

UNIVERSITI PUTRA MALAYSIA

MODELING WATER AND FERTILIZER USE IN WICK IRRIGATION SYSTEM FOR SMALLHOLDER GREENHOUSE CROP PRODUCTION

JAVED SHAHEEN

FK 2018 58



MODELING WATER AND FERTILIZER USE IN WICK IRRIGATION SYSTEM FOR SMALLHOLDER GREENHOUSE CROP PRODUCTION

By

JAVED SHAHEEN

Thesis Submitted to the School of Graduate Studies, University Putra Malaysia, in Fulfillment of the Requirements for the Degree of Master of Science

June 2017

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DEDICATIONS

This dissertation dedicated to every individual of my family. Especially my loving and caring parents "My Beloved Father Dr. Muhammad Javed" and "My Dearest Mother Sabra Javed" who always encouraged me in every step of my life. It is also dedicated to My Love and Life My Son "Ertugrul Roonjho" and also to My Sweetheart my Husband "Abdul Rehman Roonjho."



Abstract of thesis presented to the Senate of Universiti Putra Malaysia in Fulfilment of the Requirement for the Degree of Master of Science.

MODELING WATER AND FERTILIZER USE IN WICK IRRIGATION SYSTEM FOR SMALLHOLDER GREENHOUSE CROP PRODUCTION

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June 2017

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Water shortage has become the crucial issue of the current world, and it is going to be harder day by day to fulfill the food requirements of the increasing world population with the available fresh water resources using traditional irrigation systems. Therefore, there is urgent need to develop and adopt efficient irrigation methods and proper irrigation management strategies. No doubt among micro irrigation systems, drip irrigation saves a substantial amount of water and labor, increases yields, and often also improves the quality of the produce. However, the higher investment and energy cost limit the development of the low-cost irrigation system for subsistence farmers. There has been immense interest in developing new micro-irrigation systems. and wick irrigation system as promising irrigation methods to address this issue. This study, by conducting laboratory experiments, compared and confirmed hydraulic characteristics and performance of cotton-bonded nonwoven material against local materials. The performance of hanging and buried wick was compared in the laboratory and glasshouse as well. Factors, such as water level inside PVC pipe, wick length inside PVC pipe, initial volumetric water contents and pot size, related to discharge variation of the wick emitter were evaluated in the laboratory. The relationship was investigated among crop water use (ET), pot size and water level in the glasshouse. In this study, the wick emitter discharge equation was developed for both hanging and buried wick. Moreover, the wick irrigation design was developed using water circulating pump, hose pipes and PVC pipes for glasshouse to avoid algae growth and evaporation. Algae growth was observed visually, and water loss was measured before and after algae growth to evaluate the effects of algae growth on the discharge of buried wick. An experiment was carried out for tomato crop to simulate water distribution and wetting pattern using HYDRUS 2D/3D. Two water levels inside the pipe, three types of pots by size and "peatgrow" as growing media were used to develop the proper water application strategies and irrigation efficacy. Soil moisture contents were also measured. Crop nutrients management was evaluated by measuring EC and pH at a different stage of the crop using EC and pH meters, and the amount of

nutrients (N, P, K, Mg, Na and Ca) was determined in leachate. The results from this study showed and proved that cotton-bonded non-woven wick material has better capillarity action, maximum capillary height and water holding capacity than local materials. The results also showed the effects of water level inside the pipe, wick length inside the pipe, pot size, ET and initial volumetric water contents on the discharge of wick irrigation system. Factors related to the wick emitter discharge used to develop equations for compensating wick emitter discharge by replacing the pressure head of a drip emitter with controlling factors of the wicking emitter. The measured water volume was close to the simulated water using wick emitter discharge equation. The results of collected ET using different methods were in order $ET_{wBE} > ET_{gvi} > ET_{CROPWAT} > ET_{gauge}$. Algae was observed at the end of the 3rd month with 6% decreasing effects on the discharge of buried wick. Results from this study revealed that the tomato plant growth showed insignificant differences when fresh water was used at two discharge levels. In contrast, the tomato plants growth showed differences among the pot size, in small pots roots were exceeded out from the bottom of the pot. The results obtained for EC and pH showed significant difference based on the age of the plant. The leachate was observed and the results of nutrients determination in leachate revealed the highest amount of P followed by Ca, Mg, Na, K and N. The results of simulation of water movement using HYDRUS 2D/3D disclosed the water movement of wick irrigation system in a container planted with tomatoes. The findings from this study suggested opportunities to improve an effective Capillary Wick Irrigation System (CWIS) for smallholder greenhouse production.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Master Sains.

PEMODELAN PENGGUNAAN AIR DAN BAJA DALAM SISTEM PENGAIRAN SUMBU UNTUK PENGUSAHA KECIL PENGELUARAN TANAMAN RUMAHKACA

Oleh

JAVED SHAHEEN

Jun 2017

Pengerusi: Md. Rowshon Kamal, PhD Fakulti: Kejuruteraan

Kekurangan air menjadi isu penting dalam dunia sekarang, dan ia akan menjadi lebih teruk lagi hari demi hari bagi memenuhi keperluan makanan penduduk dunia yang semakin meningkat disebabkan oleh sumber air tawar yang boleh didapati dengan menggunakan sistem pengairan tradisional. Oleh itu, terdapat keperluan segera untuk membangun dan mengamalkan kaedah pengairan yang cekap dan strategi pengurusan pengairan yang betul. Tiada keraguan pada sistem pengairan mikro, pengairan titisan menjimatkan sejumlah besar air dan tenaga kerja, meningkatkan hasil, dan sering juga meningkatkan kualiti hasil. Walau bagaimanapun, pelaburan dan kos tenaga yang lebih tinggi menghadkan pembangunan kos rendah sistem pengairan bagi sara diri petani. Terdapat minat yang besar dalam membangunkan sistem pengairan mikro baru dan pengairan sistem pengairan sebagai kaedah pengairan yang dijanjikan untuk menangani isu ini. Kajian ini, dengan menjalankan ujikaji makmal, dibandingkan dan mengesahkan ciri-ciri hidraulik dan prestasi bahan kapas-terikat bukan tenunan terhadap bahan-bahan tempatan. Prestasi sumbu gantung dan ditanam telah dibandingkan di makmal dan rumah kaca juga. Faktor-faktor, seperti tahap air di dalam paip PVC, panjang sumbu dalam paip PVC, kandungan air isipadu awal dan saiz periuk, yang berkaitan dengan perbezaan pelepasan pemancar sumbu telah dinilai di dalam makmal. Hubungan itu disiasat antara penggunaan air tanaman (ET), saiz periuk dan paras air di dalam rumah kaca.

Dalam kajian ini, persamaan pelepasan sumbu pemancar telah dibangunkan untuk kedua-dua sumbu tergantung dan yang ditanam. Selain itu, reka bentuk pengairan sumbu telah dibangunkan menggunakan air pam edar, paip hos dan paip PVC untuk rumah kaca bagi mengelakkan pertumbuhan alga dan penyejatan. Pertumbuhan alga diperhatikan secara visual, dan kehilangan air diukur sebelum dan selepas pertumbuhan alga untuk menilai kesan pertumbuhan alga pada pelepasan sumbu yang terkubur. Satu eksperimen telah dijalankan untuk tanaman tomato untuk mensimulasikan pengagihan air dan corak pembasahan menggunakan Hvdrus 2D / 3D. Dua tahap air di dalam paip, tiga jenis pasu mengikut saiz dan "peatgrow" sebagai media penanaman telah digunakan untuk membangunkan strategi penggunaan air yang betul dan keberkesanan pengairan. Kandungan kelembapan tanah juga diukur. Pengurusan nutrien tanaman telah dinilai dengan mengukur EC dan pH di peringkat yang berbeza daripada tanaman menggunakan EC dan pH meter, dan jumlah nutrien (N, P, K, Mg, Na dan Ca) telah ditentukan dalam larut resapan. Hasil daripada kajian ini menunjukkan dan membuktikan bahawa bahan sutera bukan terikat kapas mempunyai tindakan kapilari yang lebih baik. ketinggian kapiler maksimum dan kapasiti pegangan air daripada bahan tempatan. Keputusan juga menunjukkan kesan paras air di dalam paip, panjang sumbu di dalam paip, saiz periuk, ET dan kandungan air isipadu awal pada pelepasan sistem pengairan sumbu. Faktor-faktor yang berkaitan dengan penunaian sumbu pemancar digunakan untuk membangunkan persamaan untuk menampung pelepasan pemancar sumbu dengan menggantikan kepala tekanan dengan mengawal faktor pemancar sumbu. Jumlah air yang diukur adalah dekat dengan air yang disimulasi menggunakan sumbu persamaan pelepasan pemancar. Keputusan ET yang dikumpulkan menggunakan kaedah vang berbeza adalah untuk ETWBE> ETgvi> ETCROPWAT> ETgauge. Alga diperhatikan pada akhir bulan ke-3 dengan 6% peratus kesan berkurangan pada pelepasan sumbu ditanam. Hasil daripada kajian ini menunjukkan bahawa pertumbuhan tumbuhan tomato menunjukkan perbezaan yang tidak ketara apabila air tawar yang digunakan pada dua tahap pelepasan. Sebaliknya, pertumbuhan tanaman tomato menunjukkan perbezaan antara saiz periuk, di dalam pasu kecil akar telah melebihi keluar dari bahagian bawah periuk. Keputusan yang diperolehi untuk EC dan pH menunjukkan perbezaan yang ketara berdasarkan umur tumbuhan. Larut resapan diperhatikan dan keputusan penentuan nutrien dalam larutan resapan mendedahkan jumlah tertinggi P diikuti oleh Ca, Mg, Na, K dan N. Keputusan simulasi pergerakan air menggunakan Hydrus 2D / 3D mendedahkan pergerakan air sistem pengairan sumbu dalam bekas yang ditanam dengan tomato. Penemuan kajian ini mencadangkan peluang untuk memperbaiki Sistem Pengairan Silikon Kapilari (CWIS) yang berkesan untuk pengeluaran rumah hijau pekebun kecil.

ACKNOWLEDGEMENTS

Before all, let me thank Almighty Allah, who is kind gracious, magnificent, benevolent and most merciful and creator of all creations. I extend my countless salutations in the honor of his messenger Holy Prophet Muhammad (peace be upon him) who encouraged pursuing learning from birth until death.

I would take the opportunity to express my humble appreciations to my research supervisor Dr. Md. Rowshon Kamal for diligent supervision and regulation during the entire research process. Here also I would like to appreciate the services rendered by my co-supervisor Dr. Aimrun who helped me during my research whenever I needed. I am highly thankful to Mr Hadi for his valuable support throughout the studies. Thanks to the Soil and Physics laboratory assistant Mr. Abdul Aziz for timely assistance.

Additionally, I would like to express my gratitude to my husband Abdul Rehman Roonjho for his technical and moral support during my entire studies and I am also grateful to my parents, siblings, and all family members for their love, amiable attitude and moral support.

I gratefully acknowledge the funding received for my masters from the Lasbela University of Agriculture, Water and Marine Sciences, Uthal and off course this study would not have been possible without this financial support. This thesis was submitted to the senate of university Putra Malaysia and has been accepted as fulfillment of the requirements of the Degree of Master of Science. The members of the Supervisory Committee were as follows:

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Date:

Declaration by graduate student

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LIST OF ABBREVIATIONS

°C	Temperature
2D/3D	Two-dimension/ Three-dimension
ai	experimental coefficient
AI	Airspace
AMIT	Affordable Micro-irrigation Techniques
CC	Container capacity
CDF	Convection-dispersion equation
CNW	Cotton bonded non woven wick
CM	centimeter
CM	Cotton Material
	Capillary wick irrigation system
	Drainage
	Pulk dopoity
DB	Distribution uniformity
	Distribution uniformity
Cm ³	Centimeters cube
EAW	Easily available water
Ebb	Ebb and flow irrigation system
EC	Electrical conductivity
Eq	Equation
ET	Evapotranspiration
ETo	Potential evapotranspiration
ETA	Actual evapotranspiration
ETc	Evapotranspiration of the crop
FW	Final Weight
FC	Controlling factor
g	Gramme
ĞBM	Gunny bag material
h	Pressure head
h _e	Pressure head of emitter
h	Hour
1	Irrigation
IAE	Irrigation application efficiency
IE	Irrigation efficiency
IW	Initial Weight
IDE	International Development Enterprises
$K(\theta)$ or K	Unsaturated hydraulic conductivity
(h)	onoutantice nyaratilo conductivity
(II) Ka	Cron coefficient
k.	Emitter discharge coefficient
kna	Kilonascal
K	Saturated hydraulic conductivity
I S	
	Lillers Wiek length
Lw	
l	Pore-connectivity parameter
	wass per mass
M° M⁻³	volume per volume
MCH	Maximum capillary height

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Md	Mass of dry wick
Mm	Millimeter
Ms	Mass of wet wick
Mg	milligram
МĬ	milliliters
NFW	Nutrient-flow wick culture
NGO	Non-Government Organization
P	Experimental constant
PAW	Plant available water
nD	Particle density
PT	Pour-Through
PVC	polyvinyl chloride
a	Water flux
Ч ().	Discharge of emitter
RAW	Readily available water
RH	Relative humidity
S	Sink term
5	Effective saturation
SM	Soil moisture
Sivi S.	Standard Deviation
5d 6D	Sufficient distilled
5D SDC	Sufficient distilled
SDC	Swiss Development co-operation
	I otal porosity
	Uniformity coefficient
UC	University of California
Vavg	Volume Average
VG	Van Genuchten
Vlq	Volume of lowest value
VWC	Volumetric water content
WBC	Water buffering capacity
WC	Water collected
WEDE	Wick emitter discharge equation
WHC	Water holding capacity
WRC	Water retention Curve
WL	Water level
x	Exponent
α,n.m	Van Genuchten fitting parameters
θ	Water content
θr	Residual water content
θs	Saturated water content
dSm ⁻¹	deciSiemens per meter

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CHAPTER 1

INTRODUCTION

1.1 Background

Water shortage today has become a pressing issue of global concern. It is hard to fulfill the food requirements of the increasing world population by providing available fresh water resources using traditional irrigation systems. Therefore, there is a crucial requirement to investigate, develop and implement efficient irrigation techniques and effective irrigation management strategies. Among micro-irrigation systems, drip irrigation has been proven to save both significant amounts of water and labor costs, increase yield, and frequently also enhance the product quality. However, the high investment and energy costs are obstacles that hamper efforts to develop low-cost irrigation systems for subsistence farmers. There is therefore much interest in the design and development of novel micro-irrigation systems to address the rising water crisis

Greenhouse plant production plays an important role in agriculture and helps to meet the food demands of today's world population but it has undergone dramatic change from the use of mineral soils to new soilless growing media in the last few decades as a result of developments in the growing media system. Many different types of growing media are produced by various manufacturers. Peat-based substrates are frequently used in the growing systems, but sometimes inorganic substrates like perlite and rock wool are used in potted plant production. These growing media can differ in their physical and chemical properties. It is important to optimize the conditions in the root zone of potted medium. Although researchers have paid much attention to the chemical and physical nature of the substrates in the past, there is still a knowledge gap that exists in modeling water in the root zone of potted plants to achieve high yields with minimal waste of water and fertilizer. The water movement in potted plants should be known to set the adequate discharge as per crop water requirement. As the laboratory and greenhouse experiments are costly and time consuming, the numerical models are mostly used to predict water movement. Recently the two- and/or three-dimensional simulation model HYDRUS 2D/3D, which provides a numerical solution to the Richard's equation for saturatedunsaturated water flow and the convection-dispersion equation for solute flow has been used in micro-irrigation systems and emerged as a dependable indicator of modeling water (Gärdenäs et al., 2005).

The uniform distribution is also a crucial parameter in the development, control and adoption of micro-irrigation. A properly-designed irrigation system provides the approximately equal amount of water distributed to every plant and is economically viable. The uniform nature of the system ensures that an irrigation system's distribution of water is even over the root zone. Excess irrigation applications to the potted plants cause disease, contamination of ground water and low yield (Klock-Moore and Broschat, 2001b). Many studies have been conducted to find efficient water application approaches to potted plants (Dole et al., 1994). A drip irrigation system is a widely-used method to irrigate crops efficiently under protected cultivation. The sub-irrigation system is an efficient water application model to save labor costs, time and water compared to other methods (Dole et al., 1994). Unfortunately, due to the high start-up costs smallholder farmers have not been able to afford the installation and use of the drip irrigation system (Wesonga et al., 2014). However, advanced irrigation systems with improved performance are still needed, especially to apply water to potted plants. Among smart irrigation systems, wick irrigation system is a promising irrigation method.

Capillary Wick Irrigation System (CWIS) is a sub-irrigation system that utilizes a device that provides water through capillary movement from a reservoir to the plant growing medium. Sub-irrigation systems are economical in terms of labor, time and water costs in comparison with overhead irrigation systems for potted plants (Dole et al., 1994; Klock-Moore, 2001; Son et al., 2006). Capillary Wick Irrigation System is ideal for greenhouse production as it is water and nutrient efficient for crop plants production (So et al., 2003). The system produces better quality produce with less water loss in the absence of runoff, lower labor costs, and decreased cases of diseases besides saving time and costs operation. This irrigation innovation also offers easy and economy of installation and operation (Bainbridge, 2002).

Myung et al. (2007) analyzed the water contents of root media for various wick lengths, pot sizes and media compositions to establish the proper irrigation requirements in a nutrient-flow wick culture (NFW) system. This study found that water content fluctuated more with reduced pot size in the NFW system. Factors, like wick length, pot size, and medium composition, affected the water contents of the medium in the NFW system. The water contents in the media were reduced by more than 8% and 5% in 2 cm and 3 cm wick lengths within 15 minutes respectively.

It is unfortunate that there have been very few studies, regarding the optimal moisture contents of soilless substrates in pots, the hydraulic characteristics and water contents of growing medium in capillary wick irrigation systems (CWIS). On the other hand, Kirkham and Powers (1972) stated that ideal level of moisture for plant growth in mineral soils is 25% of the soil volume. Son et al. (2006) indicated that water content ranging from 30% to 60% in growing medium provided good growth in Kalanchoe. The CIWS consists of a fabric strip, which is put on the pots from the bottom and absorbs water from a water reservoir delivering to the root zone. Research has already been carried out on a capillary wick irrigation system for potted plants in Japan and South Korea (Kwon et al., 1999). This system cannot raise water to more than 20 cm. In relation to this issue, Wesonga et al. (2014) reported that the maximum capillary height of wick materials ranged from 14 to 19 cm. Therefore, the

precise water application will remain greatly important and societies worldwide need to develop strategies by designing efficient techniques for agricultural irrigation. This current research was conducted to determine the hydraulic characteristics of the capillary wick irrigation system from the top. This theme was adopted bearing in mind the coefficient and distribution uniformity as the relevant parameters for irrigation management. The other reason for adopting this topic was, negligence, as very limited attention has been given to the hydraulic characteristics and water contents of different growing media for potted plants cultivation under CWIS. However, the algae growth in wick irrigation has been recorded and is now a major hurdle in practicing the wick irrigation system widely. Therefore, it is required to make agricultural water useful and more efficient through the enhancement and application of the current irrigation science and technologies (Hsiao et al., 2007). Therefore, in this study available local materials are compared with commercially available non-woven cotton wick, while hydraulic characteristics and irrigation efficacy are also carried out and a comparison made between hanging and buried wicks by using Peat Grow (soilless media) under laboratory conditions. Furthermore, the capillary wick irrigation is designed to minimize algae growth and evaporation. An experiment was conducted in a greenhouse with potted tomatoes and evaluated CWIS's performance for the best management practices in smallholders greenhouse production.

1.2 Problem Statement

Agricultural producers worldwide are facing massive challenges in producing enough to feed the 9.6 billion global population that the FAO projects by 2050. Increasing world population will increase the demand for food production which must be raised by 70%. It seems quite impossible to meet the food demand of around 10 billion people because of limited available arable lands and the competitive demand for limited fresh water, among other factors.

In today's globalized and wired world, over half of the worldwide population (54%) resides in urbanized areas even though there are still significant differences in the levels of urbanization from country to country. The decades ahead there will bring even more significant changes to the size and spatial distribution of the human population. The ongoing urbanization and overall increase of the world's population is expected to add 2.5 billion people to the urban population by 2050, with almost 90 % of the increase in Asia and Africa (Brenner and Schmid, 2014). Therefore, smallholders have to play a key role to produce more with less input. Drip irrigation is the method mostly used by smallholder greenhouse farmers to save water and reduce fertilizer losses, but this still needs energy for operation, lots of tools and cost of installation, making it difficult and putting it out of reach of the majority of low-income farmers.

Lee et al. (2010) investigated sub-irrigation using capillary wick system for a specialized pot with a wick in the bottom (13.5 cm diameter x 10.5 cm height).

The results revealed that the height of the pots was limited to the wick's ability to irrigate the upper part of the pots due to the limit of rising water. Wesonga et al. (2014) conducted research on capillarity action, water holding capacity and maximum capillary height for five types of wick materials. They concluded that the maximum height of capillarity is less than 20 cm. The wick irrigation system can be applied to the bottom and from the top of the pot. Only a few researches have been undertaken to measure the results of CWIS, and no one has yet tried to develop a systematic wick irrigation system. However, a research recorded algae growth as a serious problem in wick irrigation. Irrigation efficiency by wick is related to proper water distribution in growing medium, minimizing algae growth and limited capability of rising water when irrigated from the bottom of the pot. Therefore, this study focuses on improving wick irrigation system to maximize the application of water and fertilizers using experiment and 2D-HYDRUS simulation for smallholder greenhouse production.

1.3 Aim and Objectives

The aim of this study is the modeling of the capillary wick irrigation system (CWIS) to characterize the principle components and to determine the best management practices of water and fertilizers for the smallholders' crop production. The specific objectives are:

- 1. To develop the equation for compensating wick emitter discharge;
- 2. To determine the optimum water and nutrients use for tomato grown in different pot sizes;
- 3. To minimize algae growth and evaporation losses WIS
- 4. To determine the optimum pot size and zero leachates for potted crops in greenhouse; and
- 5. To evaluate two dimensional water distribution pattern in potted growing media using HYDRUS 2D simulation

1.4 Significance of the Study

The modified design for wick irrigation system will enable the wide adoption of this irrigation system and prove the equation for cotton-bonded non-woven wick material, which will help to establish the discharge rate of the wick material. By measuring hydraulic characteristics of the wick materials, the most suitable wick material for capillary wick irrigation system was determined. The best size of the pot and enough discharge were known to manage nutrients in potted tomatoes for wick irrigation. Moreover, simulation of water movement under wick irrigation enables farmers and researchers to schedule irrigation for the best management practices.

1.5 Scope of Work

The research approach includes modification in the design of capillary wick irrigation system to minimize the algae growth and evaporation, modification of wick emitter discharge equation and produce an effective low-cost irrigation system for smallholders' greenhouse production. This is achieved as follows:

- 1. Conduct laboratory experiments to identify best material as wick emitter and develop the equation for wick emitter discharge.
- 2. Finding the correlation of controlling factors affecting the capillary wick discharge rate.
- 3. Evaluating the best size of pot for potted tomatoes in CWIS.
- 4. Managing nutrients and water discharge application in CWIS
- 5. Simulation of 2D-water movement using HYDRUS 2D/3D in different size pots at different discharge rate under CWIS.

REFRENCES

- Al-Amound, A.I (1995). Significance of energy losses due to emitter connections In trickle irrigation lines. *J. Agric. Eng. Res.* 60, 1-5.
- Andriolo, J.L., G.L. Luz., C. Giraldi., R.S. Godoi. and G.T. Barros. (2004). Growing lettuce plants in hydroponics using substrates: an alternative for the NFT. *Horticultura Brasileira* 22, 794-798.
- Anlauf, R. (2014). Using the EXCEL solver function to estimate the van genuchten parameters from measured pF/water content values. Retrieved from <u>http://www.al.hsosnabrueck.de/analauf.html</u>. On 29, august, 2014.Anlauf, R. (2014).
- Argo, W.R., Biernbaum, J.A. (1994). Irrigation requirements, root medium pH and nutrient concentrations of Easter lilies grown in five peat-based mediawith and without an evaporation barrier. J. Am. Soc. Hot. Sci. 119, 1151-1156.
- Argo, W.R. (1998). Root medium physical properties. *HortTehnology, 8*(4), 481-485.
- Arguedas, F. R., Lea-Cox, J.D. and Mendez, C.H. (2006). Calibration of ECH@Oprobe sensors to accurately monitor water status of traditional and alternative substrates for container production. *Proc. South. Nursery. Assoc. Res. Conf, 51,* 501-505
- Bainbridge, D.A. (2002). Alternative irrigation systems for arid land restoration. *Ecological Restoration*, 20(1), 23-30.
- Bainbridge, D.A., Almoril, R., and Javier, J. (2008). More efficient irrigation systemfor desert and dry land restoration. *Restoration and management notes*, 8(1),1-14.
- Bainbridge, D. (2014). Get started with more efficient irrigation systems. Irrigation, water conservation, water harvesting. <u>http://permaculturenews.org./Accessed on 13 December 2014</u>.
- Beaker, K.F. (1957). The U.C system for producing healthy container grown plants through the use of clean soil. Clean stock, and sanitation. *University of California, Division of agricultural Sciences,p.* 332.
- Beeson, R.C. (2005). Modeling irrigation requirments for landscape ornamentals. *HortTechnology*, *15*(1),18-22.
- Beeson, R. C. and Yeager, T.H. (2003). Plant canopy affects sprinkler irrigation application efficiency of container-grown ornamentals. *HortScience*, *38*(7).1373-1377.

- Beeson, R. and Knox, G. (1991). Analysis of efficiency of overhead irrigation in production. *HortScience*, *26*(7), 848-850.
- Birch, P.D.W. (1971). Choice of three systems for peat substrate culture. *Ibid.* 75:865-8.
- Blom, T.J. and Piott, B.D. (1992). Preplant moisture content and compaction of peatwool using two irrigation techniques on potted chrysanthemums. *Journal of the Amarican Socity for Horticultural Science, 117*(2),220-223.
- Bogena, H., Huisman, J., Oberdorster, C. and Vereecken, H.(2007). Evaluation of a low-cost soil water content sensor for wirless network application. *Journal of the Hydrology, 344*(1), 32-42.
- Borrero, C., Trillas, M. I., Ordovas, J., et al. (2004). Predictive factore for the supperession of Fusarium wilt of the tomato in plant growth media. *Phytopathology*, *94*, 1094-1101.
- Bos, M. and Wolters, W. (1990). Water charges and irrigation efficiencies. *irrigation and drainage system*, 4(3), 267-278.
- Brooks, R. and Corey, A. (1964). Hydraulic properties of porous media, Colorado state univ. *Hydrol.paper*, (3).
- Brooks, R. and Corey, A. (1964). Hydraulics Properties of porous media, Colorado state univ. *Hydrol.paper*, (3).
- Burger, D., Hartin, J., Hodel, D., Lukaszewski, T., Tjosvold, S. and Wagner, S. (1987). Water use in California's ornamental nurseries. *California Agriculture*, *41(9)*, 7-8.
- Burt, C.M., Clemmens, A.J., Strelkoff, T.S., Solomon, K.H., Bliesner, R.D., Hardy, L.A. and Eisenhauer, D.E. (1997). Irrigation performance measures: efficiency and uniformity. *Journal of irrigation and drainage engineering*, 123(6), 423-442.
- Burt, C.M. and S. W. Styles. (2007). Drip and Micro irrigation design and management for trees, vines, and Field crops. *3rd edition irrigation training and Research Center*, 2007.
- Camberato, D.M., R.G.Lopez, and M.V. Mickelbart. (2009). pH and electrical conductivity measurements in soilless substrates. *Purdue Univ. Ext. Serv. Bul. HO*-237-W.
- Caron, J., Riviere, L.M. and Guillemain, G. (2005). Gas diffusion and air-filled porosity: Effect of some oversize fragments in growing media. *Can. J. Soil Sci.* 85:57-65.

- Cavins, T.J., B.E.Whipker., W.C.Fonteno., B. Harden., I. McCall, and J.L. Gibson. (2000). Monitoring and managing EC using pourthru extraction method. *North Carolina State Univ. Coop.Ext. Ser. Bul.*590.
- Celia, M.A., Bouloutas, E.T and Zarba, R.L. (1990). A general massconservative numerical solution for the unsaturated flow equation. *Water Resources Research*, *26*(7), 1482-1496.
- Chen, Q., Zhang, XS., Zhang, HY., Christie, P., Li XL, Horlacher. D, and Liebig, HP. (2004). Eevaluation of current fertilizer practice and soil fertility in vegitable production in the Beijing region. *Nutr Cycle Agroecosyst* 69:51-58.
- Cooper, A.J. (1973). Root temperature and plant growth. Reserch review No. 4 C.A.B. Slough, England:Farham Royal .
- Dane , J.H., Topp, C., Cambell, G.S., Horton, R., Jury, W.A., Nielson, D.R., and Topp, G.C. (2002). Part 4: physical Methods. *Methods of soil Analysis.* (pp. 417-535).
- De Boodt, M. and Verdonck, O. (1971). The physical properties of the substrates in horticulture. *III Symposium on peat in horticulture. 26,* 37-44.
- DE Boodt, M., Verdonck, O. and Cappaert, I. (1974). Determination and study of the water availability of substrates for ornamental plant growing. *Acta Hortic,* 5, 105-111.3
- Dolar, S.G., Keeney, D.R., (1971). A self-watering system for growing plant in potted soils. *Agron. J.* 63, 334-336.
- Dole, J.M., Cole, J.C and von Broembsen, S.L (1994). Growth of poinsettias, nutrient leaching, and water-use efficiency respond to irrigation methods. *HortScience*, 29(8), 858-864.
- Ella, V.B., M.R. Reyes. And R. Yoder. (2009). Effects of hydrullic head and slope on water distribution uniformity of a low-cost drip irrigation System. *App. Eng. In Agric*.25(3):349-356.
- Ferrarezi, R.S., Dos Santos, L.N.S., De Sousa, A.C.M., Pareira, F.F.S., Elaiuy, M.L.C., Torrel, U. and Matsura., E.E. (2012). Water depth, filling time and volume of wick irrigation equipment and determination of water distribution uniformity in substrates. *Bragantia*,*71*, 273-281.
- Fonteno, W. C., Bailey, D.A. and Nelson, P.V. (1995b). Properties of greenhouse substres. *North Carolina FlowerGrowers Bull*, 40(4), 3-8.
- Fonteno, W., Hardin, C. and Brewster, J. (1995a). Procedures for determining physical properties of horticulture substrates using the NCSU porometer. *Horticultural substes Laboratory, North Carolina State University.*

- Food and Agriculture Organization. (2016). Crop evapotranspiration: guidelines for computing water requirements, *Natural Resources Management and Environment department.* Retrieved from <u>http://www.foa.org.</u> on 13 october 2015.
- Gardenas, A., Hopmans, J., Hanson, B., and Simunek, J. (2005). Towdimensional modeling of nitrate leaching for various fustigation scenarios under micro-irrigation. *Agricultural Water Management*, *74*(3), 219-242.
- Gladiz Z. (2005). Irrigation management options for containerized-grown nursery crops.(No.E30 2). Rutgers NJAES Cooperative Exxtension.
- Goodwin, P.B., M. Murphy, P. Melville, and W. Yiasoumi. (2003). Efficiency of water and nutrient use in containerized plants irrigated. *Aust. J. Exp. Agr.* 43: 189-194.
- Hadi, H.M. (2015). Modeling of capillary wick irrigation system for potted plant and small scale plantation. Thesis submitted to the school of Graduate studies, Universiti Putra Malaysia, in fulfilment of the requirements for the degree of Master of Sciences. August 2015.
- Hammond, R.F. (1975). The origin, formation and distribution of peatland resources. *In peat in Horticulture* (D.w. Robinson and J.G.D. lamb,eds). London: ACADMIA.PRESS.PP 1-22.
- Hamalainen, A. (1962). Pressed peat sheets as a growing substrate. *Pautarha,* 65, 312.
- Handreck, K.A. and Black , N.D. (2002). Growing media for ornamental plants and truf UNSW press
- Helmut, G. (1972). Automatische dochbewa. Sserung Von gefa. Bversuchen. *Rrch. Acker- u. Pflanzenbau u. Bodenkd. 16,* 185-198.
- Hoitink, H. A. J., VanDoren, DM. J.R. and Schmithenner, A.F. (1977). Suppression of phytophthora cin-ormentals in a wcomposted hardwood bark potting medium. *Phytopathology*, *67*, *561*-565.
- Hsiao T.C., Steduto P. and Fereres, E. (2007). A systematic and quantitative approach to improve water use efficiency in agriculture. *Irrigation Sci. 25*, 209-231.
- Hussain, I. and Hanjra. M.A. (2005). Irrigation and poverty alleviation: Review of the empirical evidence. *Irrigation and drainage*, *53*, 1-15.
- In, S., Kang, H., Cho, K. and lee, C. (2003).Production of cyclamen using capillary wick system. I. Influence of wick material and root substratre composition. J. Kor.Flower Res. Soc, 12:199-206.

- Incroccia, L., F. Malorgio, A. Della Bartola, and A. Pardossi. (2006).The influence of drip irrigation or sub irrigation on tomato grown in closedloop substrate culture with saline water. *Sci. Hort.* 107, 365-372.
- Joseph G. Masabin, (year unkown). Vegetable Gardening in containers. Agri LIFE EXTENTIONS, TAMU; E-545,3-09
- Kang, S.W., S.G. Seo, and C.H Pak. (2009). Capillary wick width and water level in channel affects water absorption properties of growing media and growth of chrysanthemum and poinsettia culture in C-channel subirrigation system. *Korean Journal of Horticultural Science* &*Technology* 27(1), 86-92.
- karlovich, P.T. and W.C. Fonteno. (1986). The effects of soil moisture tension and volume moisture on the growth of chrysanthemum in three container media. *J. Amer. Sco. Hort. Sci. 111*:191-195.30: 197-202.
- Keller, J. and Blinsner, R. (1990). 1990, Sprinkler and trickle irrigation, van nostrand Reinhold, New York. Pp. 652.
- Kirkham, D. and Powers, W. L. (1972). Advanced Soil physics Wiley.
- Kirnak, H., Kaya, C., Tas, I and Higgs, D. (2001). The influence of water deficit on vegetative growth, physiology, fruit yield and quality in eggplants. *Bull J Plant Physiol*, *27*(3-4), 34-46.
- Kizito, F., Campbell, C.S., Campbell, G.S., Cobos, D.R., Teare, B., Carter, B., and Hopmans, J.W. (2008). Frequency, electrical conductivity and temperature analysis of a low –cost capacitance soil moisture sensor. *J. Hydrulogy* 352: 367-378.
- Klock-Moore, K.A. and Broschat, T.k. (2001b). Irrigation systems and fertilizer affect petunia growth. *HortTechnology*, 11(3), 416-418.
- Klock-Moore, K.A. and Broschat, T.K. (2001a). Effect of four growing substrates on growth of ornamental plants in two irrigation systems. *HortTechnology*, 11(3), 456-460.
- Klute, A. and Dirksen, C. (2003). Hydraulic conductivity and diffusivity: Laboratory methods. SOIL SCIENCE SOCIETY OF AMERCA BOOK SERIES, (1), 687-734.
- Kwon, O.Y., Huh, M.R. and Park, J.C. (1999). MK style bottom watering system for vegetable cultivation. *Kor. Res. Soc. Protected Hort, 12*(1), 112-120.
- Laviola, B.G., H.E. Martinez, and A.L. Mauri. (2007). Influence of the level of fertilization of the matrix plants in the formation of seedlings of coffee plants in hydroponic systems. *Ciencia e Agrotecnologia 31*, 1043-1047.

- Lee, C., So, I., Jeong, S., and Huh, M. (2010). Application of subiirigation using capillary wick system to pot production. *Journal of Agriculture & Life Science, 44*(3), 7-14.
- Majsztrik, J.C., Ristvey, A.G. and Lea-Cox, J.D. (2011). Water and nutrient management in the production of container-grown ornamentals. *Horticultural Reviews*, *38*, 253.

Mari Gowda, M.H. (1974). Dry orcharding. The lal Baugh 19(1/2), 1-85.

- Marr, C.W. and M. Jirak. (1990). Holding tomato transplants in plug trays. *HortScience*, 25, 173-176.
- Mason, J. (2004). Nursery management. Landlinks press, Victoria, Australia
- Masuda, M. (2008). Innovative cultivation method using capillary wick covered with water permeable root-barrier material. *Agr. Hort.* 83:20-25.
- Mathers, H.M., Case, L.T. and Yeager, T.H. (2005). Improving irrigation water use in container nurseries. *HortTechnology*, *15*(1), 8-12.
- Matsura, (2012). Water depth, filling time and volume of wick irrigation equipment and determination of water distribution uniformity in substrates. *Bragantia* 71, 27328.
- Melinda, L.H., Jack, W.B, and Leslie, A.W. (1996). Using subirrigation to maintainsoil moisture content in greenhouse experiments. *Weed Sci.* 44, 397-401
- Micheal, A.M. (1997). Irrigation theory and practice. Evaluating land for Irrigation Commands. Reprinted edition, Vikas publishing house, New Delhi, India
- Mohamed, A.N., Ismail, M.R. and Rahman, M.H. (2010). In vitro response from cotyledon and hypocotyls explants in tomato by inducing 6-benzylaminopurine. *Afr. J. Biotechnol.9*(30), 4802-4807.
- Molitor, H.D., (1990). The European perspective with emphasis on subirrigation and recirculation of water and nutrients. *Acta Hort.* 272, 165-174.
- Monteith, J. (1965). Evaporation and the environment, the state and movement of water in living organisms. XIXthe symposium.
- Mualem, Y. (1976). A new model for predicting the hydraulic conductivity of unsaturated porous media. *Water Resources Research*, 12(3), 513-522.
- Myung, M.O., Young, Y.C., Kee, S.K. and Junf, E.S. (2007). Comperisions of water content of growing media and growth of potted Kalanchoe

among nutrient-flow wick cultureandother irrigation systems. *HortTechnology, January-March, 17*,62-66.

- Naasz, R., Michel, J. and Charpentier, S. (2008). Water repellency of organic growing media related to hysteretic water retention properties. *European Jpournal of Soil Science, 59*(2), 156-165.
- Nelson, P.V. (1991). Greenhouse operation and management. 4th ed. Prentice hall, Englewood Cliffs, N.J.
- NeSmith, D.S. and J. R. Duval. (1984). The effect of container size. *HortTech.* 8(4), 495-498.
- NIAE (1965). Effects of the environment on tomato growth. *The National Institute of Agricultural Engineering*, 1963-64 50:2.
- Oh, M.M. and J.E. Son. (2008). *Phytophthora nicotianae* transmission and growth of potted kalanchoe in two recirculating subirrigation systems. *Scientia Horticulturae* 119:75-78.
- Penman, H.L. (1948). Natural evaporation from open water, hare soil and grass. Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences, 193(1032), 120-145.
- Pennisi, B.V. and P.A. Thomas. (2009). Essential pH management in greenhouse crops. Part 1: pH and plant nutrition. *Univ. Georgia coop. Ext. Serv. Bul.* 1256
- Penningsfeld, F. and Kurzman, F. (1966). Hydrokultur und Torfkultur. Stuttgart: Eugen Ulmer Verlag
- Prieto, I., C. Armas and F.I. Pugnaire. (2012). Water release through plant roots: new insights into its consequences at the plant and ecosystem level. *New phytologist* 193, 830-841.
- Puustjarvi, V. (1962). Peat as a substrate for tomatoes and cucumber. *Report* of the 16th International Horticultural congress.2, 191.
- Raviv, M. and Lieth, J.H. (2007). Soilless culture: Theory and practices: Theory and practices, Elsevier, United States of America
- Raviv, M.,Wallach, R. and Blom, T. (2001). The effect of physical properties of soilless media on plant performance – A review. *International Symposium on Growing Media and Hydoponics* 664, 251-259.
- Ritchey, K.D. and R.H. Fox. (1974). Use of wick-watering for greenhouse pots in the tropics. *Trop. Agr.* 51, 577-578.
- Rippy, J.F.M., and Nelson, P.V. (2007). Cation exchange capacity variation among Alberta, Canada, moss peat. *HortScience. 42:* 349-352.

- Rhoades, J., Chanduvi, F. and Lesch, S. (1999). Soil salanity assessment: Methods and interpretation of electrical conductivity measurements. *Food & Agriculture Org.*
- Ruff, M., D. Krizek., R. Mireck, and D. Inouye. (1987). Restricted root zone volume: influence on growth and development of tomato. J. Am. Soc. Hortic. Sci., 122(5), 763-769.
- Ruter, J.M. and M.P. Garber. (1993). Measuring soluble salts and pH with the Pour-Thru method. *Univ. Gorgia coop.Ext.Serv. Hort. Fact sheet.* H-93-015.
- Salama, M.A. (2011). Estimating water consumptive use for some crops under stress conditions neutron scattering method. Thesis submitted to Department of Soil Science Faculty of Agriculture Ain Shams University, in fulfillment of the requirement of doctorate degree.2011.
- Santamaria, P., G. Campanile, A. Parente, A. Elia. (2003). Subirrigation vs drip-irrigation Effects on yield and quality of soilless grown cherry tomato. *J. Hort. Sci. Biotechnol*, 78, 290-296.
- Santos, K.M., Fisher, P.R. and Argo, W.R. (2008). A survey of water and fertilizer ;management during cutting propagation. *HortTechnology*, *18*(4), 597-604.0
- Sauer, P., Havlik, U.A., Schneider, E. Schmid, G. Kindermann, and M. Obersteiner. (2010). Agriculture and resource availability in changing world: the role of irrigation. *Water resources research*, 46(6).
- Schaap, M.G., Leij, F.J. and Van Genuchten, M.T. (2001). Rosetta: A computer program for estimating soil hydraulic parameters with hierarchical Pedotransfer functions. *Journal of Hydrology*, 251(3), 163-176.
- Schuch, U.K. and Burger, D.W. (1997). Water use and crop coefficients of woody ornamentals in containers. *Journal of the American Society for Horticultural Science*, 122(5), 727-734.
- Schroder, F. and Lieth, J. H. (2002). Irrigation control in hydroponic. Hydroponic production of vegetables and Ornamentals, 263-298.
- Shi, K., X. T. Ding., D. K. Dong., Y.H. Zhou, and J.Q. Yua. (2008). Root restraction-induced limitation tophotosynthesis in tomato (lycopersicon esculentum Mill.) leaves. *Sci. Hortic-Amsterdam*, 117
- Shopova, N. and D. Cholakov. (2014). Effects of the age and planting area of the tomato (solanum Licoperscium L.) seedlings for late field production on the physiological behavior of plants. *Bulg J. Agric. Sci.* 20, 173-177.

- Simunek, J., Van Genuchten, M. T. and Sejna M. (2012). The HYDRUS software package The HYDRUS software simulating two-and threedimensional water movement of water, heat, and multiple solutes in variably-saturated media. *Technical Manual, version 2.3, PC progress, Prague, Czech Republic*
- Sonneveld, C. (Ed). (1989). A method for calculating the composition of nutrient solutions for soilless cultures. 3rd translated. Glasshouse cropsreserch station, Naaldwjk, Netherland.
- Son, J., Oh, M., Lu, Y., Kim, K. and Giacomelli, G. (2006). Nutrient-flow Wick Culture system for potted plant production: system characteristics and plant growth. *Scientia Horticulturae*. 107(4), 392-398.
- Son, J.E. (1996). Experimental model and neural network based electrical conductivity estimation in soilless culture system. *Acta.Hort.*440, 344-349.
- So, I.S., Kang, H., Cho, K.H. and Lee, W.C. (2003) Production of cyclamen suing capillary wick system : I . influence of wick material and root substrates composition. Journal of Korean Flower research Society, 11(2),199-206.
- Solomon, K.H. (1983). Irrigation uniformity and yield theory .*PhD. dissertation,* Deparment of Agricultural and irrigation Engineering. Utah State University, logan UT, 287 p.
- Spectrum Technologies Inc. (31/12/2014). Spectrum Technologies Inc. Retrieved from <u>http://www.specmeters.com/sm100</u>.
- Thornwaite, C. (1944). Report of the committee on transpiration and evaporation. *Tran Amer Geophys Union*, 25, 683-693.
- Thompson, R.B., Martinez-Gaitan, C., Gallardo, M., Gimenez, C. and Fernandez, M.D. (2007). Identification of irrigation and N Management practices that contribute to nitrate leaching loss from an intensive vegetable production system by use of a comprehensive surveys, *Agricultural water management , Vol.89,pp.* 261-274.
- Toth, J., Nurthen, E. and Chan, K. (1988). Simple wick method for watering potted plants which maintains a chosen moisture regime. *Animal Production Science*, 28(6), 805-808.
- Treder, T., Matysik, B., Norwak, J. S., Nowak, J. (1999). The effects of potting media and concentration of nutirnt solution on growth and nutrient content of three Ficus species cultivated on ebb and flow benches *Acta Hort. 481*, 433-439.

- Tyler, H.H., Warren, S.L. and Bilderback, T.E. (1996). Cyclic irrigation increases irrigation application efficiency and decreases ammonium losses. *Journal of Environmental Horticulture*, 14,194-198.
- Van Genuchten, M.T. (1980). A closed-form equation for predicting the hydraulic conductivity unsaturated soils. Soil Science Society of America Journal, 44(5), 892-898.
- Van Iersel, M., Dove, S. and Burnett, S. (2009). The use of soil moisture probes for improved uniformity and irrigation control in greenhouses. International Symposium on High Technology for Greenhouse Systems: GreenSys 20009 893, 1049-1056.
- Vogel, T. and Cislerova, M. (1988). On the reliability of unsaturated hydraulic conductivity calculated from the moisture retention curve. *Transport in Porous Media*, *3*(1), 1-15.
- Warren, S.L. and Bilderback, T.E. (2005). More plant per gallon: Getting more out of your water. *HortTechnology*, 15(1), 12-18.
- Wells, D.A. and Postlethwaite, J.D. (1970). Capillary irrigation, the effects of soil volume on tomato production. *Journal of Horticultural Science* 45, 207-14.
- Weston, L.A. and B.H. Zandstra. (1986). Effects of root container size and location of the production on growth and yield of tomato transplants. *J. Am. Sco. Hortic. Sci.*, 111, 498-501.
- Widders, J.E., (1989). Pretransplant treatments of N and P influence growth and elemental accumulation in tomato seedlings. *J. Am. Sco. Hortic.Sci.* 114(3), 416-420.
- Wesonga J.M., Wainaina C., Ombwara F.K., Masinde P.W. and Home P.G. (2014). Wick material and media for capillary wick based irrigation system in Kenya. *International Journal of Science and Research.*
- Woods, M, J. and Kenny, T. (1968). Nutritional and cultural aspects of the peat as a growing media for tomatoes. *Porc.* 6th coll. Int. Potash Int., 342-351.
- Woods, M.J. (1966). Tomato production in peat filled troughs. *Irish Journal of Agricultural Research* 5, 155-62.
- Yeager, T.H. (2003). Implementation guide for container-grown plant interim measure University of Florida Cooperative Extension Service, *Institute of Food and Agricultural Sciences, EDIS.*