Development and Evaluation of a Plant-Controlled Capillary-Irrigation System

By

Vanathy Nalliah

A Thesis submitted to the Faculty of Graduate Studies of
The University of Manitoba
In partial fulfilment of the requirements of the degree of

MASTER OF SCIENCE

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ABSTRACT

The increasing scarcity and competition for water resources has motivated irrigated-agriculture towards developing different innovative irrigation techniques to improve irrigation efficiency. A capillary-irrigation system can offer better irrigation efficiency compared to the conventional irrigation systems by maintaining desired soil moisture that is adequate for plant growth and allowing irrigation only when necessary.

A plant-controlled capillary-irrigation system was designed, and the influence of the system was investigated on the performance of two different plants (hot pepper (*Capsicum annuum*) and marigold (*Tagetes patula* L.) under a controlled environment. Four treatments were established where plants were subjected to three capillary pressures (-0.2, -0.4, and -0.6 m) and a manual irrigation as control. The plant's vegetative growth in terms of plant height, leaf count, and leaf area were recorded periodically. The plant yield (fruits and flowers) and biomass yield together with water use efficiency (WUE) were also used to assess the plant performance.

The plant's vegetative growth and biomass yield in the lower capillary pressure irrigation (-0.2 m) treatment were significantly greater ($P<0.05$) than in the higher capillary pressure (-0.4 and -0.6 m) treatments. This may have been a consequence of the water stress during the critical periods of plant growth in the higher capillary pressure treatments. There was no significant difference in vegetative growth between the control and lower capillary pressure irrigation treatment.

The control treatment used more water than the capillary-irrigation treatments. Comparing the lower pressure capillary-irrigation to the control treatment, water savings of 33% and 35% were attained for marigold and pepper production, respectively. The water savings were even higher (58% to 73%) for the higher capillary pressure irrigations. However, the plant growth and yields were negatively correlated to the capillary pressure. In general, compared to the high capillary pressure irrigation, the lower capillary pressure irrigation treatment was more efficient in maintaining better plant yields that is comparable to the control treatment.

Thus, the capillary-irrigation system that uses lower capillary pressure (-0.2 m) represents a promising technology especially for greenhouses, due to the water and labour savings that can be achieved, while maintaining acceptable plant yields and quality.

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DEDICATION

To my late father and my family for their encouragement, support, patience, and help throughout the execution of my graduate studies.

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ABBREVIATIONS

ABA = Abscisic acid

ARDI = Agri-Food Research & Development Initiative

ASABE = American Society for Agricultural and Biological Engineering

ASAE = American Society of Agricultural Engineers

ASCE = American Society of Civil Engineers

CAP = Capsaicinoids

CSBE = Canadian Society for Bioengineering

DI = Deficit irrigation

DICAP = Dihydrocapsaicinoids

FAO = Food and Agricultural Organization

G = Green image band

GIS = Geographic Information System

GLM = General Linear Model

HPLC = High Performance Liquid Chromatography

HW = Hand-watered

LEPA = Low-energy precision-application

LSD = Least Significant Difference

NSERC = Natural Science and Engineering Research Council

P = Probability

R = Red image band

RG^{-1} = Red green ratio

RGB = Red green blue regions of the electromagnetic spectrum

ppm = parts-per-million

PRD = Partial root zone drying

psi = Pound per square inch

SDI = Subsurface drip irrigation

SI = Subsurface irrigation

SHU = Scoville Heat Units

WUE = Water use efficiency

CHAPTER 1 : INTRODUCTION

1.1 General

Water is often the limiting input in crop production. Irrigated agriculture plays an essential role in crop production in arid climatic zones. In areas receiving moderate rainfall, irrigation provides the supplemental needs. A limited quantity and quality of water resources and a growing competition for water makes it less available for irrigation. In order to meet the increasing food requirements, it is important to increase the crop production with less water.

In 2001, the agricultural sector was the fourth largest water user in Canada. It accounted for 9% of all the water used in Canada (Statistics Canada 2003; Environment Canada 2008). The total amount of agricultural water use in 2001 was 4.8 billion cubic metres (Beaulieu et al. 2007). According to Statistics Canada (2003), irrigation accounted for 92% of the total national agricultural water use in 2001.

Increasing competition for water among municipal and industrial sectors will steadily reduce its allocation for irrigation. Therefore, to meet this challenge, more efficient irrigation systems are needed. There are different methods of irrigation that have led to an increase in water application efficiency by delivering water to crops more precisely. In this context, compared to less efficient traditional surface irrigation methods, micro irrigation can play a vital role in increasing water use efficiency while minimizing adverse impact on yield. All irrigation methods that provide more frequent water application in small flow rates either on or below the soil surface are referred to as micro irrigation (Haman and Izuno 1989).

Micro irrigation includes mainly sprinkler, drip, and subsurface irrigations. In

2001, 49.8% of the farms in Canada used sprinkler irrigation, 23.2% used the travelling gun, 13.1% used the drip system, and only 13.8% of the farms used other irrigation systems such as flooding and subsurface irrigation (Statistics Canada 2007). The subsurface irrigation methods are preferable to surface methods because of their ability to precisely control the amount of water applied. The subsurface irrigation, unlike surface irrigation, delivers sufficient water directly to the root zone of the plant and therefore reduces evaporation, runoff, and deep percolation losses from the soil surface. It also minimizes the risks of foliage diseases and weed growth while improving the water and nutrient management, and thus improving yields and crop quality (Skaggs 2001; Shu et al. 2007). Further, Camp et al. (2000) stated that crop yields using subsurface irrigations such as drip irrigation were equal or greater when compared to the yields from surface irrigation including surface drip irrigation. Therefore, improving the efficiency of subsurface irrigation using different innovations will be beneficial in crop production not only for improving the crop yield but also for saving a substantial amount of water.

The conventional subsurface irrigation system requires precise pressure control to attain uniform water application through each of the emitters. Maintaining precise pressure control is a difficult task in the field. This problem can be overcome by using negative pressures instead of positive pressures in subsurface irrigation. In this technology, the water leaving the porous tube is at less than atmospheric pressure and it is drawn out of the pores by capillary action of the surrounding soil. When the plants evapotranspire, the soil becomes dry and the soil water potential decreases. The reduced soil water potential acts as a driving force to draw the water from the porous tube (Jiang et al. 2004). Few studies have examined the performance of a negative pressure subsurface irrigation system in crop production (Livingston 1918; Richards and Loomis 1942; Moinat 1943; Read et al. 1962; Kato and Tejima 1982; Iwama et al. 1991; Liu et al. 2000). These studies mainly used porous clay cups or porous ceramic pipes with or without electrical pumps to regulate the negative pressure in the irrigation system. The productive response of plants under different negative pressures in the system was not reported. Studies on practical application of this irrigation system are limited (Liu et al. 2000).

In the context of improving the efficiency of negative pressure subsurface irrigation, a capillary-irrigation system was developed, whereby the water is drawn into the root zone from the system exclusively by the plant water demand. The proposed system consists of a hydrophilic polyethersulfone membrane placed directly in the soil near the plant's root zone to assist the water movement from the water reservoir to the soil. Unlike some of the previous studies on capillary-irrigation systems, the present system needs neither the energy to pressurize the system nor the sophisticated equipment and skilled labour to monitor the system.

1.2 Objectives

The primary objective of this research was to compare the growth performance of plants using capillary-irrigation systems operating under different capillary pressures with a hand-watered control treatment. The specific objectives were:

1. To assess the performance of a capillary-irrigation system under different capillary pressures by studying the productive response of plants to the irrigation system, analyzing also the quality of plant products (hotness of pepper fruits).

2. To determine the operational capillary pressure of the system that gives plant performance comparable to that of manual irrigation.
3. To compare the water use efficiency of different capillary pressures in capillary-irrigation for better growth of container-grown plants.

1.3 Scope

In order to facilitate the precise monitoring of individual plant water uptake, the plants had to be grown in containers. All the tests were carried out in a laboratory under controlled conditions. Hot pepper was chosen as the high value crop for testing. Marigold was chosen as an ornamental plant that is commonly grown in greenhouses as a bedding plant.

1.4 Thesis Organization

This thesis has been written in the manuscript style as outlined by the Department of Biosystems Engineering, University of Manitoba. The thesis has six major chapters. Chapter one provides the general introduction, main objectives of the research and defines the scope. Chapter two presents a review of literature on overview of irrigation systems, types of improved irrigation methods, advantages and disadvantages of subsurface irrigation, plant response to water stress, and environmental impact of irrigation development. Chapter three and four consist of two manuscripts, each having an abstract, introduction, materials and methods, results and discussion, and conclusions. In chapter three, the yield and quality of hot pepper grown under different capillary pressures was compared to hand-watered hot pepper plants. Chapter four focuses on the growing of marigold, an ornamental plant, using a capillary-irrigation system under different capillary pressures. Chapters three and four also explain an image analysis technique for non-destructively measuring the plant leaf area. Chapter five summarises the main findings of this research and chapter six outlines recommendations for future research. All the references for this thesis including the two manuscripts have been provided at the end of this thesis.

CHAPTER 2 : LITERATURE REVIEW

2.1 An Overview of Irrigation Systems

The major purposes of irrigation are to increase the crop yields and to improve the crop quality. Irrigation of high-value crops such as vegetables and fruits is generally more profitable than irrigation of corn and pasture (Turner and Anderson 1971). However, yields may vary according to different climate, soil, and crop varieties. In order to ensure the best performance of an irrigation system it is also important to use good management practices. Good management practices include planting recommended varieties, providing proper cultivation techniques, controlling insects and pests, and applying the right fertilizers with proper amounts at the right time.

Frequent irrigation of a sufficient quantity of water helps to increase crop yields (Hillel 2004). This can be achieved by maintaining a high level of moisture content in the root zone at all times during the growing season with no severe water stress. Micro irrigations have the potential to provide these favourable conditions compared to the traditional surface irrigation methods. It is capable of optimizing soil moisture, fertility, salinity, and aeration simultaneously (Hillel 2004). Micro irrigation refers to a variety of irrigation methods including drip, micro sprayers, low-intensity sprinklers, and subsurface irrigation.

Evaporation and deep percolation losses are substantial in conventional irrigation methods i.e., surface irrigation. In contrast, in irrigation systems like drip, where water application is limited to a confined soil volume at the root zone, the water applied can be matched to transpiration losses of plants. Further, subsurface drip irrigation (SDI) system can virtually eliminate the evaporation losses from the soil surface.

The basic function of the soil is to serve as a water storage medium. When an irrigation system provides small amounts of water more frequently, the soil volume may not be a significant factor for storing water between irrigations. Since an SDI system can provide fertigation to a confined volume of root zone, it is possible to simultaneously replenish the water and nutrients that are removed by the crops. It would thus be beneficial in terms of soil fertility.

Crop rooting pattern is influenced by the type of irrigation system used. Normally irrigation tends to produce high concentration of roots near the soil surface and limit the root penetration vertically (Charles 1975). When using conventional irrigation methods, there is a possibility for roots from adjacent crops to overlap in the process of scavenging for water and nutrients. In systems like SDI, the rooting system is restricted to the wetted volume of soil and the highest root concentration will be observed in the zone of readily available water and aeration.

The water use efficiency can be improved by genetic modification of plants, which is a long-term solution for efficient use of water (Zobel 1983). Plant breeders are interested in developing more-productive drought-resistant varieties that thrive under low moisture conditions especially under current climate change conditions. However, it will be a long-term effort to develop plants with improved water-use characteristics and it has to be done jointly by a plant-breeder, crop physiologist, and a soil-crop management scientist (Heichel 1983). Breeding for water stress or drought resistance has already been initiated in different crops such as beans and rice (Frahm et al. 2004; Bernier et al. 2008).

Using industrial or municipal wastewater and brackish water, and reusing agricultural drainage water in irrigation are excellent water-use alternatives to alleviate water scarcity (Patel et al. 2003; Bolanos et al. 2005). Patel et al. (2003) reported that brackish water could be used in sub-irrigation to produce green peppers and potatoes especially without significant yield reduction under semiarid and arid conditions. Although the irrigation system may need wastewater treatment units to attain certain water quality requirements for irrigation, it will be a novel technology particularly in micro irrigation.

2.2 Types of Improved Precision Water Application Systems

2.2.1 Subirrigation

Subirrigation, also sometimes referred to as water table management, has been in practice for several years in field crops especially in areas where there are high water tables. Irrigation in this method is accomplished by artificially controlling the water table using a subsurface drainage system. In subirrigation, water is furnished directly below the plants' root zone by capillary action from the saturated portion of the soil profile commonly known as perched water table. The wetted soil profile can be obtained after wetting the soil by quickly raising and lowering the water table or by using a buried perforated or porous pipe system that supplies the water directly into the plant root zone (Ahmed et al. 2000; Burt et al. 2000; Dumroese et al. 2006). Using a system of canals, weirs, gates, and pumping systems, the water level in a network of subsurface ditches or pipe drain is raised or lowered, thereby controlling the water table height. The subirrigation is commonly used in most medium to shallow rooted crops or orchards (Burt et al. 2000).

Subirrigation systems are also adopted in commercial greenhouse production, usually in container-grown plants. There are three types of re-circulating subirrigation systems, namely ebb-and-flow benches, trough benches, and flooded floor systems. In the ebb-and-flow system, a shallow bench top is used to hold the plants and it is flooded to irrigate and fertilize the plants. Following the irrigation, the excess solution drains from the bench back to a storage tank for reuse. The trough system is operated by applying a film of irrigation water down to a slightly inclined, shallow trough that holds the plants. In the flooded floor systems, the entire concrete covered floor of the greenhouse is flooded from a carefully designed pitch toward flood or drain openings in the floor. When flooding is completed, the remaining solution drains back to a storage tank.

The subirrigation system minimizes labour requirements for irrigation. Additionally, the system can save considerable amount of water and fertilizer by re-circulating the water and not losing them by leaching or runoff. Moreover, the subirrigation ensures uniform plant growth and less foliar diseases. The increased plant uniformity is ascribed to even and thorough wetting of the growth medium and better distribution of nutrients taken up by capillary flow. Keeping the foliage dry with subirrigation probably results in less foliar diseases. However, the greatest challenge in subirrigation is the high initial cost for the system installation. The system is only suited to soils that drain quickly with a higher water table and moreover, it increases the accumulation of fertilizer salts in the upper portions of the root zone.

2.2.2 Partial root zone drying (PRD)

The partial root zone drying (PRD) is a relatively new water-saving irrigation strategy whereby only a part of the root system is wetted at each time of irrigation, and the balance is left to dry to a pre-determined level and the wet and dry sides are periodically changed (Zegbe et al. 2004). The dry part of the root enhances the production of a plant hormone, abscisic acid (ABA) (Stoll et al. 2000), and results in stomatal closure which leads to reduction in leaf transpiration (Davies et al. 2000). However, the other half of the well-watered root ensures the maintenance of the reproductive growth, while vegetative growth is reduced. Repeated flows of ABA to the shoots due to alternating the wet and dry zones of the roots maintain reduced shoot growth and transpiration with no significant effects on flowering and fruit development. The prediction of rewetting frequency under PRD is in practice identified from the rate of soil moisture depletion or the estimation of plant water use based on evaporative conditions or from the sap flow measurements (Kriedemann and Goodwin 2003). The system requires close monitoring of soil water content and thus high management skill is essential.

The PRD is designed to improve water use efficiency by limiting the vegetative vigour usually in perennial crops such as grapevines and fruit trees (Spreer et al. 2007). Loveys et al. (2000) stated that the PRD could save up to 50% of water while maintaining yield as shown for some cultivars of grape. The PRD can be applied to crops using drip and flood irrigation systems. It is not suitable for deep clay soils, where the wetting of root zone will not be fast enough to meet the demand of canopy transpiration. In addition, not enough roots on the drying side dry fast enough to generate sufficient root signals to produce ABA. Maintaining a clear separation between wet and dry roots is difficult on clay soils due to increased lateral spread of wetted zones. Also, the root function can be impaired by poor aeration after re-wetting and greater soil strength after drying the root zone.

2.2.3 Deficit irrigation (DI)

Deficit irrigation, also known as regulated deficit irrigation, is a promising practice for improving water savings with no loss in crop yields. It is a new irrigation technique, where "the plant water status is maintained within prescribed limits of deficit with respect to maximum water potential for a prescribed part or parts of the seasonal cycle of plant development" (Kriedemann and Goodwin 2003). Rewetting time after a decrease in plant water potential below a prescribed limit will be determined using soil moisture depletion or estimates of plant water use based on evaporative conditions or measurement of sap flow (Kriedemann and Goodwin 2003). The DI can be practiced using micro irrigation systems like micro sprinklers and is popular for perennial crops such as grapevines and fruit trees (Kriedemann and Goodwin 2003; Spreer et al. 2007).

In order to ensure the success of DI, it is not only important to know crop yield responses to water stress, but it is also necessary to consider the water holding capacity of the soil (Kirda 2002). This is because compared to low yielding crop varieties, high yielding varieties are more sensitive to water stress. In addition, coarse textured soils may undergo water stress more easily than fine textured soils under DI. However, heavy soils like clays are extremely difficult to manage under DI because they take a long time to dry out at the beginning and are then more difficult to rewet after drying. Further, rainfall events throughout the crop-growing season pose a problem for drying the soil and producing a deficit response in crops. When practicing DI, it may require modifying some of the agronomic practices such as reducing plant density, selecting shorter-season varieties, applying less fertilizer, and adopting flexible planting dates.

In DI, the water application is altered over time whereas in PRD it is altered over space. Additionally, application timing for DI is critical, unlike PRD where timing is flexible. Also, only uppermost soil profile is rewetted in DI but deeper wet/dry zones are spatially separated in PRD. These two irrigation methods however, give a similar outcome, which is that they limit vegetative growth with increased water use efficiency for crop production. Therefore, adopting a DI or a PRD system would lead to substantial water savings in irrigation.

2.2.4 Low-energy, precision-application (LEPA) system

The low-energy, precision-application (LEPA) irrigation concept was developed in order to establish a system that would reduce the energy requirements and increase the irrigation efficiencies and uniformity of center pivot systems. The system consists of a moving truss system with water delivery tubes or drop tubes extending from the system mainline to near the soil surface (Bordovsky et al. 1992). A very low-pressure regulated nozzle is attached to the drop tubes and located at a height of 5 to 10 cm above the furrow to discharge the water directly onto the furrows (Lyle and Bordovsky 1983). This helps to reduce water losses from wind drift and evaporation, phenomena that are common in sprinklers and avoids the wetting of the leaves. The LEPA has sometimes been described as a hybrid between center-pivot and drip irrigation (Gerston 2000). The bubbling of the irrigation water from the LEPA system reduces spray drift losses. The LEPA has been successfully applied to row crops such as cotton, sorghum, corn, and soybean (Yazar et al. 2002). Gerston (2000) reported that the LEPA system offers 95% to 98% of efficiency compared to sprinklers, which has 75% efficiency. He further stated that the LEPA system uses very low operative pressures (< 6 psi) compared to high pressures (> 65-85 psi) for sprinklers. However, high initial system cost and frequent replacement of many system components are two major concerns in this system.

According to the applicator type and the height of the applicator above the furrow, the low pressure-irrigation system is classified into three types including the LEPA. The other two systems are LESA (low elevation spray application) and MESA (medium elevation spray application). The LEPA systems apply water directly to the soil surface; whereas both LESA and MESA systems spray water on to the crop canopy. The irrigation efficiency of LEPA, LESA, and MESA is 95 - 98%, 85 - 90%, and 65 - 75%, respectively (Gerston 2000).

2.2.5 Subsurface drip irrigation (SDI)

The subsurface drip irrigation (SDI), a part of drip irrigation, is an efficient irrigation technique that increases crop yields and quality, improves soil and water conservation, and reduces environmental degradation. It is a low-pressure irrigation system where polyethylene tubing or drip lines are buried below the soil surface to drip the water directly to the crop root zone (Payero et al. 2005). The applied water moves in the soil profile by soil matrix suction eliminating ponding. Further, the lateral spread of water throughout the soil profile maximizes the wetted root volume while minimizing the percolation losses. In order to maintain proper irrigation uniformity under varying field conditions, drip lines of different diameter and thickness are used in the system. Unlike sprinklers or furrow systems, smaller pumps will be used to maintain desired operative pressure (4-15 psi) for SDI system (Payero et al. 2005). The SDI has been found to be suitable not only for field crops but also for greenhouses and gardens where it offers labour-saving automation. Although initially SDI systems were applied primarily for vegetables, fruits, and nuts, later they have been spread out to agronomic and forage crops such as cotton, corn, and alfalfa (Camp et al. 2000).

The SDI system ensures the delivery of very small amounts of water, which can save energy and minimize the leaching of chemicals compared to conventional surface irrigation systems. The SDI presents a viable technology to use brackish water and treated effluent for irrigations while simultaneously saving the water and meeting the irrigation requirements for better crop yields (Badr and Taalab 2007; Mark Kahl 2007). Since the irrigation takes place below ground, it reduces odour and ammonium losses compared to any other surface irrigation methods. However, there are some drawbacks in SDI including high initial investment cost, clogging of emitters, need for well-trained labour, and periodic system maintenance. Since the SDI systems discharge water from point sources, it forms water-saturated anaerobic areas in the plant root zone that are not suitable for plant growth. Adoption and success of SDI for a long system life depends on proper design, installation, operation, and maintenance of the system.

2.2.6 Capillary-irrigation

Capillary-irrigation or negative pressure irrigation is one of the subsurface irrigation methods in which the irrigation system utilizes capillary pressures/negative pressures to transmit water from the reservoir to a plant. The practical application of this technique is becoming increasingly popular in crop production, even though this concept has long been discussed (Livingston 1908). Porous/perforated pipes or porous membranes that are located directly in the plant root zone provide a means of manipulating negative pressures in the system. These porous emitters are specially designed to transmit water but not allowing air into the system. The water in the porous emitters is held just below the root zone. Since the emitters are kept above the air inlet point of water reservoir, the water will not freely flow out of the emitters unless there is a driving force exerted from the dry soil. When the soil becomes dry due to transpiration and evaporation, the soil water pressure becomes increasingly negative. The higher negative pressure of the soil water acts as a driving force to draw the water from the water reservoir by capillary action.

Capillary action is the process where the water movement from one soil particle to another takes place due to a stronger adhesive intermolecular force between water and soil particle compared to a weaker cohesive intermolecular force between water molecules. The direction of this action can be upwards, sideways, or downwards. Unlike SDI, capillary-irrigation creates a wide and continuous wetting pattern providing all plants equal access to water and air. A larger volume of moist, unsaturated soil under this irrigation leads to greater nutrients and oxygen availability for plant roots.

This method of irrigation makes it possible to activate irrigation using plant responses to water. Using the plants' water status as feedback for manipulating the irrigation would be the most accurate way for controlling the irrigation system (Prenger et al. 2005). This plant-water status control system enables irrigation automation. As a result, the system automatically controls and adjusts the required amount of irrigation to meet the demands of various plants subjected to different environments. Further, this would help to eliminate the possibility of over- or under- irrigation. Over-irrigating crops result in water wastage and it increases expense for pumping energy, and disease and pest incidents due to damp conditions. On the other hand, under-irrigating crops leads to high water stress in crops that in turn results in poor crop yield. An automated irrigation system not only facilitates high crop yields, more water, energy, and labour savings but it is also result in greater precision, more efficient use of water as a result of high frequency and low volume irrigation compared to manual systems (Abraham et al. 2000).

Therefore, using capillary-irrigations, accurate water management in crop production can be accomplished by irrigating when necessary and in the right amount. This system is both simple and economical and it presents a potential opportunity for efficient irrigation. Few studies have reported the responses of capillary-irrigation on plant growth and production (Richards and Loomis 1942; Moinat 1943; Read 1962; Liu et al. 2006).

2.3 Advantages of Subsurface Irrigation

Subsurface irrigation, a breakthrough in irrigated agriculture, is now becoming a reality. It delivers water and other nutrients directly below the soil surface. It offers significant benefits to the growers or to the horticulturists and McNamara (1970) stated that there are substantial indications for each of these benefits of subsurface irrigation to prove its usefulness.

2.3.1 Increased water use efficiency

The ability of subsurface irrigation to provide small irrigation amounts below ground can greatly reduce or eliminate soil evaporation, surface runoff, and deep percolation. Reduced runoff into streams and reduced deep percolation leads to lower nutrient and chemical leaching and that in turn eliminates environmental problems such as soil erosion and pollution of surface and groundwater resources. The subsurface irrigation with smaller and more frequent applications helps to maintain optimum soil moisture content in the root zone, which is especially important for shallow rooted crops (Burt et al. 2000).

Payero et al. (2005) reported that the water use efficiency of SDI systems can be very high (95% or higher) and that means for every inch of water pumped, 0.95 inch or more water remains in the crop root zone. Since the system distribution uniformity depends only on hydraulics and equipment design instead of depending on management and soil variability, the distribution uniformity of the system can also be very high (93% or higher) (Burt et al. 2000). As a result of the potential high irrigation efficiency that can be achieved through subsurface irrigation, it can be a better alternative for areas where water is scarce.

2.3.2 Enhanced crop yield and quality

The subsurface irrigation system is capable of providing a small volume of water more frequently. It also can be used to supply fertilizers and other chemicals such as pesticides with water. The planting density can be increased by using subsurface irrigation. The inherent ability of small and frequent applications enables the system to adjust and match the supply of water and nutrients according to the needs of crops. Further, significant yield increases in many vegetable crops using SDI have long been reported (Ayars et al. 1999; Camp et al. 2000).

2.3.3 Improved plant health

Providing the irrigation below ground and keeping the soil surface dry results in drier soil surface and less-humid canopies above ground. It reduces the potential for plant diseases, weed germination and weed growth. Disease-affected plants can induce transpiration losses through external mycelium, blocked xylem transport, or destroyed root system (Loomis 1983). Hence, healthy crops make better use of water compared to crops that are subjected to disease, pest, and weeds.

2.3.4 Improved fertilizer and pesticide application efficiency

Fertilizer and other chemicals such as pesticides can be directly applied uniformly to the plant root zone at any stage of growth, any time, and at any quantity especially without wetting the plant foliage. McNamara (1970) stated that when using surface liquid ammonia application, over 50% of the ammonia was lost to the atmosphere before reaching the crop. The subsurface irrigation can minimize the runoff and deep percolation losses and as a result, fertilizer contamination of ground water and run off streams would be virtually eliminated. Precise and timely application of fertilizer and other chemicals according to crop demand, using a subsurface irrigation system not only provides greater efficacy but also reduces their use.

2.3.5 Shorter growing season

The subsurface irrigation can induce early crop maturity and shorten the crop-growing season (McNamara 1970). The shorter growing season means that the product will be on the market earlier before the competition for that product arises and that is the premium price time (McNamara 1970). A shorter growing season can also permit double cropping opportunities because the systems need not be removed or re-installed between crops.

2.3.6 Reduced energy and labour cost

Subsurface irrigations often deliver water at small flow rates with relatively low operating pressures. Hence, subsurface irrigation systems can be operated without pumps compared to sprinkler or furrow irrigation systems. Srivastava et al. (2003) reported significant energy savings by shifting from surface irrigation to drip irrigation.

The subsurface irrigation system can be operated automatically using sensors and specialized controllers and thus it can considerably reduce the labour requirements. After the system is properly installed, the manual irrigation labour is reduced to near zero. In addition, most components used in the system are plastic and less subject to corrosion. The system need not to be removed and re-installed between crops and thus long system life enables amortizing initial investment costs over several years.

2.4 Disadvantages of Subsurface Irrigation

However, there are certain situations that present difficulties in using subsurface irrigation systems and they are discussed below.

2.4.1 Soil wetting pattern

Soil characteristics are important in any irrigation system since they influence the water-intake rate, the water-holding capacity, and the fertility of the soil. For example, fine textured soil has low water-intake rate and high water-holding capacity, whereas coarse textured soil has high water-intake rate and low water-holding capacity. Although the subsurface irrigation has been used on virtually all soils, coarse textured soils may have too small a wetting pattern, which leads to too small a crop root zone. This can further lead to insufficient irrigation capacity and make the system reliability critical. If the water application rates exceed the infiltration rates of the soil, a saturated zone or undesirable wet spots will develop on the soil surface. It produces a chimney effect that favours a preferential flow path, which may be difficult to remove permanently (Lamm 2002; Payero et al. 2005).

2.4.2 Plant development

Seed germination using a subsurface irrigation system may be limited due to the installation depth and soil characteristics. Below ground irrigation systems keep the soil surface dry and as a result, seed germination and early growth can be limited by water stress. This limitation is evident especially in sandy soils, where little water movement occurs upward in the soil profile. In such cases, a backup irrigation system may be required to promote seed germination. Moreover, when the crop root zone is relatively small, it may not be enough to avoid crop water stress diurnally, even though the root zone is well watered. Lamm (2002) stated that under some soils and environmental conditions, some crops might not be able to develop properly. Tree crops for example, may grow well under larger soil-wetting patterns instead of smaller patterns.

2.4.3 Monitoring and evaluation of irrigation events

Since the irrigation system is placed underground, water applications may mostly be unseen. That results in difficulties to monitor and evaluate the system operation and application uniformity. It can be more difficult to locate system failures, particularly for deeper subsurface irrigation systems. If the system is mismanaged, under- or over-irrigation may take place. Over-irrigation leads to poor soil aeration and deep percolation losses. Both under-irrigation and over-irrigation leads to reduction in crop yield and quality.

2.4.4 Soil salinity

Salt accumulation with time is an important concern in subsurface irrigation. Although it may take a relatively longer time to spread, it is advisable to use good quality water for irrigation. However, this problem may not occur in areas receiving sufficient rainfall that helps to leach the salts downward in the soil profile. Salinity reduces the availability of soil moisture leading to increased plant water stress.

2.4.5 Costs

Initial investment cost is high for most of the subsurface irrigation systems compared with other irrigation systems. Payero et al. (2005) stated that cost per acre for using SDI system varies greatly according to field size, shape, water source location, and the desired level of automation. They suggested that the SDI system could be a better option for small fields compared to large fields, particularly when irrigation water is limited.

However, the capital expenditure on the subsurface irrigation system can be offset by the reduction in size of pumping unit, decreased energy and labour requirement, increased system longevity, and increased yield. The system can be economically viable when considering the need to save water and to protect the environment from the negative impacts of irrigation.

2.5 Plant Responses to Water Stress

This sub-section covers a very broad subject but the intention of this review is to select only areas that are closely related to plant modification for efficient use of water. Drought or water stress is one of the environmental stressors that affect plants at the cellular level as well as the whole plant and cause serious economic losses in agriculture. The effect of stress at the whole plant level is associated with reduction in photosynthesis and growth (Mwanamwenge et al. 1999), whereas at the cellular level it is associated with processes such as increases in solute concentration and reductions in turgor pressure. Stress responses can either be in the forms of avoidance or in the forms of tolerance mechanisms (Sullivan and Eastin 1974).

A drought-avoiding plant can maintain high plant water potential when subjected to extended water stress. This will be accomplished by means of adjusting their life cycles for dry periods and conserving the available water to use them over dry periods. In order to avoid the drought stress, plants adjust their life cycles by having their germination, vegetative growth, and reproductive growth during favourable moist periods and the dry periods are avoided by passing through dormant states or producing dormant seeds. The conservation of available water in plants for dry periods is accomplished by using three mechanisms (Clarke and Durley 1981): 1) improving water uptake by means of efficient extensive root systems; 2) manipulating transpiration losses by means of reduced leaf area, increased leaf drop, reduced stomatal number and size, and modified leaf configuration and hairiness; and 3) saving water in plant tissues by means of leaves, stems, and roots. Each plant species can have various combinations of the drought-avoiding mechanisms, described above, in their lifecycle.

The ability of plant tissues to withstand water stress is called drought tolerance and it differs greatly depending on plant species and growth stages within the species (Clarke and Durley 1981). Tolerance is negatively correlated with plant development, early seedling stage shows more tolerance to water stress compared to later stages of development (Sullivan and Eastin 1974). The reduction in osmotic potential, normally referred to as osmotic adjustment in plants helps plants to tolerate water stress by maintaining turgor pressure and cell configuration. When the water is lost from the cell, the solute concentration increases and that in turn reduces the osmotic potential and leads to desiccation at severe drought conditions.

Changes in internal water status of cells due to drought include the reduction in cellular water potential, solute potential, and turgor pressure. Consequently, the following changes will take place: decrease in stomatal opening, photosynthesis, leaf expansion, root development, and seed set; increase in leaf senescence, abscission, and inhibition of flowering; and a longer (drought tolerance) or shorter (drought avoidance) lifecycle (Levitt 1972). Many of the above-mentioned processes have been influenced by various hormones. The ABA, for example, reduces stomatal opening, metabolic rate, and seed set under drought conditions. On the other hand, cytokinins and gibberellins react oppositely to ABA and ethylene is responsible for leaf abscission and reduced cell extensibility. By understanding the plant response to water stress, the efficiency of the use of available water can be maximized by means of selecting drought-resistant species, breeding of drought-resistant genotype, and using the most efficient management practices.

2.6 Environmental Impact of Irrigation Development

Irrigation is an important factor in agricultural development. The developments in irrigation to address the problems such as water scarcity and decrease in supply of good quality water may have both positive and negative impacts on the environment. Letey (1994) stated that the sustainability of irrigation can be achieved when irrigation maximizes positive impacts while minimizing negative impacts. Intensifying food production in favourable lands is the positive impact of irrigation (Hillel 2004). This reduces the pressure on marginal lands where rain-fed cultivation or grazing is common and where there is an opportunity for irrigation development. In addition, impoundments and canals for irrigation can offer increased fish habitat and weeds along the canals can give cover and nesting habitat.

The negative aspects of irrigation include ground and surface water degradation due to pollution by leaching, erosion, and percolation of chemicals used in agriculture, and saline water intrusion. Moreover, the generation of drainage water by irrigation is one of the adverse effects in irrigated agriculture (Qadir and Oster 2004). Although generating drainage water is necessary to control soil salinity through leaching, it may contain harmful organic wastes, residues of fertilizers and pesticides, pathogenic organisms, and concentrated salts and lead to poor water quality. There is a potential for health hazards when using polluted open water resources for drinking, washing, and disposing human and animal wastes. Improving the irrigation management by eliminating the excess water application over that needed for evapotranspiration and leaching is one strategy to address these negative impacts of irrigation (Wichelns 2002). The advent of micro irrigation along with a comprehensive approach to soil, water, and crop management will play key roles in sustainable irrigation in a productive environment.

CHAPTER 3 : EVALUATION OF A CAPILLARY-IRRIGATION SYSTEM FOR BETTER YIELD AND QUALITY OF HOT PEPPER (*Capsicum annuum*)

3.1 Abstract

A capillary-irrigation system using porous membrane with different negative pressures was successfully developed and tested by growing jalapeno hot peppers. The water drawn into the root zone from this irrigation system was controlled exclusively by the plant water demand. In order to find a moderately negative pressure that is suitable for jalapeno peppers, three different negative pressure irrigations, namely -0.2, -0.4, and -0.6 m were tested and compared against a conventional manual irrigation. There was no significant difference in number of leaves, plant height, and leaf area between -0.2 m negative pressure and the manual irrigation treatment, but they were significantly lower in the -0.4 m and -0.6 m treatments. A similar trend was also observed for pepper biomass yield. Moreover, pepper fruits were qualitatively analyzed for their hotness or pungency level using high-performance liquid chromatography (HPLC). The results showed that the hotness of fruits in water starved plants were greater than in the plants under sufficient water. In addition, 35% reduction in water consumption was observed in the -0.2 m treatment compared to manual irrigation. Overall, the -0.2 m negative pressure irrigation had better performance in terms of growth and yield parameters when compared to manual irrigation while saving a substantial amount of water. The capillary-irrigation technique offers precise water delivery with minimal labour requirement, which is suitable for use in greenhouse pepper production and in areas with limited water supply and scarce labour.

3.2 Introduction

Water conservation has become important for meeting the increasing demands for food for a growing population. It is not only imperative for areas experiencing severe climatic conditions, but also vital for areas having plenty of water where there is competition for water among the different users. Agricultural sector is under great pressure to improve the sustainability of water resources by improving the efficient use of water. To face the significant challenges in irrigated agriculture, micro irrigation is being used as the most efficient irrigation system in providing water to plants (Hills and Brenes 2001; Arbat et al. 2008).

Micro irrigation is a term used to describe all irrigation methods that ensure frequent water application in small flow rates either on or below the soil surface (Haman and Izuno 1989). There are different types of micro irrigation systems based on the type of emitters used in the system. These are drip, bubbler, spray jet, and subsurface system (ASAE 1984). In Canada 49.8% of the farms with irrigation in 2001 used sprinkler irrigation, 23.2% used the travelling gun, 13.1% used the drip system, and 13.8% used other irrigation systems such as flooding and subsurface irrigation (Statistics Canada 2007). Subsurface irrigation has become a well-established method for irrigating fruits and vegetables during the last 20 years (Camp et al. 2000). It applies water directly to the plant root zone more precisely and uniformly. Hence, it minimizes water losses. Several studies have investigated crop yields using subsurface irrigation such as drip irrigation and reported that the yield was equal or greater with reduced water application when compared to the yield from surface irrigation (Ayars et al. 1999; Camp et al. 2000).

Subsurface irrigation has some potential advantages over surface irrigation. They include lower risk of evaporation, runoff, and deep percolation losses from the soil surface; greater savings of water, nutrient, and labour; fewer chances of foliar diseases; and more uniform plant growth. In addition, the subsurface irrigation is very adaptable to different soil conditions, and it optimizes the use of fertilizer and other chemical applications, lowers the rate of weed growth (Skaggs 2001; Shu et al. 2007). The subsurface irrigation using negative pressure (capillary-irrigation) can also be considered as a micro irrigation. The principle of an irrigation system running by positive pressure is different from the principle behind the negative pressure irrigation system. Understanding the basic principle of this technique could help to create a better design for the capillary-irrigation system.

In the positive pressure irrigation system, the water source is placed at a higher elevation with respect to the emitters (water delivery points). The pressure can also be developed using a pump to positively pressurize the system. Unlike the positive pressure system, the negative pressure system has its water source below the emitters. As a result, the water will not freely flow from the water source to the plants as in the positive pressure system. The soil will become drier with evaporation and the capillary pressure of the soil will increase. It acts as a driving force pulling the water from the source below to the upper soil surface (Jiang et al. 2004). Therefore, the water movement in the system is ideally controlled by the suction force of the plants in the soil. Compared to the positive pressure irrigation, the pumping requirement and energy for pressurizing the system in the negative pressure irrigation is minimal to zero. Thus, the negative pressure technology is less expensive to install and it does not require consistent maintenance and monitoring. Numerous studies have been conducted on subsurface irrigation based on positive pressure. However, few studies have investigated the potential for using the negative pressure subsurface irrigation.

Livingston (1908) carried out a study on irrigation methods using negative pressure with porous clay cups. In 1918, he developed an auto irrigator using cylindrical porous clay cones to compensate the need for increasing the contact between the soil and the porous water-supplying surface of the previous clay cups (Livingston 1918). In 1942, Richards and Loomis studied the performance of improved double-walled irrigator pots that is suitable for low rates of water use at low tensions (Richards and Loomis 1942). Read (1962) did research on self-irrigating pots with negative pressure that can regulate the capillary pressure within the soil whilst minimizing the rapid fluctuation in soil moisture content. A theoretical analysis of subsurface irrigation was performed by Kato and Tejima (1982) on the basis of different negative pressures.

Lipiec et al. (1988) proposed a porous tube negative pressure water circulation technique, which is suitable for measuring soil water consumption or plant water uptake continuously under laboratory conditions. The performance of this technique was further examined by Iwama et al. (1991) and they proposed some guidelines to control the soil moisture content in this technology. Jiang et al. (2004) studied the efficiency of subsurface irrigation under various pressures ranging from 0.5 m positive pressure to 4.0 m negative pressure. In their study, water infiltration into soil was observed up to 2.0 m soil depth without applying any pressure to the system.

Liu et al. (2000) used a new porous ceramic pipe having numerous capillaries to develop an auto-irrigating system with negative pressure. An electric pump was used to maintain the negative pressure in their system. The effectiveness of the system was examined using lettuce cultivation. Liu et al. (2000) found that the soil moisture content for plant growth can be maintained satisfactorily throughout the growth period regardless of plant type. Liu et al. (2006) further incorporated a soil cooling system along with their previous auto-irrigating system where the irrigation and soil cooling can be done simultaneously by circulating cold water in porous ceramic pipe. All these studies on subsurface irrigation based on negative pressure promise the practical application of the technique in the future. Hence, studies on this technique with further advancement should be developed to enable adoption in commercial plant production.

The main objective of this study was to compare the yield and quality of hot pepper using capillary-irrigation systems under different negative pressures. A secondary objective was to identify a moderately negative pressure for the system for producing pepper under controlled-environment. The productivity of the capillary-irrigation was verified by analyzing plant growth parameters of hot pepper as well as the yield of hot pepper fruits.

3.3 Materials and Methods

3.3.1 System design

An experiment was carried out to assess the performance of capillary-irrigation system based on negative pressure using inexpensive materials such as plastic drinking cups and Tygon® tubes. Plastic cups of 95 mm height, 75 mm top diameter, and 55 mm bottom diameter were used as individual pots in this design. Acrylic discs, 57 mm in diameter and 3 mm thick were machined and 3 mm holes were drilled to allow water flow. The polyethersulfone membrane disc, GE PES, (GE Osmonics Labstore, Minnetonka, MN) was glued on each acrylic disc using silicon-I glue. The hydrophilic membrane had a pore size of 1.2 micron. The membrane-assembled acrylic disc was soaked in water to remove entrapped air and it was then positioned at the bottom of the cup submerged under water completely. Rubber bands, 3 mm x 76 mm dimension were used to maintain the acrylic discs snugly in place at the bottom of the cups. A Tygon® tube assembly 1.5 m long with 4.8 mm outer diameter and 1.6 mm inner diameter connected to the lower side of the cup was used to supply the water from Plexiglas® tubes that were used as reservoirs for the water source. The Plexiglas® tubes, 300 mm height, 32 mm outer diameter, and 28 mm inner diameter covered by rubber stoppers at both ends supplied water to the cups through the Tygon® tubes (Fig. 3.1). To maintain a constant negative pressure, an additional Tygon® tube was connected to the bottom of the Plexiglas® reservoir and opened to atmosphere. As a result, a constant pressure was maintained between the bottom of the disc and the bottom tip of the Tygon® tube that opened to atmosphere regardless of the water level inside the Plexiglas® tube. Thus, different negative pressures could be maintained by simply adjusting the height between the membrane disc in the cups and the air inlet location on the Plexiglas® water reservoir.

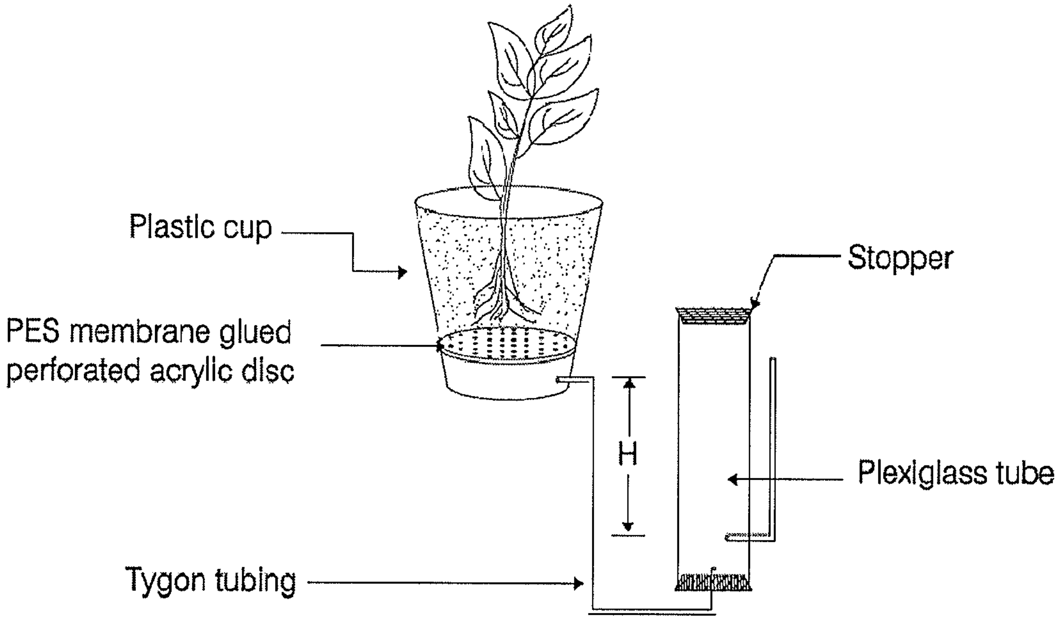

Fig. 3.1. Schematic representation of the capillary-irrigation system for container-grown plants. (PES - polyethersulfone, H - capillary pressure head)

3.3.2 Evaluation of the system design

The capillary (negative pressure) irrigation system was used in an experiment for growing jalapeno hot pepper *(Capsicum annuum)* plants at the University of Manitoba, Winnipeg, Canada, from October 2007 to January 2008. Hot pepper is a high value crop from the family Solanaceae, and it is widely cultivated and eaten as a spice. The jalapeno hot pepper, which is a Mexican variety, is popular for its addition of nutrients, pungency, flavor, and colour to food. The growing demand for hot peppers has stimulated interest in increasing their production whilst optimizing the water use efficiency.

Seeds of the jalapeno hot pepper were germinated in a soilless medium (Terra-Lite 2000 metro-mix growing media) and grown in a controlled-environment growth chamber. Thirty days after seeding, the seedlings were transplanted into individual cups assembled as previously described in the design and moved to a growing area. The temperature of the controlled-environment in the laboratory was maintained at 26 ± 2^0C and the relative humidity was 50%. The humidity was maintained by using a humidifier (Honeywell, HCM-630, Kaz Canada, Inc., Milton, ON) and by closing the entire experimental area with a transparent polythene sheet. The illumination was provided by nine pairs of fluorescent tubes (Philips F40T12/utility 40 W USA) at an average intensity of 125-μE m^{-2} s^{-1}. A daily photoperiod was set to 16 hours (Polowick and Sawhney 1985; Estrada et al. 1999). Plants were subjected to four different irrigation treatments, namely -0.2, -0.4, and -0.6 m negative pressure irrigations, and hand-watered as a control treatment for comparison purposes.

As growing media, 150 g of all-purpose potting mixture was used to fill each cup. The cups were set up in rows on a bench 0.2 m apart both between and within rows.

Plants were randomly assigned to each treatment. To minimize any edge or position effects within treatments, the treatment replications were randomly arranged over the bench. The experiment had a completely randomized design with four treatments replicated seven times. Immediately after transplanting, 30 mL of a commercial fertilizer solution, made by mixing 10 g of (10-52-10 NPK) in 1 L of water, was manually applied to each of the plants to acclimatize the transplanting shock. Thereafter, plants were fertilized with 20-20-20 commercial NPK fertilizer (3 g per 1 L) once in two week at a rate of 75 mL per plant. During the bud formation stage, the initial buds were clipped and removed from all the plants to induce more bud production.

During the early stages of plant growth, the pepper plants exhibited symptoms of aphids and thrips infestation. A single soil application of Admire (*imidacloprid*) systemic insecticide corrected the symptoms for the aphids. Foliar spray of Success Naturalyte (*spinosad*) Insect Control Insecticide was used to control the thrips. A single application of these two chemicals was adequate to assure normal plant growth throughout the rest of the growing period.

3.3.3 Measurement of plant growth

To continuously monitor the plant growth under different irrigation treatments, plant height, number of leaves, and leaf area were measured weekly. Individual plant height was obtained by measuring the height from the surface of the potting medium to the apex of the main stem. The number of leaves was manually counted and the leaf area was measured non-destructively using the image analysis technique. The image analysis ensures rapid data acquisition and repeated measurements over time without the need for detaching the leaves from the plants. Three comparatively bigger leaves were selected from each plant to estimate the respective leaf area. A scale of 30 mm x 10 mm strip of grid paper was placed on top of each of the selected leaf and the image was taken using a digital camera with a resolution of four-mega pixel (Canon Power Shot A520, Canon Inc., Tokyo, Japan). The PCI Geomatica (Version 10) software (PCI Geomatics Enterprises Inc., Richmond Hill, ON, Canada) and Arc GIS (Version 9.2) software were used to non-destructively estimate the leaf area.

3.3.4 Measurement of plant water consumption

The quantity of water consumed by each plant was recorded weekly by measuring the decline in water level in the Plexiglas® tubes connected to each of the plants. All the three negative pressure irrigation treatments consumed water directly from the scaled Plexiglas® tubes attached to the cups using the Tygon® tubes. The volume of water consumed by each plant was calculated by multiplying the depth of water recorded in the Plexiglas® tube by the area of the tube. The Plexiglas® tubes were refilled before the water level receded to the air entry point at the bottom of the tube. In the control irrigation treatment where the water was applied manually, plants were well-watered daily at a constant rate until the applied water just started to flow out of the bottom of the cups. The water use efficiency (WUE) for each treatment was calculated using two different methods (Kang et al. 2001). One method was based on the ratio of fruit yield to the total amount of water applied to the plant. The second method determined the WUE by dividing the total dried biomass yield (both shoot and root) by the total amount of water applied to the plant.

3.3.5 Measurement of plant biomass

After 120 days from transplanting, all the plants were removed from the cups ready for the above and below ground biomass measurements. The plants were partitioned into shoots and roots. The fresh weight of shoots was measured immediately after partitioning. The roots were carefully washed to remove as much potting medium as possible and were allowed to air dry prior to taking the fresh weight measurements. The maximum root length was measured from the stem base to the tip of the longest root. A balance with an accuracy of ± 0.01 g was used to record all the weights. The separated plant portions were oven-dried at 105°C for 24 hours to determine the dry weight.

Mature green fruits were harvested twice during the experimental period and they were evaluated for fresh fruit mass, length, diameter, and after drying, fruit dry mass. The fruit length and diameter were measured using a vernier caliper (Mitutoyo Digimatic 6" caliper, Model CD 6"P 500-351, Mitutoyo Corporation, USA). The fruit length was measured from the end of the sepal to the tip of the fruit (Ishikawa et al. 2004). The fruits were oven-dried at 60°C for 5 days until completely dried to a constant weight. Following the dry weight measurements, the dried fruits were used to quantify the pungency level of pepper under different irrigation treatments.

3.3.6 Quality analysis of jalapeno hot pepper fruits

Studies have investigated the effect of water stress on pungency level of hot pepper fruits using HPLC (Jaimez et al. 1999; Sung et al. 2005). The current study also quantifies the pungency level of jalapeno hot pepper fruits for each irrigation treatment using the HPLC. The hotness or pungency of hot pepper fruits has been attributed to two major capsaicinoids, namely capsaicin (*trans*-8-methyl-*N*-vanillyl-6-nonenamide) and dihydrocapsaicin (8-methyl-*N*-vanillylnonanamide) (Collins et al. 1995; Betts 1999; Laskaridou-Monnerville 1999; Barbero et al. 2006). The jalapeno pepper fruits were tested for their hotness by determining the capsaicin and dihydrocapsaicin concentration present in the fruits. The capsaicinoids extraction from jalapeno pepper fruits was performed using the technique developed by Collins et al. (1995) with some modifications.

The harvested jalapeno pepper fruits were oven-dried at 60°C for 5 days until completely dried to a constant weight. The dried fruits were then ground with a mortar and pestle, and sieved through a 1-mm sieve. The samples were stored in sealed plastic bags at room temperature prior to extraction. The capsaicinoids were extracted from 0.5 g of the ground pepper mixed into 5 mL of acetonitrile (100% HPLC grade) by heating at 80°C for 4 hours. The samples were shaken manually every hour. The supernatant was allowed to cool to room temperature, and was filtered through a 0.2-µm Corning syringe filter attached to a 5-mL disposable syringe (Corning Inc. Corning, NY) into a 2-mL glass sample vial. It was then capped and stored at 5°C ready for the analysis.

The HPLC system consisted of an Agilent-1100 series unit (Agilent Technologies Canada Inc., Mississauga, ON) equipped with an auto sampler (G1313A). The diode array detector was set at 280 nm, and the fluorescence detector was set at 420 nm. Excitation and emission wavelengths were set at 280 nm and 338 nm, respectively. The column used for separation was a 4.6 x 250 mm, Eclipse XDB-C18, 5-µm particle diameter (Agilent Technologies Canada Inc.). A pre-column guard cartridge of Agilent Zorbak high-pressure reliance cartridge was also used. The HPLC operating conditions for determining capsaicinoids were as follows: ambient temperature, a flow rate of 1 mL

min^{-1}, and a 10 min run. The mobile phase for this column was isocratic, with 90% solvent B (100% methanol) and 10% solvent A (10% methanol by volume in water). The injection volume of capsaicinoid extract for each HPLC injection was 20 μl.

Standards of capsaicin (≥ 99%) and dihydrocapsaicin (approximately 90%) (Sigma Chemical Co. St. Louis, MO) were dissolved in 100% HPLC grade methanol to obtain 2500, 1000, 500, 100, 50, and 10 ppm standards solutions by dilution of a 3000 ppm stock solution. These standard solutions were used to identify and quantify the capsaicin and dihydrocapsaicin concentration in each sample. The wave peak of capsaicin and dihydrocapsaicin under these conditions were observed at 3.27 and 3.54 min, respectively. These two capsaicinoids were identified in HPLC chromatograms by comparing the retention times, absorption spectra, and areas of different peaks.

3.3.7 Statistical data analysis

Comparison of treatments was performed by the general linear model (GLM) procedure of the SAS 9.1 statistical software (SAS Inc., Cary, NC). Means and standard errors were used to determine the variability of the sample means. Treatment means were separated by least significant difference (LSD) test. A probability of $P<0.05$ was considered significant. Missing data for pepper fruits in two negative pressure irrigations were obtained through the missing data formula technique discussed by Gomez and Gomez (1984).

3.4 Results and Discussion

3.4.1 Analysis of vegetative growth performance of pepper

Figure 3.2 shows fully-grown hot pepper plants subjected to capillary-irrigation treatments at a later stage of the experiment. The pepper plant growth performance in this experiment was evaluated by the plant height, leaf number, and leaf area over time. For all the four irrigation treatments, the plant height increased over time (Fig. 3.3). Results of the statistical analysis of plant height of pepper showed that during the initial few weeks after transplanting there was no significant difference observed among any of the four irrigation treatments, although the plant height increased over time. As the plant growth progressed (after fifth week), plant height from the -0.2-m and hand-watered treatments was significantly higher than that in the -0.4- and -0.6-m treatments. However, no significant difference in plant height was observed either between -0.2 m and hand-watered treatments or between -0.4 and -0.6 m treatments. The results from -0.2 m pressure irrigation treatment indicated that plants subjected to -0.2 m negative pressure irrigation was able to draw sufficient water for their vegetative growth, same as in the control treatment.

Fig. 3.2. Fully-grown jalapeno hot pepper plants subjected to capillary-irrigation.

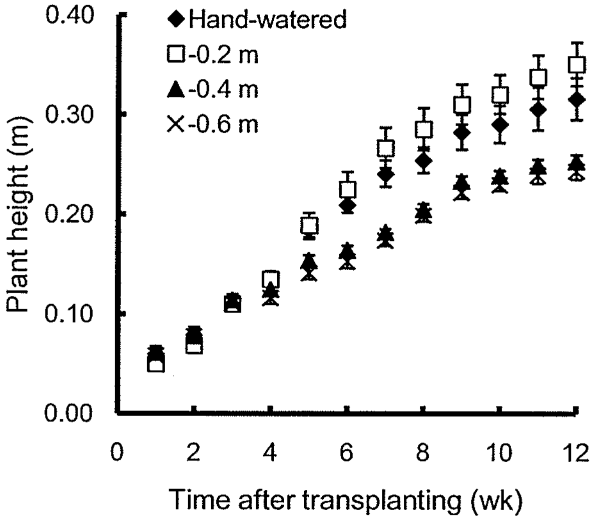

Fig. 3.3. Average plant height over time for pepper plant under -0.2 m, -0.4 m, and -0.6 m capillary pressures, and hand-watered treatment. Error bars indicate standard errors of measurement.

Plant leaf number (Fig. 3.4) further confirmed the effectiveness of the -0.2 m pressure irrigation treatment by showing a similar trend as that of plant height. These results are in agreement with Liu et al. (2000 and 2006) who evaluated the productiveness of an auto-irrigating system with negative pressure using lettuce culture. They found that plant height and leaf number were significantly higher in plants subjected to negative pressure irrigation.

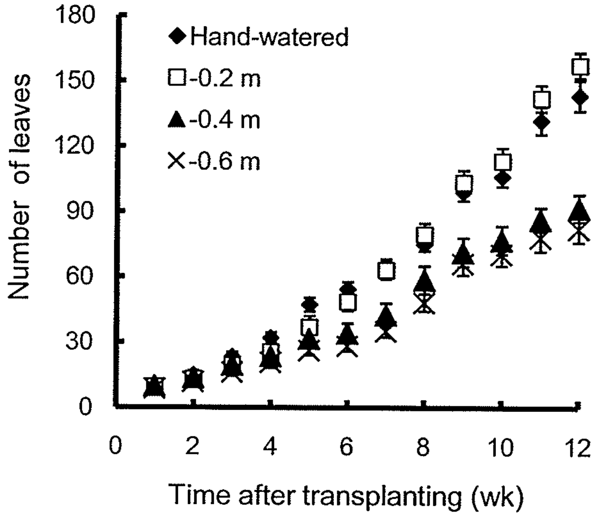

Fig. 3.4. Average number of leaves over time for pepper plant under -0.2 m, -0.4 m, and -0.6 m capillary pressures, and hand-watered treatment. Error bars indicate standard errors of measurement.

The different irrigation treatments also influenced the leaf area of the pepper plant. Leaf area over time was plotted in Fig. 3.5. The general trend of leaf area of pepper over time when subjected to regular watering was reported by Katerji et al. (1993). In their study, the leaf area was small in initial vegetative stage and continued to increase during the early flowering stage. It reached a plateau during the early fruit setting stage and then slightly decreased during the fruit development stage. The reduction in leaf area during the fruit development was due to increasing competition for water from developing reproductive parts, therefore decreasing amount of leaf water potential.

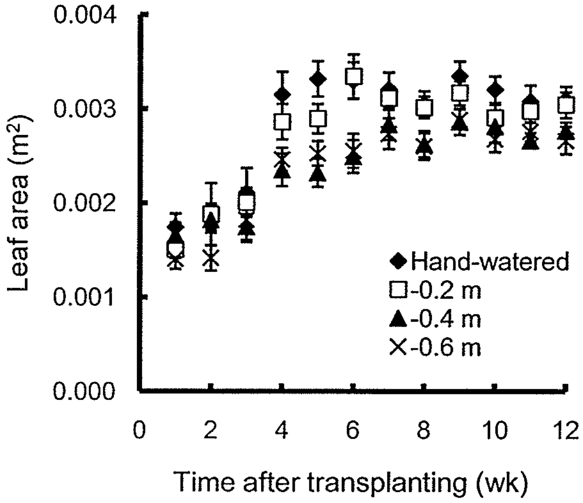

Fig. 3.5. Average leaf area over time for pepper plant under -0.2 m, -0.4 m, and -0.6 m capillary pressures, and hand-watered treatments. Error bars indicate standard errors of measurement.

Moreover, Katerji et al. (1993) found that the influence of water stress was more pronounced during early flowering and fruit setting stage. A similar trend was also noticed in the present study. Further, although the differences in leaf area were not always significant for all treatments at all stages of the growth, the leaf area in the -0.2 m and control treatment was significantly greater than in the other two capillary-irrigation treatments during the early stages of flowering and fruit setting (Fig. 3.5).

However, there was no significant difference observed in leaf area between -0.2 m and control treatments at any stage of plant growth. Leaf growth rate is controlled by leaf water status, which in turn depends on water availability or water deficit to the plant. Munns et al. (2000) reported that the changes in leaf water status greatly affected the leaf expansion rate in water-stressed barley and maize, but the effect was often only transient.

The leaf area results presented in this study suggest that the plants subjected to -0.2 m negative pressure irrigation maintained sufficient leaf water status for better leaf growth compared to -0.4 and -0.6 m negative pressures, where water deficit was noticeable.

3.4.2 Biomass analysis of pepper

Table 3.1 shows the results for shoot and root biomass of hot pepper plants subjected to different capillary-irrigation treatments. Fresh shoot mass was 39% higher in the -0.2 m treatment than in the -0.4 m treatment and 81% higher than in the -0.6 m treatment. There was no significant difference in fresh shoot mass between the -0.2 m and control treatment. Higher plant water status in the -0.2 m capillary-irrigation compared to the other two capillary-irrigation treatments may have caused the higher fresh shoot mass in the -0.2 m capillary-irrigation treatment. The -0.2 m treatment had 24% higher dry shoot mass relative to -0.4 m treatment and 50% greater relative to -0.6 m treatment. High capillary-irrigation reduced the fresh and dry shoot mass of pepper plant. A possible reason for this response is that water and nutrient movement into the shoot was reduced as a result of progressive development of water deficit in high capillary-irrigations. Greater capillary pressure with greater evaporation in high capillary-irrigation treatments may have exerted a greater effort by the plants to uptake water. When the plants under high capillary-irrigations were unable to uptake sufficient water, water deficit was developed progressively resulting in reduced plant biomass. Although the fresh and dry root mass were high in the control treatment, the differences between the -0.2 m and control treatments were not significant (Table 3.1). The fresh root mass of the -0.2 m treatment was 38% higher than in the -0.4 m treatment and 62% higher than in the -0.6 m treatment.

Table 3.1. **Total water consumption and biomass yields of hot pepper plant subjected to different capillary-irrigation treatments.**

Irrigation treatments	Irrigation water use (kg)	Average biomass yields and WUE from the four treatments [a]				
		Fresh shoot (g)	Dry shoot (g)	Fresh root (g)	Dry root (g)	WUE (total dry biomass/water applied) (g kg^{-1})
Hand-watered	6.770	44.73 a ± 1.63	6.20 ab ± 0.19	2.18 a ± 0.17	1.50 a ± 0.18	1.14 c ± 0.05
-0.2 m pressure	4.437	45.16 a ± 1.55	6.67 a ± 0.49	1.94 a ± 0.21	1.20 ab ± 0.13	1.78 a ± 0.14
-0.4 m pressure	2.335	32.51 b ± 1.72	5.39 b ± 0.22	1.41 b ± 0.18	0.98 b ± 0.11	2.73 b ± 0.09
-0.6 m pressure	1.802	24.93 c ± 2.13	4.44 b ± 0.35	1.20 b ± 0.13	0.80 b ± 0.11	2.93 b ± 0.30

[a] Means in the same column followed by different letters are significantly different using LSD at $P<0.05$.

Although the capillary-irrigation had no significant effect on the dry root mass of the plant, the trend of dry root mass was decreasing with increasing capillary pressures. More root development or increased root surface area in the -0.2 m treatment indicates that the water and nutrient uptake capacity was increased and this in turn might have increased the water and nutrient supply to the shoot, causing increased shoot growth.

The average root length from the -0.4 and -0.6 m treatments was higher than the -0.2 m and control treatments. However, there was no significant difference among the treatments. The values were 0.24 m for -0.2 m and control treatment and 0.27 m for -0.4 and -0.6 m treatments (data not shown). The increased root length in high capillary-irrigation can be associated with water stress that in turn caused the plants to develop longer roots in search of more water. However, the root mass in high capillary-irrigation was less compared to the mass in low capillary-irrigation. This implies that the severe water stress facilitated root elongation, but inhibited the radial root growth. Based on visual observations, the soil in the -0.2 m treatment looked wetter than in the -0.4 and -0.6 m treatments. The depth of root development in cups was greater in the -0.2 m treatment than in the -0.4 and -0.6 m treatments. Thus, plants irrigated using low negative pressure did not experience as severe water deficit as those in high negative pressure irrigations.

Pepper plants have shallow roots and thus, they are more sensitive to water deficits that would retard plant growth. Therefore, continuous water supply is essential for optimum growth and yield. Water shortages particularly during critical periods of plant growth will greatly affect the yield and quality of pepper fruits. Thus, keeping the plant roots at sufficient moisture level is very important. Although the moisture content of the growing medium was not measured in this study, based on visual observations, the -0.2 m treatment looked wetter, thus promoting better root establishment. The measured fruit size and fruit biomass of pepper are summarized in Table 3.2. Because of the reduced number of fruit setting in the -0.4 and -0.6 m negative pressure irrigations, data for these treatments were not provided.

Chalmers (1989) stated that fruits act as stronger sinks for water when compared to other vegetative parts of plant. Since the demand for water during development of reproductive sinks is greater, plants under high capillary-irrigations need to compromise between the demand for water to keep the vegetative growth, and the water required to develop the reproductive sinks.

Hence, due to water stress associated with water shortage, these plants reduced their reproductive load by flower abortion in order to maintain their vegetative growth. The reduction in fruit yield from -0.4 and -0.6 m capillary-irrigations could also be related to the reduced plant height, leaf number, and leaf area due to water stress as shown in Figs. 3.3, 3.4, and 3.5, respectively. The smaller leaf size and number of leaves, and slow leaf emergence may have reduced photosynthetic leaf area and therefore reduced the yield potential in water deficit plants (Bernstein et al. 2004).

Table 3.2. Effect of two irrigation treatments on fruit biomass, fruit size, and water use efficiency (WUE).

Irrigation treatments	Jalapeno hot pepper fruit biomass, size, and WUE [a]				
	Total fresh fruit (g)	Total dry fruit (g)	Fruit length (mm)	Fruit diameter (mm)	WUE (Fruit yield/water applied) (g kg^{-1})
Hand-watered	42.48 a	3.69 a	44.5 a	18.9 a	6.27 b
-0.2 m pressure	41.40 a	3.59 a	44.3 a	18.1 a	9.33 a

[a] Means followed by the same letter in the same column are not significantly different using LSD at $P<0.05$.

The average fruit length was 44.3 and 44.5 mm for the -0.2 m and control treatment, respectively. The average fruit diameter for the -0.2 m and control treatment was 18.1 and 18.9 mm, respectively. There was no significant difference in total fresh fruit mass and dry fruit mass between the -0.2 m and control treatments. Although the plant water status was low in the -0.2 m treatment compared to the control, pepper fruit size and fruit mass were not affected as in the other two capillary-irrigation treatments. These findings are favourable in terms of quality and market value. Therefore, the performance of the -0.2 m capillary-irrigation was comparable to the manual irrigation in terms of fruit biomass and quality.

3.4.3 Plant water consumption and WUE

The irrigation water use in the -0.2 m treatment was lower by about 35% compared to the control treatment while it was lower down to 66% and 73% in -0.4 and -0.6 m capillary-irrigations respectively (Table 3.1). The control treatment consumed more water compared to the capillary-irrigation treatments. For the control treatment, water was applied manually to the top soil of the cup and hence water evaporation rate from the surface may have been high. In addition, reducing the volume of the growing medium increased the frequency of water application to plants under manual irrigation. In the capillary-irrigation on the other hand, water was always available for plant uptake from the bottom of the growing medium and thus evaporation rate was low compared to the manual irrigation.

Water use efficiency based on dry mass was higher in all the three capillary-irrigation treatments compared to the control treatment (Table 3.1). As for the water use efficiency based on yield, the -0.2 m treatment showed significantly higher efficiency over the control treatment (Table 3.2). These results showed that -0.2 m treatment could save 35% more water while maintaining biomass yield of hot pepper.

3.4.4 Capsaicinoids quantification in peper fruits

Hot pepper is popular as a spice and as a food flavour. Pepper production is susceptible to water stress (Doorenbos and Kassam 1986) and hence the sensitivity to water stress affects the yield of pepper (Antony and Singandhupe 2004; Sezen et al. 2006). Since hot pepper is mainly cultivated in warm and semi-arid areas where water shortage is acute, determining the effect of water stress on hot pepper yield in terms of hotness of the pepper fruits is important. The current study evaluated the effect of capillary-irrigation on the pungency level of jalapeno hot pepper using HPLC. The compounds in hot pepper called *capsaicinoid*s mainly determine the pungency level (hotness, spiciness, or flavor) of the pepper fruits. More than 80% of the capsaicinoids are comprised mainly of two compounds, namely capsaicin and dihydrocapsaicin (Sung et al. 2005). The capsaicinods in jalapeno hot pepper in this study was quantified using a method proposed by Collins et al. (1995) with some modifications.

The results obtained from HPLC analysis is summarized in Fig. 3.6. Although the -0.4 and -0.6 m treatments produced fewer fruits, the missing data formula technique (Gomez and Gomez 1984) helped to estimate the missing values for capsaicinoids concentration in those two treatments. This in turn helped to perform normal statistical analysis to evaluate the effects of capillary-irrigation treatments on the pungency level of the hot pepper. Both capsaicin and dihydrocapsaicin had the same tendency for all the four irrigation treatments. The highest concentration of both capsaicin and dihydrocapsaicin concentration was observed in the -0.6 m treatment while a minimum concentration was obtained in the control treatment. The trend in Fig. 3.6 suggests that the higher the capillary pressure (water stress), the higher the concentration of capsaicinoids and thus higher the pungency in hot pepper. These results are similar to the conclusions drawn by Sung et al. (2005) comparing the pungency to water stress.

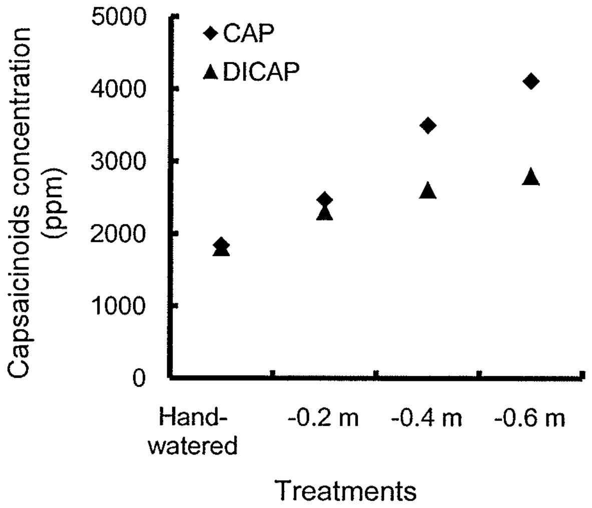

Fig. 3.6. Capsaicin (CAP) and dihydrocapsaicin (DICAP) concentration for pepper fruits under -0.2 m, -0.4 m, and -0.6 m capillary pressures, and hand-watered treatments.

The concentration of capsaicinoids increases during fruit ripening due to increased production and later it undergoes turnover and degradation (Estrada et al. 1999). The enzyme peroxidase contributes to capsaicinoid metabolism of pepper fruit by oxidizing the capsaicinoids (Estrada et al. 2000) and hence peroxidase is negatively related to the capsaicinoid concentration. Sung et al. (2005) found that water deficit lowered the peroxidase activity and capssaicinoid oxidation in pepper fruits. As a result, degradation of capsaicinoid will be slower while the capsaicinoid production continued and thus capsaicinoid concentration will be greater in plants under water stress. The capsaicinoid (capsaicin and dihydrocapsaicin) concentration in the -0.2 m treatment was 31% higher than in the control treatment, while in the -0.4 and -0.6 m treatments it was 68% and 89% higher than the control treatment, respectively (Fig 3.6).

In addition to quantifying the hotness of pepper in parts per million, it can also be expressed as Scoville Heat Units (SHU). This SHU unit was named after its founder Wilbur Scoville in 1912, who quantified hotness using a panel of trained people tasting a series of samples until its minimum dilution (Batchelor and Jones 2000). The concentration of capsaicinoids was converted to SHU by multiplying the capsaicinoid concentration in parts per million on pepper dry weight basis, by the coefficient of the heat value given in Todd et al. (1977). Both the capsaicin and dihydrocapsaicin have the same coefficient of the heat value, which is 16.1.

The SHU values for the control treatment, -0.2, -0.4, and -0.6 m treatments were 59×10^3, 77×10^3, 99×10^3, and 110×10^3, respectively. The SHU value for jalapeno hot pepper obtained in the present study was higher than the value reported by Thomas et al. (1998), which was 49×10^3. Although the SHU values were significantly high in the -0.4, and -0.6 m treatments compared to the control and the -0.2 m treatment, based on the growth and yield potential of pepper, the capillary-irrigation using -0.2 m negative pressure can be considered to be a better option compared to the other two capillary-irrigation treatments.

3.5 Conclusions

In order to evaluate a capillary-irrigation system for better yield and quality of pepper, three negative pressures, namely -0.2, -0.4, and -0.6 m were tested in this study with a hand-watered comparison. The provision of water to the plants using different capillary-irrigations influenced the plant vegetative and reproductive growth, and the hotness or pungency level of pepper plants. The plant height, leaf number, leaf area, and plant biomass were significantly lower in the -0.4, and -0.6 m irrigation treatments compared to the -0.2 m and the control treatments. The vegetative growth parameters were not statistically different between -0.2 m and the control irrigation treatments. Furthermore, the reproductive growth parameters (fruit length, diameter, and fruit biomass) in the -0.2 m capillary-irrigation treatment were also comparable to the control treatment, unlike in the -0.4, and -0.6 m irrigation treatments. The continuous water availability and sufficient plant water consumption in the -0.2 m treatment positively influenced the pepper quality parameters (fruit length, diameter, and fruit biomass). Hence, higher yield of peppers were obtained in this treatment compared to the -0.4 and -0.6 m irrigation treatments.

The hotness of pepper, which is one of the important marketing characteristics of hot pepper, increased in the -0.2 m capillary-irrigation compared to the control treatment. The results have shown that -0.2 m capillary-irrigation was better than the other two capillary-irrigations in terms of plant growth, yield, and quality. Results obtained from the present study also demonstrate that the lower negative pressures should be recommended instead of higher negative pressures in order to obtain reasonable plant yield and quality. Moreover, the results indicate that WUE values increased with increased capillary pressure. However, as compared to the plant performance of the manual irrigation, higher capillary pressures led to lower yields. The capillary-irrigation, under moderate negative pressures, can save a substantial amount of water while maintaining better biomass yield and improving fruit quality in pepper production, particularly in areas where water shortage is acute. The capillary-irrigation system has an advantage because it neither needs operator expertise and special system maintenance nor requires sophisticated equipment and labour. The method provides a simple, reproducible technique for growing plants in containers. Therefore, the capillary-irrigation method is a useful system to automatically irrigate container-grown pepper plants under a controlled-environment.

CHAPTER 4 : A PLANT-CONTROLLED CAPILLARY-IRRIGATION SYSTEM FOR GROWING MARIGOLD (*Tagetes patula* L.)

4.1 Abstract

Marigold growth performance was evaluated with a capillary-irrigation system under -0.2, -0.4, and -0.6 m negative pressure treatments along with a hand-watered control. The capillary-irrigation system allowed the release of a precise quantity of water in response to plant water demand. Periodic measurements of plant heights, number of compound leaves, leaf canopy area, and flower count were done on each plant for the different treatments. In addition, the biomass yields in the capillary-irrigation treatments were compared against the control treatment. The mean of plant height, number of compound leaves, and leaf canopy area were significantly greater in the control and the -0.2 m treatments compared to the -0.4 and -0.6 m treatments. Moreover, the same trend was also consistent on the plant biomass yield observations. The flower counts were lower when plants were grown under high capillary-irrigations. Further, water savings of up to 33% were achieved in the -0.2 m capillary-irrigation while still maintaining acceptable plant yield compared to the hand-watered irrigation. In general, the marigold plants under -0.2 m capillary-irrigation compared favorably to the hand-watered irrigation. Lower capillary pressures such as -0.2 m are more advantageous in attaining the desired yields compared to the higher capillary pressures such as the -0.4 and -0.6 m. Additionally, the capillary-irrigation system is less demanding in terms of operator expertise, system maintenance, required volume of potting media, and labour requirements while saving a considerable amount of water.

4.2 Introduction

As available irrigation water becomes scarce and expensive, increasing the irrigation efficiency by using alternative irrigation application methods is crucial in irrigated-agriculture. Continuous improvement on different irrigation methods, particularly in ornamental plant production is becoming increasingly important (Lieth and Burger 1989). Doorenbos and Kassam (1986) stated that ornamental plants are sensitive to both over- and under-irrigation, and therefore, using controlled-irrigation is important to obtain high yields while increasing the efficient use of irrigation water. In recent years, the trend for types of irrigation has been towards conversion of surface to subsurface irrigation, which is considered to be a more efficient water delivery system.

Subsurface irrigation (SI) can be a better option to save water in the ornamental plant production. It is one of the micro-irrigation methods that delivers water directly and precisely to the root zone of the plant (Haman and Izuno 1989) while maintaining relatively high water content within the root zone. In addition, the advantages of SI methods include improved yields and crop quality, minimized evaporation and run off losses, restrained weed growth, and improved water and nutrient management (Hoffman and Martin 1993; Howell et al. 1997; Ayars et al. 1999). The most commonly used SI systems employ positive pressure to control water movements in the system. To further improve the efficiency of water use in SI, recent research has incorporated negative pressure to subsurface irrigation. In this irrigation technology, the emitters are kept above the air inlet point of water reservoir and the emitters are specially designed to allow the water to pass through but not allow the air. When the soil becomes dry, the soil water potential decreases. The reduced soil water potential acts as a driving force to draw the water from the water reservoir to the emitter (Jiang et al. 2004).

To reduce the excessive labour requirement and time, and to increase the water usage in irrigation technologies, automation is a great option. Automating the irrigation systems can also facilitate higher yields, greater precision, lower water use for irrigation, and more efficient use of water as compared to manual systems (Abraham et al. 2000). The current developments in electronics have helped to automate the irrigation systems, and consequently, considerable improvements in irrigation management options and water application efficiencies have been achieved. It is very common for irrigation to be automated using sensors, specialized controllers, and electrodes. However, these equipments are often expensive to use (Caceres et al. 2007). In the capillary-irrigation, no such sensors are needed because the plants draw the water from the root zone as a result of the negative pressure that creates a hydraulic gradient causing the water from the irrigation system to flow towards the root zone. Prenger et al. (2005) stated that the status of plants would be a more accurate control system for controlling the greenhouse environment and irrigation. However, studies on practical application of this capillary-irrigation system are limited.

A capillary-irrigation system using porous clay cups and porous clay cones was successfully developed by Livingston (1918). Richards and Loomis (1942) developed double-walled irrigator pots using the same principle and their system is particularly suitable for low rates of water use at low tensions. Further, Moinat (1943) investigated a porous clay plate irrigator based on the capillary rise of water through a column of sand to deliver the water for plants growing in soil above a porous plate embedded in the surface of the sand. However, at low water content, the sand had a low hydraulic conductivity and could not keep pace with the plant demand. Read (1962) studied the performance of self-irrigating pots that regulate the capillary pressure in the soil and minimize the rapid fluctuation in soil moisture contents. Kato and Tejima (1982) performed a theoretical study on SI using different negative pressures. Recently, Liu et al. (2006) developed porous ceramic pipes using negative-pressure water circulation technique for cultivating vegetables. They reported that the system could automatically maintain the soil moisture at a suitable level for growing plants while cooling the soil simultaneously to alleviate the high ambient temperature impact on plant processes during the summer. Past studies have mostly given consideration for irrigating vegetable plants and cereal grains, and studies on capillary-irrigation for ornamental plants are sparse.

In greenhouse ornamental plant production, it is important to produce compact, high quality plants to reduce the shipping costs. This can be attained by limiting the water uptake by the plants (van Iersel and Nemali 2004). The capillary-irrigation, where the water is supplied precisely to the root zone without over- or under-irrigating, will be a better option for conditioning the plants for greenhouse production. Moreover, ornamental plants can be grown indoors using capillary-irrigation system. The indoor plants will help to remove pollutants from the air, humidify the interior space, and provide oxygen, while improving the water use efficiency. Studies on the effect of water stress on the growth parameters such as leaf area, dry mass, and flowering of bedding plants are minimal (van Iersel and Nemali 2004). Hence, studying the effect of capillary-irrigation on the growth of ornamental plants is crucial. The current study used marigold as one of the annual bedding plant to examine the performance of a capillary-irrigation system. The aim of this research was to design and evaluate a plant-controlled capillary-irrigation system under different negative pressures in container-grown marigold plants.

4.3 Materials and Methods

4.3.1 Experimental setup

The experiment was carried out under controlled conditions at the University of Manitoba in Winnipeg, Canada. A capillary-irrigation system consisted of four irrigation treatments, i.e. -0.2, -0.4, and -0.6 m capillary-irrigations and a hand-watered as a control treatment. The containers used in this study for growing marigold were plastic drinking cups 95 mm deep, with 75 mm top diameter and 55 mm bottom diameter. Acrylic discs, 57 mm in diameter and 3 mm thick were machined and drilled to make approximately thirty 3-mm diameter holes to facilitate water movement from the water source to the soil. A hydrophilic polyethersulfone membrane disc of 1.2 micron pore size, (GE PES, GE Osmonics Labstore, Minnetonka, MN), was glued on each acrylic discs using silicon-I glue. All the entrapped air in the membrane-assembled acrylic disc was removed by soaking it in the water. After removing the entrapped air, the disc was then fixed snugly at the bottom of the cup using a rubber band of 3 mm x 76 mm dimension. All the assembling was performed under water.

Plexiglas® tubes were used as water reservoirs to supply water to the plants. The Plexiglas® tubes were 300 mm long, 32 mm outer diameter, and 28 mm inner diameter. The tubes had rubber stoppers at both ends. A Tygon® tube (1.5 m long with 4.8 mm outer diameter and 1.6 mm inner diameter) was used to connect the lower side of the cup to the lower side of the Plexiglas® tubes. In addition, a second Tygon® tube was fixed at the bottom of the Plexiglas® tube and opened to atmosphere to facilitate a constant head water supply in the system. Regardless of the water level in the Plexiglas® tubes, different capillary pressures can be developed between the membrane disc in the cups and the air entry point as a reference depth on the Plexiglas® tubes. The whole assembly was then used to plant the marigold and to provide the irrigation through capillary action as influenced by the plant water demand.

4.3.2 Experimental procedure

Plant growth of a dwarf French petite mixed variety of marigold (*Tagetes patula* L.) was studied under different capillary-irrigations. Dwarf varieties are more appropriate to use in containers due to their compact growth. Thirty-day old marigold seedlings were transplanted into the previously assembled cups and the potted plants were placed on a bench. The growing medium was 120 g of all-purpose potting soil for each plant in the cup. The potted plants were randomly arranged on the bench to eliminate the edge or position effects among the four treatments. A completely randomized block design with four irrigation treatments replicated seven times was adopted. The spacing between two cups was 0.2 m between and within the rows. Temperature and relative humidity of the experimental area were controlled at 26°C to 28°C and at 50% to 55%, respectively. In addition to a humidifier, the entire experimental area was fully covered by a transparent polythene sheet in order to maintain the humidity at a desired level throughout the experiment.

Fluorescent lamps (Philips F40T12/utility 40 W USA) were used to provide the illumination for the plants. The lamps were placed at about 100 mm from the top canopy of the plant and they were moved according to the height of the plant when the plant growth progressed with time. All the plants were exposed to a 13 hours photoperiod throughout the study period. The plants were manually fertilized once in two weeks with 3 g/L 20N-20P-20K water-soluble fertilizer. The experimental area was sprayed with Admire (*imidacloprid*) systemic insecticide and Success Naturalyte (*spinosad*) Insect Control Insecticide to control aphids, thrips, and mites during the period of plant growth. Old flowers were being removed to keep the plants blooming continuously.

4.3.3 Plant measurements

Individual plant height, number of compound leaves, leaf canopy area, and flower count were recorded weekly. The plant height was measured from the surface of the growing media to the top of the leaf canopy using a ruler. The marigold has pinnate compound leaf with leaflets arranged along a central axis. Since counting each single leaf was difficult and time consuming, the number of compound leaves instead of a single leaf was manually recorded. The number of flowers was also counted for each treatment. The leaf canopy area was estimated non-destructively using an image analysis technique as described later.

At the end of the experiment, plants were removed for fresh and dry biomass studies. Shoots were separated from roots and the fresh mass of shoot was recorded immediately. The separated roots were then thoroughly washed to remove the growing medium and they were air-dried, ready for the measurement of fresh mass. The maximum root length was measured from the stem base to the tip of the longest root. After taking the fresh mass, both the shoots and roots were oven-dried at 105°C for 24 hours for dry mass records. The compactness of the plants under capillary-irrigation treatments was assessed by estimating the ratio of dry shoot mass to plant height using a method described by van Iersel and Nemali (2004). In their experiment van Iersel and Nemali (2004) indicated that the higher the ratio, the higher the compactness of the plant.

4.3.4 Leaf canopy area measurements

Leaf area is an indicator of plant growth and productivity (Peksen 2007). It can also be a useful tool for interpreting the relationship between plant growth and environmental factors such as water availability, radiation interception, and energy exchange (de Jesus et al. 2001; Peksen 2007). Hence, accurate measurement of leaf area is essential. The leaf area can be measured either destructively or non-destructively. Destructive measurement of leaf area is not only time consuming and tedious, but also affects vegetative and reproductive growth of the plant over time. The common instrument for measuring single leaf area is a leaf area meter. However, the equipment is expensive and not suitable for large leaves (Peksen 2007). To track the growth and development of the same plant at different times, non-destructive leaf area measurement is essential. The photographic technique allows rapid and non-destructive measurement of leaf area (Bignami and Rossini 1996). Digital images together with computer image processing technique facilitate easy and quick data acquisition while providing accurate leaf area estimations.

The marigolds were grown under fluorescent lights positioned horizontally above the canopy. As the plants grew, the leaves grew outward to maximize the exposure to light. In the present study, a 30 mm-long and 10 mm-wide strip of grid paper was placed on the surface of the canopy whenever images were taken. The strip helped to scale the canopy area for the images taken with the camera placed at different heights as the plants continued to grow. The images were taken using a digital camera with a resolution of four-mega pixel (Canon Power Shot A520, Canon Inc., Tokyo, Japan). The method for extraction of green leaf area from digital camera images was similar to previous research (Zakaluk and Sri Ranjan 2006; Zakaluk and Sri Ranjan 2008). Green leaf area extraction from the images was performed using PCI Geomatica (Version 10) software (PCI Geomatics Enterprises Inc., Richmond Hill, ON, Canada). To extract green leaf area in the RGB digital camera images from background effects (leaf shadow, soils, leaf senescence, and flowers), a ratio of the R and G image bands was calculated in a fourth image channel and re-scaled to fit within the 8-bit image format (Eq. 4.1).

$$RG^{-1} = \frac{R}{G} \tag{4.1}$$

where:

RG^{-1} = red green ratio,

R = red image band, and

G = green image band.

Using a spectral scatter plot, a range within the RG ratio image channel defined the decision boundaries for green leaf area from background effects that was subsequently re-selected into a fifth image channel. Thus, only green leaf area remained in the fifth image channel for further analysis. The fifth image channel, containing only green leaf areas for all plant samples imaged was then vectorized for calculation of green leaf area in a geographic information system (GIS). The GIS converted green leaf areas into a tabular format for each plant sample found in the image that facilitated the combining the plant water status measurements and subsequent statistical analysis. The process of calculating RG ratio into a fourth image channel, identifying the range of green leaf area within the fourth RG ratio image channel, reselecting the RG ratio range containing only green leaf area into a fifth image channel, and vectorizing green leaf area from the fifth image channel was repeated for each digital camera image acquired in the study. The use of a RG ratio derived from the RG digital camera bands served as a tool to isolate green leaf area from background noise.

4.3.5 Water supply and WUE

In all the three capillary-irrigation treatments, water was applied from the Plexiglas® reservoir through Tygon® tubing. In the control treatment, water was applied manually. The amount of water consumed by each plant in the capillary-irrigation treatments was recorded weekly. The volume of water consumed by each plant was determined using the depth of water receded in the Plexiglas® tube and the area of the tube. The Plexiglas® tube was refilled every time before the water level in the Plexiglas® tube reached the air inlet point at the bottom of the tube. The plants in the control irrigation treatment were watered daily at a constant rate until the water just started to flow out of the bottom of the cups.

Determining the water use efficiency (WUE) of capillary-irrigation system is helpful to understand the effective use of water in plant production. In this study, the WUE for each treatment was calculated using a method proposed by Kang et al. (2001). In this method, the WUE was determined by dividing the total dry biomass yield (both shoot and root) of marigold by the total amount of water applied to the plant.

4.3.6 Data analysis

The data were analyzed by using a general linear model (GLM) procedure of the SAS 9.1 statistical software (SAS Inc., Cary, NC). A least significant difference (LSD) test was used to separate the treatment means. A probability of $P<0.05$ was considered significant. Means and standard errors were used to determine the variability of the sample means.

4.4 Results and Discussion

Marigold plants were provided with different capillary-irrigations over an 8-week growing period, to determine the influence of the irrigation treatments on subsequent growth performance and flowering of marigold plants in the containers under controlled-environment. Fully-grown marigold plants subjected to capillary pressure irrigation are shown in Fig. 4.1.

Fig. 4.1. Marigold plants grown under capillary-irrigation system.

4.4.1 Influence of capillary- irrigation on marigold plant height and leaf count

The marigold plant growth in terms of plant height and leaf count was greatly influenced by the capillary-irrigation. The average plant height and the average number of compound leaves in all the four irrigation treatments increased with time (Figs. 4.2 and 4.3).

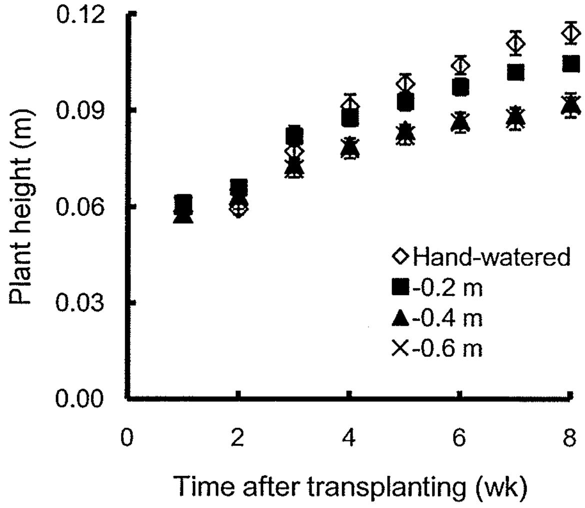

Fig. 4.2. The marigold plant height over time under -0.2, -0.4, and -0.6 m capillary pressures, and hand-watered treatments. Data were averaged from seven replicates. Error bars indicate standard errors of measurement.

During the later weeks, the average plant height and the average number of leaves were significantly higher in hand-watered and -0.2 m capillary-irrigation treatments compared to -0.4 and -0.6 m treatments. However, no significant differences were noted in both plant height and leaf count between hand-watered and -0.2 m capillary-irrigation treatments. The -0.4 and -0.6 m capillary-irrigation treatments also had no significant difference in plant height and leaf count between them. Increased plant height or stem elongation in moisture-stressed plants are attributed to lower resistance to water movement in the xylem tissue in stems and thus the stem cells can maintain a higher turgor pressure at a particular moisture stress level (Steudle 2000; van Iersel and Nemali 2004).

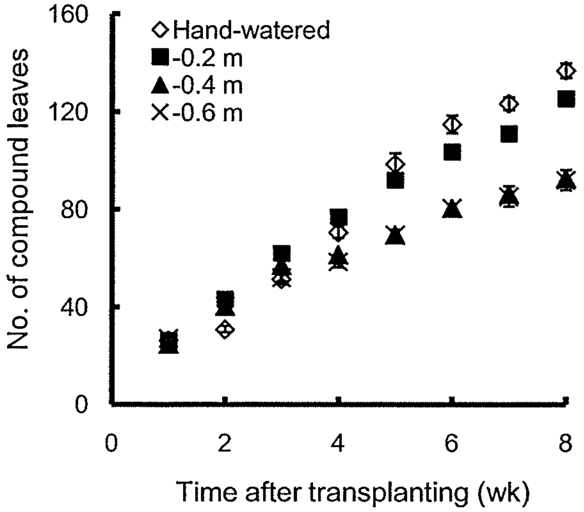

Fig. 4.3. Number of compound leaves over time for marigold plant under -0.2, -0.4, and -0.6 m capillary pressures, and hand-watered treatments. Data were averaged from seven replicates. Error bars indicate standard errors of measurement.

High leaf count and plant height in the -0.2 m capillary-irrigation treatment compared to the other two capillary-irrigation treatments demonstrated that the -0.2 m capillary-irrigation may have provided sufficient tugor pressure to both stem cells and leaf cells, similar to the well-watered plants in the control treatment.

Although the marigold plant height is less sensitive to drought stress (van Iersel and Nemali 2004), the results from the present study shows that the severe drought stress as a result of higher capillary pressures may result in significant reductions in plant height. Hence, it is possible for the low capillary-irrigation such as the -0.2 m pressure to maintain a comparable plant height and number of leaves as in the manual irrigation system.

4.4.2 Influence of capillary-irrigation on marigold canopy area

The relationship between the capillary-irrigation and the mean leaf canopy area over time is shown in Fig. 4.4. The non-destructive leaf canopy area measurement in the present study was estimated using an image analysis technique that enabled the measurement of the leaf canopy area of the same plant precisely and repeatedly. The results demonstrated that the hand-watered and the -0.2 m capillary-irrigation treatments had significantly more canopy area while the other two high capillary-irrigation treatments had significantly lower canopy area over time. When the plants are subjected to drought stress, leaf stomates close to prevent the water loss from the leaves (Chapman and Auge 1994). As a result of the closure of the stomates, transpiration is reduced and thus resistance to water movement to leaf veins increases, and this in turn reduces the turgor pressure of the leaf cells. The turgor pressure acts as a driving force for enlargement of cells and the differences in turgor pressure and the low membrane extensibility result in small leaf areas for plants under drought stress (Hsiao and Xu 2000; van Iersel and Nemali 2004). However, the lower capillary-irrigation (-0.2 m) in the current study maintained sufficient turgor to produce a leaf canopy area that was comparable to the manual irrigation.

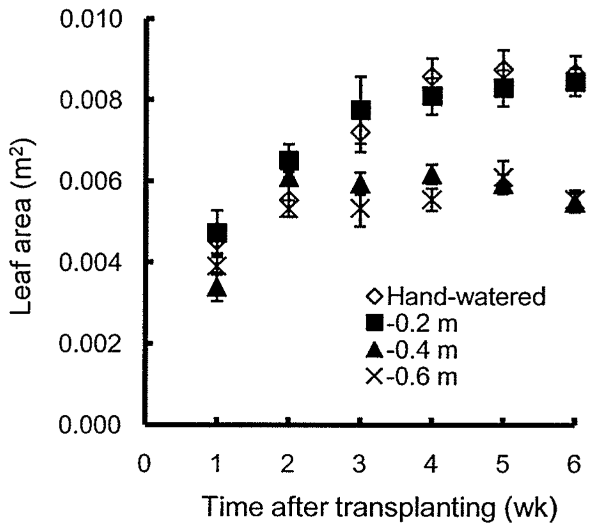

Fig. 4.4. Leaf canopy area over time for marigold plant under -0.2, -0.4, and -0.6 m negative pressures, and hand-watered treatments. Data were averaged from seven replicates. Error bars indicate standard errors of measurement.

The digital image analysis of vegetative cover of the plant designed to estimate the area of marigold leaf canopy is efficient for non-destructive leaf area measurements because of its accuracy and affordability for researchers and plant growers.

4.4.3 Marigold plant biomass yield

Results for the marigold plant biomass yield are presented in Table 4.1. The dry shoot weight and fresh root weight were significantly lower in the high capillary-irrigation (-0.4 and -0.6 m) compared to the manual irrigation. There was no significant difference between the lower (-0.2 m) capillary-irrigation and the manual irrigation. This might be related to increased resistance to water and nutrient movement into the shoot and roots as a result of progressive development of water deficit in the high capillary-irrigation treatments. van Iersel and Nemali (2004) also reported that the dry shoot mass of marigold was linearly decreased with decreasing moisture content in the growing medium. No significant difference was found between the plants dry root mass in all the irrigation treatments. More root development associated with different capillary pressures may have resulted in a similar magnitude of dry root mass in the capillary-irrigation treatments.

The capillary-irrigation, when compared to manual irrigation, affected the root length of the marigold (Table 4.1). The root length increased with increasing capillary pressure. The higher capillary pressure treatments had significantly longer root length compared to the manual irrigation. There was no significant difference between the manual irrigation and the -0.2 m capillary-irrigation.

Table 4.1. Total water consumption and biomass yield of marigold plants subjected to different capillary-irrigation treatments.

Treatment	Irrigation water use (kg)	Means and SE of the four treatments [a]					
		Fresh shoot weight (g)	Dry shoot weight (g)	Fresh root weight (g)	Dry root weight (g)	Root length (m)	WUE (total dry biomass/water applied) (g kg^{-1})
Hand-watered	1.90	10.61 a ± 1.19	2.37 a ± 0.34	1.18 a ± 0.08	0.51 a ± 0.03	0.257 a ± 0.02	1.50 a ± 0.19
-0.20 m pressure	1.28	5.79 b ± 1.24	1.79 ab ± 0.30	0.95 ab ± 0.14	0.53 a ± 0.06	0.306 ab ± 0.01	1.81 a ± 0.24
-0.40 m pressure	0.79	4.36 b ± 0.77	1.48 b ± 0.14	0.76 b ± 0.06	0.47 a ± 0.05	0.311 b ± 0.01	2.48 b ± 0.19
-0.60 m pressure	0.72	4.13 b ± 0.53	1.44 b ± 0.19	0.75 b ± 0.06	0.43 a ± 0.05	0.326 b ± 0.03	2.60 b ± 0.26

[a] Means followed by different letters in the same column are significantly different ($P<0.05$).

The root length findings demonstrate that the plants in the soil can favour longer root growth when soil dries due to high capillary pressure, sending roots further and deeper into the soil to scavenge for water. This agrees with a previous study (Chylinski et al. 2007) on drought response of two other bedding plant species, whereby the roots were longer on plants that were exposed to more drought stress.

4.4.4 Plant compactness and flowering response of marigold

The compactness in marigold plants varied between the different capillary-irrigation treatments. The trend for compactness, defined as the ratio of dry shoot mass to plant height, decreased with decreasing moisture content or in other words decreased with increasing capillary pressures (Fig. 4.5). This response demonstrates that the plants grown under lower moisture level or high capillary-irrigations weighed less per unit stem length than those grown under the higher moisture level or low capillary-irrigations (van Iersel and Nemali 2004). However, the variations in compactness were not significantly different among the treatments. This indicates that the capillary-irrigation produced shorter but less compact plants. Similar results were also reported by van Iersel and Nemali (2004) in their study on marigold plants. The quality and marketing value in ornamental plant production requires the production of relatively short bedding plants with better appearance, hence reducing shipping costs, and allowing ease of handling. In addition, the capillary-irrigation can be used as an alternative to plant growth regulators that are normally used to control the plant height in greenhouses.

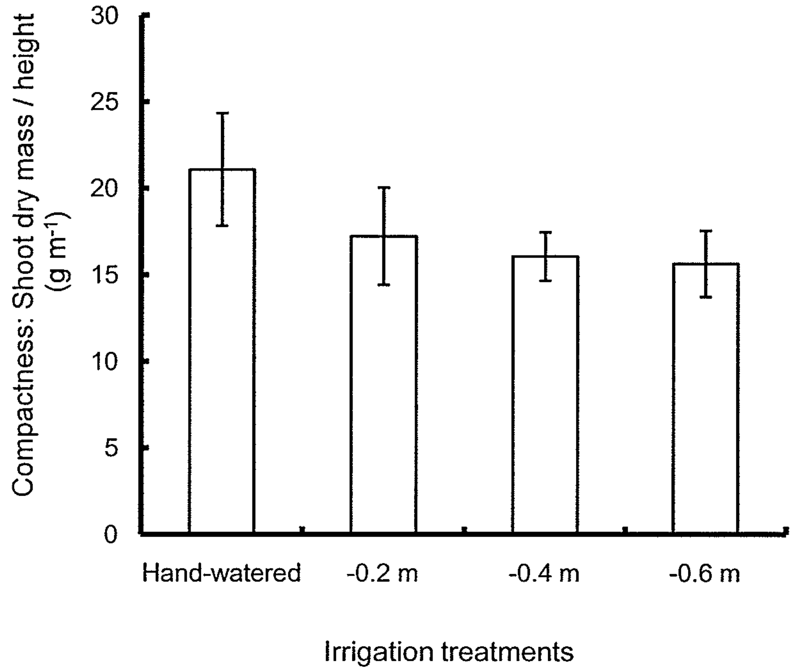

Fig. 4.5. **The effect of different irrigation treatments (-0.2, -0.4, and -0.6 m negative pressures, and hand-watered treatments) on the ratio of dry shoot mass to plant height of marigold plant. Data from seven replicates were averaged. Error bars indicate standard errors of measurement.**

Within the 8-week period of measurement, the average flower count per plant in the -0.2, -0.4, and -0.6 m treatments was 17%, 37%, and 47% fewer respectively, compared to the control. Kurup et al. (1994) reported that the pre-blooming stage in marigold was more sensitive to water stress, where it increased phenolic biosynthesis and enhanced lignin formation to cope with drought stress. As such, the flower production in the capillary-irrigation can be improved by further reducing the pressure particularly during the pre-blooming stage of marigold.

4.4.5 Plant water consumption and WUE

The plants subjected to manual irrigation consumed more water while the plants under capillary-irrigations consumed less water for the entire period of the experiment (Table 4.1). Compared to the hand-watered control treatment, water consumption was 33% low in the -0.2m treatment, 58% and 62% lower in the -0.4 m and in -0.6m treatments, respectively. Moreover, the WUE, expressed as the ratio of plant dry mass to water consumption, was positively correlated with capillary-irrigations. The higher the capillary pressure, the higher the WUE. However, the plant yield in terms of plant height, leaf count and area, and plant biomass were negatively correlated with capillary pressure. Generally, the lower capillary pressure (-0.2 m) had a better plant growth performance similar to the control treatment despite the lower amount of water used. Based on the water requirements and the WUE for the species of marigold studied here, it is probable that low capillary-irrigation can favor a comparable plant yield while conserving considerable amount of water.

4.5 Conclusions

Irrigation systems that optimize the water use efficiency in ornamental plant production are needed to maximize the yield and crop quality while minimizing water wastage. Capillary-irrigation system can be a better option to fulfill these needs. A dwarf variety of marigold plant was grown to evaluate its performance with three different capillary pressure levels (-0.2, -0.4, and -0.6 m), and manual irrigation as a control. The marigold plants responded favorably to the -0.2 m capillary-irrigation system similar to the manual irrigation. The response declined with increased capillary pressure from the -0.4 to -0.6 m capillary-irrigations. The plant height, number of compound leaf, and leaf canopy area in the -0.2 m treatment were not significantly different from the control treatment while they were significantly lower in the -0.4 and -0.6 m treatments.

Despite the similar appearance of flowers in the -0.2 m and control treatments, a reduction in the number of flowers was observed in the -0.2 m treatment. This reduction was even more magnified in the high capillary-irrigation treatments, probably due to the water stress during the critical periods of plant growth. The production of flowers can be greatly enhanced by decreasing the capillary pressure during those critical periods of plant growth consequently decreasing the water stress that affected flower initiation. Moreover, the results for the compactness in plants indicated that the capillary-irrigation produced shorter but less compact plants. Relatively shorter plants are more favorable in the ornamental plant production industry.

The biomass yields were significantly lower in the -0.4 and -0.6 m capillary-irrigations compared to the manual irrigation. There was no significant different between the -0.2 m and the control. Further, the root length increased with increasing capillary pressure. Reduced plant growth associated with high capillary pressures may have attributed to increased resistance to water uptake by plants and consequently reduced water availability to plant growth.

The WUE was higher in the capillary pressure treatments compared to the control. However, despite the higher WUE, the plant yield decreased with increasing capillary pressure. The lower capillary pressure treatment (-0.2 m) had better growth performance similar to the control. Water savings of up to 33% compared to the manual irrigation were achieved in the -0.2 m capillary-irrigation while maintaining an acceptable plant yield. Hence, the -0.2 m was the most successful capillary pressure treatment in growing marigold plants compared to the -0.4 and -0.6 m treatments. Although the increased capillary pressure levels did not cause a complete failure of marigold plants, it would be more advantageous to use lower capillary pressures in the irrigation to obtain the desired yields while minimizing the water consumption.

The hand-watered treatments required watering more frequently due to the small root volume. The capillary-irrigated plants had continuous supply of water and therefore did not require frequent attention. The comparative labour savings is very high. In the conventional greenhouse operation, the potting soil volume is kept larger to facilitate less frequent irrigation. Consequently, this adds to the cost of production. However, the capillary-irrigation system with its access to continuous supply of water does not require a large root volume. This has an added advantage of lowering the volume of potting media required for the greenhouse operation.

The capillary-irrigation system requires less operator expertise, system maintenance, and sophisticated equipment. It also provides additional benefits for greenhouse plant production such as reduced labor and automated simple technique for container-grown plants.

CHAPTER 5 : CONCLUSIONS

A plant-controlled capillary-irrigation system was studied for its applicability in growing vegetable and ornamental plants under a controlled-environment. Two experiments were conducted using hot pepper and marigold plants under different capillary pressures to determine the performance of capillary-irrigation systems. The following general conclusions were drawn from the results of this research:

1. The vegetative growth measurements (plant height, leaf count, and leaf area) revealed that the plants grown under low capillary pressure (-0.2 m) treatment had the greatest vegetative growth as compared to those grown under higher capillary pressure (-0.4 and -0.6 m) irrigations. The plants under low capillary pressure treatment grew fairly well similar to the control treatment, producing no significant differences in vegetative growth.
2. The low capillary pressure treatment had on average more plant yields and biomass yield compared to the higher capillary pressure irrigations. The trend was consistent as observed in vegetative growth.
3. Specifically, in hot pepper plants, the fruit size and biomass yield were similar in both low capillary pressure irrigation and the control treatment. The hotness of pepper fruits, which is one of the important marketing characteristics of hot pepper, increased with increasing capillary pressure. It ranged from 31% to 89% higher than the control for the capillary pressures from -0.2 to -0.6 m, respectively.
4. The capillary-irrigation treatments were significantly more efficient in saving water than the control treatment. Compared to the control treatment, the water

savings were 33% and 35% in the marigold and pepper production, respectively, for the low capillary pressure irrigation, while maintaining better yields similar to the control treatment. However, for the higher capillary pressure irrigations, while the water savings increased (58% to 73%) the plant yields were lower. The WUE of the higher capillary pressure irrigation treatments was significantly greater than the lower capillary pressure irrigation.

5. The low capillary pressure irrigation is better than both the manual irrigation and the higher capillary-irrigations since it avoids both the over- and under-irrigation. Over- irrigation causes water and energy wastage, while under-irrigation causes excessive water stress to the plants leading to poor growth performance and yield losses.
6. The digital image analysis of vegetative cover of the plant designed to estimate the leaf area is efficient for non-destructive leaf area measurements because of its accuracy and affordability for researchers.
7. The water drawn into the root zone from the capillary-irrigation system was automatically controlled exclusively by the plant water demand. Thus, the automated capillary-irrigation system has the potential to provide maximum WUE by maintaining adequate soil moisture for better plant growth and yields; while saving energy, equipment, and skilled labour requirements to monitor the system.
8. The capillary-irrigation system offered continuous water supply with readily available water to meet evapotranspiration needs and to replace the moisture from the soil reservoir. As such, there is no need in the system for using large soil reservoir to save the water. The system used relatively small amount of growing

medium for plant growth. Thus, the system will be appropriate to supply water to the crop as needed; minimizing evaporation losses; improving irrigation management with continuous and slow applications; and improving plant yields.

Therefore, appropriately designed and properly installed capillary-irrigation system using moderately low capillary pressures could lead to considerable water savings to plant growers, while leading to sound economic and environmental benefits.

CHAPTER 6 : RECOMMENDATIONS FOR FUTURE RESEARCH

Based on this current study, the following suggestions outline the directions for future research on capillary-irrigation technique, which will lead to better refinement and improvement of the technique:

1. The reduction in plant yield was observed for higher capillary pressure irrigation systems (-0.4 and -0.6 m) compared to the manual irrigation. The yield reduction in these experiments may have been the result of water stress during the critical periods of plant growth. Imposing lower capillary pressures ($\leq$ -0.2 m) only during those critical periods will help to improve the plant yield similar to the manual irrigation. However, the resulting reduction in yield may be small when compared with the benefits gained through water savings. Therefore, carrying out a similar experiment on this system using different low capillary pressures at different growth stages would create a better understanding of the effects of the system on plant yield.
2. The proposed capillary-irrigation system design did not incorporate a system for fertilizer application. The fertilizer was manually applied. Future research should be designed to incorporate systems for both irrigation and fertilizer application together (fertigation). An efficient irrigation system that performs fertigation while irrigating the plants would provide further insight into the development and evolution of the capillary-irrigation technique.
3. The growing medium that was used in this work was a commercial potting soil. The physical and chemical composition of the growing medium can have a significant effect on water and air supply to the growing plant and wetting

properties of the medium. The capillary-irrigation system particularly favours a medium with increasing available water holding capacity, which helps to alleviate difficulties in rewetting the dried-medium. Studies looking at different growing mediums (improved peat-based media or incorporating hydrogels) in the capillary-irrigation system would contribute to the understanding of the effect of the growing medium on the capillary-irrigation and the plant performance.

4. The current research on capillary-irrigation used a constant volume of growing medium for the plant growth. Limited amount of growing medium that is available for root growth may have influence on below- and above-ground growth of plant. The optimum amount of growing medium for a given cultivar varies according to moisture availability and root and shoots growth of the cultivar. Therefore, comparing different amounts of growing medium using a capillary irrigation system operating under low pressure would be beneficial to understand the effect of different amounts of growing medium on different cultivars under capillary-irrigation system.
5. In this study, hot pepper was used as one of the vegetable plants and marigold as one of the ornamental plants. Different plants respond differently to water availability and to water stress. As such, experiments on capillary-irrigation could be done with different types of plant to be able to generalize the findings.

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