylem sap ABA. Sci. Hortic. (Amsterdam). 74, 257–268.

Jago, R.A., Cutler, M.E.J., Curran, P.J., 1999. Estimating canopy chlorophyll concentration from field and airborne spectra. Remote Sens. Environ. 68, 217–224.

Jarvis, A.J., Davies, W.J., 1998. The coupled response of stomatal conductance to photosynthesis and transpiration. J. Exp. Bot. 49, 399–406.

Johnson, M.S., Piper, C.D., 1997. Cross-linked, water-storing polymers as aids to drought tolerance of tomatoes in growing media. J. Agron. Crop Sci. 178, 23–27.

Kabiri, K., Mirzadeh, H., Zohuriaan-Mehr, M.J., 2008. Undesirable effects of heating on hydrogels. J. Appl. Polym. Sci. 110, 3420–3430.

Kabiri, K., Omidian, H., Hashemi, S.A., Zohuriaan-Mehr, M.J., 2003a. Synthesis of fast-swelling superabsorbent hydrogels: effect of crosslinker type and concentration on porosity and absorption rate. Eur. Polym. J. 39, 1341–1348.

Kabiri, K., Omidian, H., Zohuriaan-Mehr, M.J., 2003b. Novel approach to highly porous superabsorbent hydrogels: synergistic effect of porogens on porosity and swelling rate. Polym. Int. 52, 1158–1164.

Karimi, A., Naderi, M., 2007. Yield and water use efficiency of forage corn as influenced by superabsorbent polymer application in soils with different textures. Agr. Res. J 187–198.

Kazanskii, K.S., Dubrovskii, S.A., 1992. Chemistry and physics of “agricultural” hydrogels, in: Polyelectrolytes Hydrogels Chromatographic Materials. Springer, pp. 97–133.

Khadem, S.A., Galavi, M., Ramrodi, M., Mousavi, S.R., Rousta, M.J., Rezvani-Moghadam, P., 2010. Effect of animal manure and superabsorbent polymer on corn leaf relative water content, cell membrane stability and leaf chlorophyll content under dry condition.

Laird, D.A., Fleming, P., Davis, D.D., Horton, R., Wang, B., Karlen, D.L., 2010. Impact of biochar amendments on the quality of a typical Midwestern agricultural soil. Geoderma 158, 443–449.

Lehmann, J., 2007. A handful of carbon. Nature 447, 143–144.

Lehmann, J., da Silva Jr, J.P., Steiner, C., Nehls, T., Zech, W., Glaser, B., 2003. Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: fertilizer, manure and charcoal amendments. Plant Soil 249, 343–357.

Lehmann, J., Joseph, S., 2009. Biochar systems. Biochar Environ. Manag. Sci. Technol. 147–181.

Lehmann, J., Rondon, M., 2006. Bio-char soil management on highly weathered soils in the humid tropics. Biol. approaches to Sustain. soil Syst. CRC Press. Boca Raton, FL 517–530.

Lentz, R.D., 2007. Inhibiting water infiltration into soils with cross-linked polyacrylamide: Seepage reduction for irrigated agriculture.

Lentz, R.D., Sojka, R.E., 1994. Field results using polyacrylamide to manage furrow erosion and infiltration. Soil Sci. 158, 274–282.

Lentz, R.D., Sojka, R.E., 2009. Long-term polyacrylamide formulation effects on soil erosion, water infiltration, and yields of furrow-irrigated crops. Agron. J. 101, 305–314.

Lentz, R.D., Sojka, R.E., Carter, D.L., Shainberg, I., 1992. Preventing irrigation furrow erosion with small applications of polymers. Soil Sci. Soc. Am. J. 56, 1926–1932.

Liang, B., Lehmann, J., Solomon, D., Kinyangi, J., Grossman, J., O’neill, B., Skjemstad, J.O., Thies, J., Luizao, F.J., Petersen, J., 2006. Black carbon increases cation exchange capacity in soils. Soil Sci. Soc. Am. J. 70, 1719–1730.

Liu, M., Guo, T., 2001. Preparation and swelling properties of crosslinked sodium polyacrylate. J. Appl. Polym. Sci. 82, 1515–1520.

Liu, M., Liang, R., Zhan, F., Liu, Z., Niu, A., 2006. Synthesis of a slow-release and superabsorbent nitrogen fertilizer and its properties. Polym. Adv. Technol. 17, 430–438.

Liu, X., Tong, Z., Hu, O., 1995. Swelling equilibria of hydrogels with sulfonate groups in water and in aqueous salt solutions. Macromolecules 28, 3813–3817.

Liu, Z.S., Rempel, G.L., 1997. Preparation of superabsorbent polymers by crosslinking acrylic acid and acrylamide copolymers. J. Appl. Polym. Sci. 64, 1345–1353.

Lovisolo, C., Schubert, A., 1998. Effects of water stress on vessel size and xylem hydraulic conductivity in Vitis vinifera L. J. Exp. Bot. 49, 693–700.

Lucero, M.E., Dreesen, D.R., VanLeeuwen, D.M., 2010. Using hydrogel filled, embedded tubes to sustain grass transplants for arid land restoration. J. Arid Environ. 74, 987–990.

Ma, B.L., Dwyer, L.M., Costa, C., Cober, E.R., Morrison, M.J., 2001. Early prediction of soybean yield from canopy reflectance measurements. Agron. J. 93, 1227–1234.

Mahalleh, J.K., Heidari, H., Abad, S., Farrokh, G.N., Haravan, I.M., Valizadegan, E., 2011. PhD student of Agronomy of Science And Research Branch, Islamic Azad University(IAU). Scientific members of Science And Research Branch, Islamic Azad University(IAU). 3 Scientific member of Khoy Branch, Islamic Azad University. 5, 2579–2587.

Mohan, D., Pittman, C.U., Bricka, M., Smith, F., Yancey, B., Mohammad, J., Steele, P.H., Alexandre-Franco, M.F., Gomez-Serrano, V., Gong, H., 2007. Sorption of arsenic, cadmium, and lead by chars produced from fast pyrolysis of wood and bark during bio-oil production. J. Colloid Interface Sci. 310, 57–73.

Montour, M.R., Hageman, P.L., Meier, A.L., Theodorakos, P., Briggs, P.H., 1998. EPA method 1312 (synthetic precipitation leaching procedure); leachate chemistry data for solid mine waste composite samples from Silverton and Leadville, Colorado. US Geological Survey,.

Moslemi, Z., Habibi, D., Asgharzadeh, A., Ardakani, M.R., Mohammadi, A., Sakari, A., 2011. Effects of super absorbent polymer and plant growth promoting rhizobacteria on yield and yield components of maize under drought stress and normal conditions 6, 4471–4476. doi:10.5897/AJAR10.462

Nazarli, H., Zardashti, M.R., Darvishzadeh, R., Najafi, S., 2010. The Effect of Water Stress and Polymer on Water Use Efficiency , Yield and several Morphological Traits of Sunflower under Greenhouse Condition 2, 53–58.

Novak, J.M., Busscher, W.J., Laird, D.L., Ahmedna, M., Watts, D.W., Niandou, M.A.S., 2009. Impact of biochar amendment on fertility of a southeastern coastal plain soil. Soil Sci. 174, 105–112.

Omidian, H., Hashemi, S.A., Askari, F., Nafisi, S., 1994a. Modifying acrylic-based superabsorbents. I. Modification of crosslinker and comonomer nature. J. Appl. Polym. Sci. 54, 241–249.

Omidian, H., Hashemi, S.A., Askari, F., Nafisi, S., 1994b. Modifying acrylic-based superabsorbents. II. Modification of process nature. J. Appl. Polym. Sci. 54, 251–256.

Ono, T., Sugimoto, T., Shinkai, S., Sada, K., 2007. Lipophilic polyelectrolyte gels as super-absorbent polymers for nonpolar organic solvents. Nat. Mater. 6, 429–433.

Oraee, A., Moghadam, E.G., 2013. The effect of different levels of irrigation with superabsorbent (S . A . P) treatment on growth and development of Myrobalan (Prunus cerasifera) seedling 8, 1813–1816. doi:10.5897/AJAR12.1649

Parry, M., Arnell, N., Hulme, M., Nicholls, R., Livermore, M., 1998. Adapting to the inevitable. Nature 395, 741.

Peng, X., Ye, L.L., Wang, C.H., Zhou, H., Sun, B., 2011. Temperature-and duration-dependent rice straw-derived biochar: Characteristics and its effects on soil properties of an Ultisol in southern China. Soil Tillage Res. 112, 159–166.

Po, R., 1994. Water-absorbent polymers: a patent survey. J. Macromol. Sci. Part C Polym. Rev. 34, 607–662.

Postel, S.L., Daily, G.C., Ehrlich, P.R., 1996. Human appropriation of renewable fresh water. Sci. Pap. Ed. 271, 785–787.

Rowe, E.C., Williamson, J.C., Jones, D.L., Holliman, P., Healey, J.R., 2005. Initial tree establishment on blocky quarry waste ameliorated with hydrogel or slate processing fines. J. Environ. Qual. 34, 994–1003.

Russell, G.A., Gregonis, D.E., Visser, A.S.D., Andrade, J.D., 1976. Hydrogels for Medical and Related Applications, in: ACS Symposium Series, Ser. p. 139.

Sarvaš, M., Pavlenda, P., Takáčová, E., 2007. Effect of hydrogel application on survival and growth of pine seedlings in reclamations. J Sci 53, 204–209.

Serrano, L., Filella, I., Penuelas, J., 2000. Remote sensing of biomass and yield of winter wheat under different nitrogen supplies. Crop Sci. 40, 723–731.

Shangguan, Z., Shao, M., Dyckmans, J., 1999. Interaction of osmotic adjustment and photosynthesis in winter wheat under soil drought. J. Plant Physiol. 154, 753–758.

Singh, A.K., Singh, K.M., Bhatt, B.P., 2014. Efficient water management: way forward to climate smart grain legumes production. Available SSRN 2510911.

Singh, M.C., Kumar, R., Parmar, B.S., 2007. Performance of a New Superabsorbent Polymer on Seedling and Post Planting Growth and Water Use Pattern of Chrysanthemum Grown under Controlled Environment 43–50.

Sivapalan, S., 2006. Benefits of treating a sandy soil with a crosslinked-type polyacrylamide. Anim. Prod. Sci. 46, 579–584.

Solaiman, Z.M., Blackwell, P., Abbott, L.K., Storer, P., 2010. Direct and residual effect of biochar application on mycorrhizal root colonisation, growth and nutrition of wheat. Soil Res. 48, 546–554.

Spokas, K.A., 2010. Review of the stability of biochar in soils: predictability of O: C molar ratios. Carbon Manag. 1, 289–303.

Stahl, J., Cameron, M., Haselbach, J., Aust, S., 2000. Biodegradation of superabsorbent polymers in soil. Environ. Sci. Pollut. Res. 7, 83–88. doi:10.1065/espr199912.014

Steiner, C., Teixeira, W.G., Lehmann, J., Nehls, T., de Macêdo, J.L.V., Blum, W.E.H., Zech, W., 2007. Long term effects of manure, charcoal and mineral fertilization on crop production and fertility on a highly weathered Central Amazonian upland soil. Plant Soil 291, 275–290.

Sutherland, G.J., Haselbach, J., Aust, S., 1997. Biodegradation of crosslinked acrylic polymers by a white-rot fungus. Environ. Sci. Pollut. Res. 4, 16–20. doi:10.1007/BF02986258

Taban, M., Movahedi Naeini, S.A.R., 2006. Effect of aquasorb and organic compost amendments on soil water retention and evaporation with different evaporation potentials and soil textures. Commun. Soil Sci. Plant Anal. 37, 2031–2055.

Tennakoon, S.B., Hulugalle, N.R., 2006. Impact of crop rotation and minimum tillage on water use efficiency of irrigated cotton in a Vertisol. Irrig. Sci. 25, 45–52.

Teodorescu, M., Lungu, A., Stanescu, P.O., 2009. Preparation and properties of novel slow-release NPK agrochemical formulations based on poly (acrylic acid) hydrogels and liquid fertilizers. Ind. Eng. Chem. Res. 48, 6527–6534.

Trijasson, P., Pith, T., Lambla, M., 1990. Hydrophilic polyelectrolyte gels by inverse suspension, in: Makromolekulare Chemie. Macromolecular Symposia. Wiley Online Library, pp. 141–169.

Turan, E., Caykara, T., 2007. Swelling and network parameters of pH-sensitive poly (acrylamide-co-acrylic acid) hydrogels. J. Appl. Polym. Sci. 106, 2000–2007.

Uno, Y., Prasher, S.O., Lacroix, R., Goel, P.K., Karimi, Y., Viau, A., Patel, R.M., 2005. Artificial neural networks to predict corn yield from Compact Airborne Spectrographic Imager data. Comput. Electron. Agric. 47, 149–161.

Van Cottem, W., 1999. Addressing desertification: combination of traditional methods and new technologies for sustainable development, in: Int. Conf.''integrated Drought Management for Sub Saharan Africa.

Van Genuchten, M.T., 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44, 892–898.

Vouillot, M.O., Huet, P., Boissard, P., 1998. Early detection of N deficiency in a wheat crop using physiological and radiometric methods. Agronomie 18, 117–130.

Wanas, S.A., 2006. Water and Fertilizer Use Efficiency by Cucumber Grown under Stress on Sandy Soil Treated with Acrylamide Hydrogels . 2, 1293–1297.

Xie, J., Liu, X., Liang, J., 2007. Absorbency and adsorption of poly (acrylic acid-co-acrylamide) hydrogel. J. Appl. Polym. Sci. 106, 1606–1613.

Xie, J., Liu, X., Liang, J., Luo, Y., 2009. Swelling properties of superabsorbent poly (acrylic acid-co-acrylamide) with different crosslinkers. J. Appl. Polym. Sci. 112, 602–608.

Yang, C., Everitt, J.H., Bradford, J.M., 2008. Yield estimation from hyperspectral imagery using spectral angle mapper (SAM). Trans. ASABE 51, 729–737.

Yazdani, F., Allahdadi, I., Akbari, G.A., 2007. Impact of superabsorbent polymer on yield and growth analysis of soybean (Glycine max L.) under drought stress condition. Pak J Biol Sci 10, 4190–4196.

Zohuriaan-Mehr, M.J., 2006. Super-absorbents. Iran Polym. Soc. Tehran 2–4.

Zohuriaan-Mehr, M.J., Kabiri, K., 2008. Superabsorbent Polymer Materials: A Review. Iran. Polym. J. 17, 451–477.

Zohuriaan-mehr, M.J., Kabiri, K., 2008. Superabsorbent polymer materials: A review 17, 451–477.

Zohuriaan-Mehr, M.J., Kabiri, K., 2008. Superabsorbent polymer materials: a review. Iran. Polym. J. 17, 451.