Agricultural and Marine Sciences, 9(2):31-41(2004)

Water Use Efficiency and Yield of Cucumber (*Cucumis sativus* L.) Under Greenhouse and Field Conditions

H.A. Abdel Rahman* and H.S. Al-Wahaibi

Department of Soils, Water, and Agricultural Engineering, College of Agricultural and Marine Sciences, Sultan Qaboos University, P.O. Box 34, Al-Khod 123, Muscat, Sultanate of Oman.

كفاءة استخدام المياه لانتاج الخيار في البيوت المحمية والحقل

حيدر عبدالرحمن وحمدان الوهيبي

خلاصة: ساهمت موجات الجفاف والتطور العمراني والزراعي في تعميق الفجوة المائية بين ارتفاع الطلب وكميات المياه المحدودة في سلطنة عمان. ويعتبر استخدام البيوت المحمية للزراعة جزءاً من جهود الدولة لوضع الحلول المناسبة لمشكلة المياه في السلطنة. إلا أن هناك اعتقاداً بأن الزراعة المحمية غالباً ما تمارس تحت ظروف مناخية يمكن معها الاستفادة من الزراعة الحقلية. لهذا الغرض أجريت تجارب وعلى مدى عامين لإيجاد تأثير أربع معاملات ري (١ ، ٢ ، ٣ ، ٤ مم/ يوم في البيت المحمي) و (٣ ، ٤ ، ٦ ، ٨ مم/ يوم في الحقل) على إنتاج الخيار ودراسة تأثير نظام التبريد على كفاءة استخدام وتكاليف المياه. أوضحت النتائج أن إنتاجية الخيار في البيت المحمي تتزايد بمنحنى تربيعي بزيادة معدل الري من ١ إلى ٤ مم/ يوم. كانت معدلات ٢ مم/ يوم افضل معدل للحصول على الإنتاجية المثلى (كجم/متر٣)، بينما أعطت معدلات ٣ أعلى إنتاجية دون وجود فروق معنوية تذكر. ولقد زادت الإنتاجية بنسبة ١٣٥% من ٢٧ إلى ٦٣ طن/هكتار بزيادة معدلات الري من ١ إلى ٣ مم/يوم على التوالي، ثم بدأت في الانحدار. وقد تزايدت إنتاجية الخيار في الحقل بمنحنى خطي بزيادة معدل الري من ٣ إلى ٨ مم/ يوم ، و أعطت المعاملة التي تروى بمعدل ٦ مم/ يوم الإنتاجية المثلى (٣٥ طن/هكتار) بينما أعطت معدلات ٨ مم/ يوم أعلى إنتاجية في الحقل (٤٠ طن/هكتار) دون وجود فروق معنوية تذكر. أوضحت الدراسة أن المعاملة التي تروى بمعدل ٢ مم/ يوم في البيت المحمي أنتجت محصولا أفضل من المعاملة التي تروى بمعدل ٨ مم/ يوم في الحقل. أمكن الحصول على الإنتاجية المثلى عند متوسط معامل المحصول (Kc) ٠,٥٨ و ١,٥٥ للبيت المحمي والحقل على التوالي، مما يدل على أن الاحتياجات المائية لمحصول الخيار في البيت المحمي تساوي ثلث ما يحتاجه المحصول في الحقل. كما أوضحت الدراسة أن كفاءة استخدام مياه الري كانت أعلى داخل البيت المحمي (٣١,٣ كجم/متر٣) عنه في الحقل (٧,٦ كجم/متر٣) للإنتاجيات المثلى، نتيجة للإنتاجية العالية و قلة الاحتياجات المائية داخل البيوت المحمية. لكن الكفاءة الكلية لاستخدام المياه (مضافا إليها كمية المياه المستخدمة في التبريد) تقاربت بزيادة معدلات الري وذلك لاستهلاك نظام التبريد كميات عالية من المياه، حيث بلغ استهلاك نظام التبريد ٧٩,١ لتر / يوم / للمتر المربع من الوسائد. أوضحت النتائج أن مستوى رطوبة التربة قرب الوسائد كانت أعلى مما يمكن أن تدل عليه معدلات الري إلا أن قلة إنتاجيتها عزيت لزيادة نسبة الملوحة الناتجة عن غسل الوسائد وربما لدرجات الحرارة المنخفضة أثناء ساعات الليل.

ABSTRACT: The combination of aridity, extensive urbanization and expansion of irrigated farming have brought about substantial water demand increase and intensified the gap between rising water demands and limited existing water supply in the Sultanate of Oman. Greenhouse farming has been adopted as part of the government efforts to conserve and augment water supplies. Greenhouse cropping in Oman is mostly practiced at times when crops could tolerate outside conditions. Experiments were conducted for two seasons to determine the effect of four irrigation rates (1, 2, 3 and 4 mm/day in greenhouse and 3, 4, 6 and 8 mm/day in field) and evaporative cooling on yields of cucumbers, total water use efficiency and cost. Results showed an asymptotic increase of greenhouse cucumber yield with increase in water applications from 1 to 4 mm/day. The 2 mm/day applications optimized yields (kg/m^3), whereas 3 mm/day applications maximized yields, with no significant difference from the 2 mm/day applications being observed. Yields were increased by 135% from 27 to 63 t/ha when irrigation was increased from 1 mm/day to 3 mm/day respectively, and declined thereafter. Field cucumber yields increased linearly as the irrigation water was increased from 3 mm/day to 8 mm/day. Yields were optimized at 6 mm/day applications (35 t/ha). The 8 mm/day maximized yields (40 t/ha) but fell short of the optimum 2 mm/day yields (53 t/ha) obtained in the greenhouse. Optimum yields were obtained at an average crop factor (K_c) of 0.58 ET_o and 1.55 ET_o in the greenhouse and the field respectively, indicating that water requirements for the greenhouse cucumber is about one third of that in the open field. The irrigation water use efficiency was higher in the greenhouse than that of the open field because of the lower water requirements and higher yields of cucumbers. But the total water use efficiency approached that of the field as the rates were maximized, because of the high quantity of water used in evaporative cooling. The average cooling pad water use was found to be 79.1 l m^{-2} day^{-1} of pad area. In the greenhouse, irrigation water use efficiency was highest with 2 mm/day applications (31.3 kg/m^3), whereas in the open field the highest irrigation water use efficiency obtained was only 7.6 kg/m^3 for the 6 mm/day applications. Treatments close to the cooling pads of the greenhouse were more moist than the amount of water applied would have indicated, but suppressed yields obtained were attributed to the high soil salinity levels washed from the pads and possibly due to the chilling temperatures incurred at night.

Keywords: Water management, drip irrigation, evaporative cooling, Oman.

*Corresponding author.

The Sultanate of Oman, located in the southeastern corner of the Arabian Peninsula, is characterized by high temperatures and low and erratic rainfall. Annual mean temperatures vary between 19 and 29 °C and the mean annual rainfall is between 50 mm in the interior to about 100 mm in the coastal areas, with the exception of the southern region, where heavy and regular rains (200 to 260 mm) fall between June and October because of the monsoons. Agriculture is considered to be the main user of water, amounting to more than 92 % of the total usage (MWR, 1991). All the water available for agriculture comes from two main sources, more than 12,7000 wells, irrigating 46.8 % and 4,112 aflaj, which irrigate 38% of the total farms in Oman (Abdel Rahman, 1996). Aflaj (singular falaj) are horizontal tunnels, which tap the groundwater and have a rate of descent lower than that of the surface. The total annual water consumption in the country is estimated to be around 1657 Mm^3 with a net recharge of 1267 Mm^3 and the deficit of about 390 Mm^3 is being drawn from groundwater reserves (Al Ajmi and Abdel Rahman, 2001). Excessive water pumping resulted in lowering of the groundwater table and seawater intrusion that progressively increased salinity of the irrigation water and soil, thus limiting crop productivity in the coastal areas, especially the Batinah, which sustain more than 60% of the cropped area in the Sultanate. The government has adopted an extensive integrated program of conservation and augmentation subsidizing modern irrigation techniques and greenhouse facilities. Modern irrigation systems have the advantage of conserving water with high application efficiencies and Uniformity Coefficients (Uc) as given by the equation:

$$Uc = (1 - m/x)$$

where m is the mean deviation from the average depth of water application x.

There are about 510 greenhouses in Oman, mainly growing cucumbers, with the basic problems being the age of covering plastics, high initial and operating costs, shortage of qualified personnel and lack of integrated pest management practices (Muhamadain, 1997). Cucumber (*Cucumis sativus* L.) is one of the most important market vegetables in the tropics and also the basis of an extensive pickling industry (Williams *et al.,* 1991). Water shortage is more critical to the growth of cucumbers than high temperatures because of the leaf area of plants. Cucumber is moderately tolerant to salinity (Richards, 1954), but excessive salinity affects germination, growth and yield of cucumbers. Salt injury symptoms are developed at EC > 2.7 dS m^{-1} and are more severe at higher salinities and plants couldn't survive EC > 16.2 dS m^{-1} (Chartzoulakis, 1991).

Novak and Milotay (1995) stated that the total daily water use of field cucumbers in a moderately rainy cool year ranges between 3-5 l m^{-2} (3 – 5 mm) during flowering and fruiting and in a hot and dry year between 4-8 l m^{-2} (4 – 8 mm). They found that the total water use in a square meter varied between 300-400 liters in a five weeks period; plants kept continuously at 75% of the water holding capacity highly over-yielded controls where irrigation began only at wilting (50 % water capacity). Komamura *et al.* (1990) showed in an experiment to compare drip irrigation to perforated pipe irrigation, that the average consumptive use of greenhouse cucumber of 1.5 – 2.8 mm/day was nearly equal to the potential evaporation. In a similar work Chartzoulakis and Michelakis (1990) determined that the total water consumption for greenhouse cucumbers for a 3.5 months period (when the soil water potential was kept above – 10 kPa in all treatments) was 507, 383, 366, 342, 292 mm for furrow, micro-tubes, porous plastic tubes, porous clay tubes and drippers respectively. Fruit yields per plant were 4.5, 4.4, 5.1, 3.7 and 4.3 kg for the above-mentioned systems, respectively. They also found that the root system developed mainly in the 0-30 cm soil layer and root density was highest at 15 cm depth.

Limbulkar *et al.* (1998), in a study of the yield response to micro-irrigation, reported that two and three days irrigation intervals did not influence cucumber yields significantly. However the irrigation depths of 110, 90, 70, 50 % ET_p by drip and only 90 % ET_p by surface method influenced the cucumber yield significantly. The yield obtained due to the 110 % ET_p treatment was significantly superior over all other treatments except the 90 % ET_p surface treatment. The quantity of water applied significantly influenced plant water status and yield of cucumbers. The highest consumptive use (328 mm) with low WUE was recorded in the110 % ET_p treatment while higher water use efficiency (11.04 kg/m^3) with low consumptive use (174 mm) was noticed in the 50 % ET_p treatment. The seasonal irrigation volumes were 3988, 3288, 2608, 1908 and 3288 m^3/ha for the 110, 90, 70, 50 % ET_p and 90 % ET_p by surface, respectively. The yield was 24.94, 23.17, 21.01, 19.22 and 21.19 t/h for the above mentioned treatments. The objective of this project was to study cucumber production in the Sultanate of Oman and the feasibility of growing them in greenhouses at times when field conditions are favorable.

Materials and Methods

Experiments on cucumber (*Cucumis satvisus* L.) grown in a 10-m by 20-m greenhouse and an open field were conducted at the Agricultural Experiment Station in Sultan Qaboos University, Oman during the months of November – February of the years 2000/1 and 2001/2. The greenhouse area restrictions imposed an experimental design by which the contained 4-plot treatments consisted of four drip lines, each with eight plants. These drip lines represented the replicates. The average emitter discharge under the 1.5 bar system-pressure was found to be 5.1 l h^{-1} in the greenhouse with a calculated Uniformity Coefficient (U_c) of 96 %. In the field the discharge was 5 liter/hour with a U_c of 98 %. Greenhouse treatments received 1, 2, 3 and 4 mm/day moving away from the cooling pad, whereas field treatments received 3, 4, 6 and 8 mm/day. The amount of water applied every other day was the product of the depth times the frequency over a wetted area of 25 cm radius per emitter. Impeller water meters were used to measure both the irrigation water at different treatments and the daily water consumed in evaporative cooling of the greenhouse. Reference evapotranspiration (ET_o) for the growing period was calculated by the modified Penman Method (Doorenbos and Pruitt, 1977). Soil samples from both treatments were analyzed for texture using the hydrometer method. EC/pH of the 1:5 soil extract and water samples were determined using a Jenway meter and the Na, Ca and Mg were determined using Atomic Absorption Photometry. In situ salinity and moisture measurements were obtained using a sigma probe and a calibrated Time Domain Reflectrometry (TDR) respectively.

Cucumber seeds (Dellah type) were sown on the 12^{th} of November for both seasons and were transferred directly into the greenhouse and field after 12 days. The plants were transplanted 50 cm apart in rows 100 cm apart. The plants in the field were covered with Argyll for 14 days to protect them from pests and insects. All plants were pre-irrigated (with 4 and 8 mm/day in the greenhouse and the field, respectively) three times with surface drip irrigations. Cucumber plants for both greenhouse and open field treatments were trained and trimmed. Twines were hung in the wires attached to the greenhouse structure about two meters above the ground, whereas in the field a structure of iron pipes was built to hang the twines. Then the plants were trained upward so that the main stems allowed climbing along twines. The main stems were pruned. All the laterals that developed along the main stems and all the leaves to 50 cm height were removed. 10-52-1 NPK fertilizer was applied four times during the growing and flowering periods at the rate of 7.5 g per plant for all treatments. Weeds were removed manually once a week. Pests and diseases were controlled by the application of 0.1% Torq and Decis d and 0.15% Thiodan 35 EC. Marketable fruits were harvested when they have reached the desired size. Harvest was started on the 1^{st} of January and every three days thereafter. The last harvest was around mid-February. The number, weight, length and diameter of cucumbers were measured at each harvesting. Yields were determined by harvesting all fruits of each line in each plot and extrapolated to a hectare basis. Analysis of variance (ANOVA) was used to determine the difference among treatments. Statistical analyses were performed using the SAS program (SAS, 1993). Meteorological data from the nearby automatic weather station were collected to determine the reference evapo-transpiration using the modified Penman method. In the greenhouse, temperatures and relative humidity were continuously monitored using thermo- and hygrographs at two locations.

Results and Discussion

SOIL AND WATER ANALYSIS: The greenhouse soil was a sandy loam, whereas that of the field was a loam. The percentage of clay content was the same for both soils (14%), but there was some difference in the percentage of silt (32:36) and sand (54:50), which made the soil type different. The initial Electric Conductivity values of the saturation extract (EC_e) of the greenhouse and field soils were almost identical and ranged 6.5 to 7.9. The average E.C of the greenhouse water was 0.53 dS m^{-1}, whereas that of field was 0.72 dS m^{-1} and the pH ranges were 7.49-7.78 and 7.78 - 8.36 for both treatments, respectively. The greenhouse was connected to the desalinated water network to protect the greenhouse structure from corrosion, whereas the water in the field came from the nearby wells.

METEOROLOGICAL DATA: The mean temperature inside the greenhouse was higher than the field. The mean, maximum and minimum greenhouse temperatures for the growing period were 23.6, 34.4 and 12.8 °C, whereas those of the field were 20.4, 25.4 and 15.3 °C, respectively. These temperature conditions are the most favorable for cucumber growth, as recorded by McCollum (1980). The greenhouse had a higher maximum temperature than the field but the minimum was lower. This is due to greenhouse effect, which retained solar radiation during the day. The average humidity was higher in the greenhouse and reached 74 % as compared to 61 % in the field. The two season average ET_o in the Agricultural Experiment Station was 3.9 , 3.3, 3.8 and 4.5 mm/day for the growing months of November, December, January and February respectively, with a season average of 3.875 mm/day.

EC AND SAR REDISTRIBUTION: The initial EC values of the saturation extract of the greenhouse soil were higher with the 1 mm/day treatments located close to the cooling pads. Water droplets falling from evaporative pads contain salt, which makes the soil salinity higher. These drops also kept the soil wet, dissolving the remaining chemical fertilizer. Fertilizer over application and inadequate irrigation management in greenhouse crops causes soil salinization (Blanco and Folegatti, 2000). There is a close relationship between the total soluble matter and inorganic soluble matter and the electrical conductivity of aqueous soil extract (Merkle and Dunkle, 1944). The initial EC values decreased with the distance from cooling pad. The average EC of all depths for the plots with 1, 2, 3 and 4 mm/day treatments were 26.5, 6.8, 7.1 and 4.6 dS m^{-1},

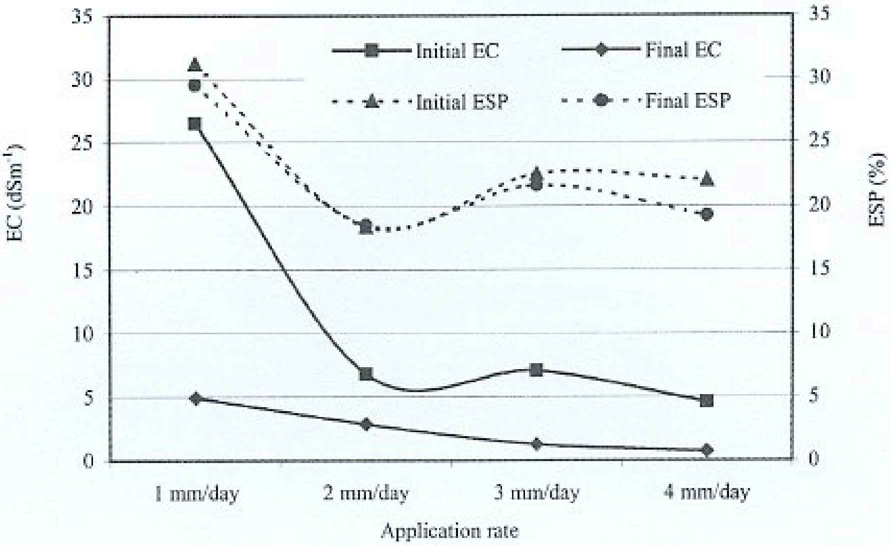

Figure 1. Change in the EC (dS/m) and ESP (%) of the greenhouse soils.

respectively. The first depth, 0-10 cm, had the higher EC values and these became constant as soil depth increased to 50 cm. Similar results were obtained by Chartzoulakis and Michelakis (1990). They reported that soil salinity (EC of saturation extract) was highest in the top layer (0-10 cm) and decreased with increasing depth. This is also in agreement with results reported by Eliades (1988) who stated that the amount of irrigation water affected the concentration and distribution of salts in the soil. Underneath the drippers salts were more effectively leached in these experiments. As the amount of irrigation water increased, large differences in salt concentrations between treatments were found in the surface 0-10 cm soil layer, where the highest salt concentration was recorded. At the end of the experiment, the EC values decreased in all treatments with the amount of water added. The average values for all depths for the 1, 2, 3 and 4 mm/day greenhouse treatments became 4.93, 2.84, 1.27 and 0.95 dS m^{-1}, respectively. As irrigation water increased, more salts were leached downwards (Fig. 1). The average percent change in the EC values was 59, 34, 76 and 84 %, respectively. This shows that a higher percentage salts were leached from the 4 mm/day treatment. The 1 mm/day had a higher percentage salt leached than 2 mm/day by virtue of the high initial salt content in the top layer. The 1 mm/day treatment had higher EC throughout the experiment than the other mentioned treatments close to and between the drippers. The EC was higher between drippers than close to drippers. The 4 mm/day treatment had almost the same EC between drippers and close to drippers, indicating more lateral wetting of the surface.

The initial EC values of the saturation extract of the field soil also decreased with soil depth, the top 0-10 cm layer having the highest value. The 4 mm/day treatment plots had a higher EC value, especially in the top layer. The average EC values for 3, 4, 6 and 8 mm/day treatments were 5.1, 7.8, 3.3 and 3.7 dS m^{-1}, respectively. At the end of the experiment, the EC of all treatments decreased. All treatments had almost the same EC values (Fig. 2). The average for 3, 4, 6 and 8 mm/day treatments were 1.76, 1.60, 1.82 and 1.58 dS m^{-1}, respectively. The top 0-10 cm layer had been leached and the salts accumulated below. The average percent change in the EC values was 62, 65, 34 and 56% for the mentioned treatments, respectively. Higher percent changes occurred in the 3 and 4 mm/day treatments because of the higher initial salt contents. The EC of all treatments had the same trend throughout the experiment. The EC value was higher between drippers than close to drippers for all treatments.

The greenhouse soil ESP was higher before the experiment and it decreased at the end (Fig. 1). The ESP was higher at 3 mm/day treatment before and at the end of the experiment. Average percent change was higher as the irrigation water increased, i.e. as irrigation water increased from 1 to 4 mm/day the reduction in ESP increased. Before the experiment all the field treatments had almost the same ESP, decreasing with depth. At the end of the experiment the ESP values increased with the soil depth (Fig. 2). The 4 mm/day treatment showed a reduction as a percent change in ESP. This shows that the ESP value was a function of the total amount of water applied.

Soil Moisture Distribution: Soil moisture contents were measured at 10- and 30-cm depths taken from three sites per plot using a calibrated Time Domain Reflectrometer (TDR). Soil moisture content was higher in the top layer for all treatments. Although the 1 mm/day treatment in the greenhouse was irrigated by less water, it had a higher soil moisture content at the first

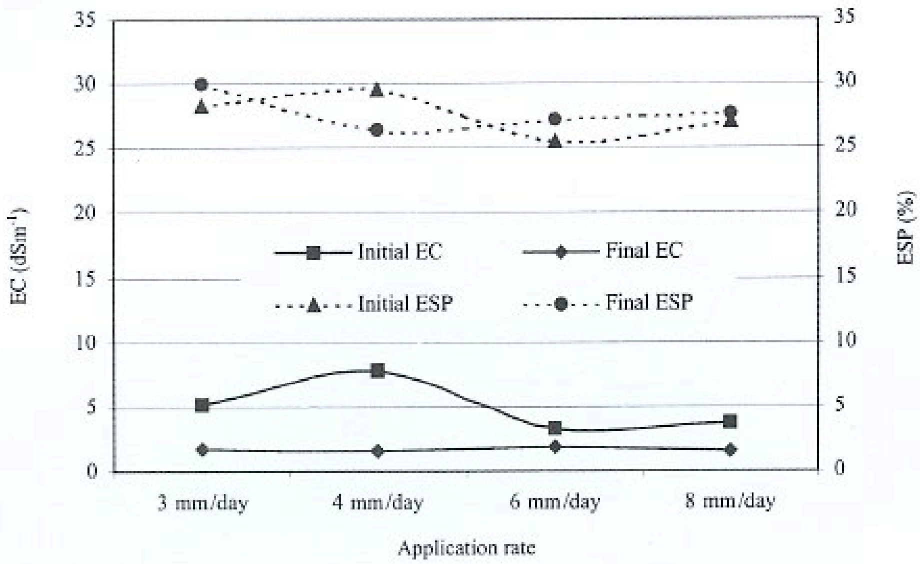

Figure 2. Change in EC (dS/m) and ESP (%) of the field soils.

and second layer, due to the effects of the cooling pad. Water drops falling into the plot made the soil wet; also there was less evaporation, as lower temperatures prevailed than as at the inner sites of the greenhouse. The soil moisture content decreased in the top layer as irrigation increased from 1 to 4 mm/day. In the second layer the moisture content was almost the same for all treatments except with the 1 mm/day treatment, which had a higher soil moisture content. The 4 mm/day treatment showed the lowest soil moisture content in the top layer although it received larger quantities of water. This can be explained by the vigorous growth and yield. As irrigation water increased, plant growth and number of fruits increased, so more water was extracted from the soil, which appears as deficit in the soil moisture content. Figure 3 shows the change in the moisture content with time for the greenhouse soils.

The soil moisture content of the field was higher in the top layer than the second depth in all treatments. The 3 mm/day treatment had the lowest moisture content of the top layer due to the lower quantities of water applied. The 4 mm/day treatment had the highest soil moisture content in the top layer but the lowest moisture content at the second depth. The 8 mm/day treatment, which received the highest amount of water, did not show a higher soil moisture content. This treatment had the same moisture content as the 6 mm/day treatment in both depths. This is explained by the vigorous plant growth and increased yields. Figure 4 shows the change in the moisture content with time for the field soils.

YIELD PARAMETERS: Weight, number, length and diameter of cucumbers were measured to determine the effect of the different irrigation quantities on the yield of cucumber.

The greenhouse cucumber yields (Y) were increased asymptotically ($R^2 = 0.74$) as the irrigation water quantity (X) increased from 1 mm/day to 4 mm/day according to the relationship:

$$Y = -9.33X^2 + 55.13X - 19.20 \qquad (X > 0)$$

Highest yields were attained at the 3 mm/day treatment, but there was no significant difference observed in the yields among 2, 3 and 4 mm/day ($p < 0.05$), as shown in Table 1. Small deviations in the water application from the actual water requirements would not be expected to affect the yield significantly (Eliades, 1988). When irrigation was increased from 1 mm/day to 2 mm/day or 4 mm/day, the yield increased by about 95%, but when it was increased from 1 mm/day to 3 mm/day, the yields were increased by 135 %. The yield at 4 mm/day declined by approximately 18 % below that obtained with 3 mm/day. This result affirms the concept that high water available to the plant may not be an important factor for obtaining high yield (O' Sullivan, 1980). The yield was significantly lower with 1 mm/day than 2, 3 and 4 mm/day. The significant lower yield obtained in this treatment may partially be explained by the lesser amounts of water applied (Eliades, 1988), or the high soil salinity in this plot, close to the cooling pad. High soil salinization results in crop yield reduction (Blanco and Folegatti, 2000), as cucumber is a moderately sensitive crop to salinity (Ayers and Westcot, 1985). Fruit weight depends to a large degree on the amount of photosynthesis available during fruit development. Since the plants were subjected to water stress that reduced the level of plant photosynthesis, yields were significantly reduced. In this

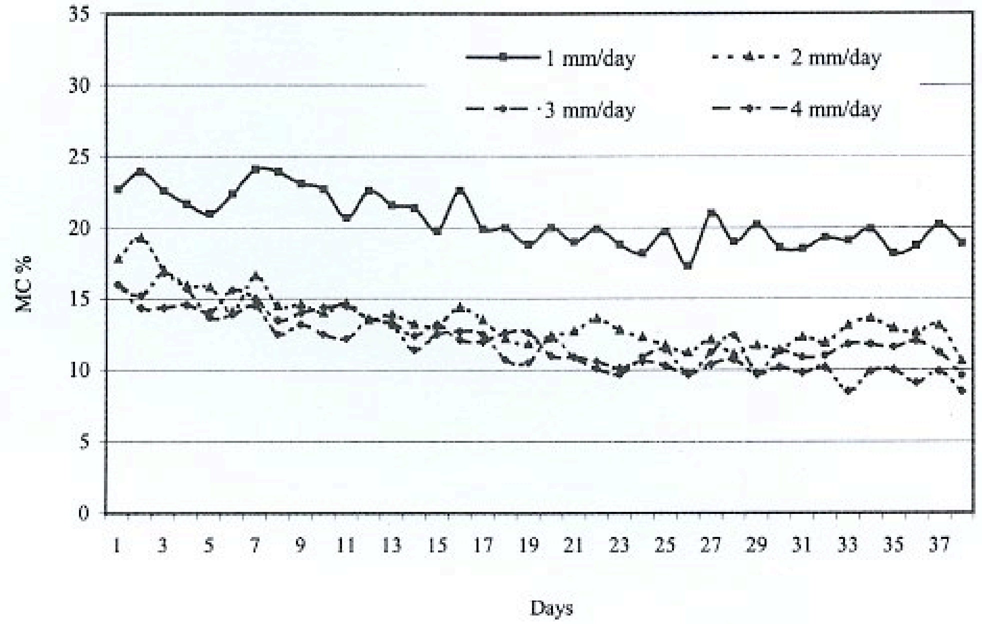

Figure 3. Greenhouse soil moisture content with time as affected by application rates.

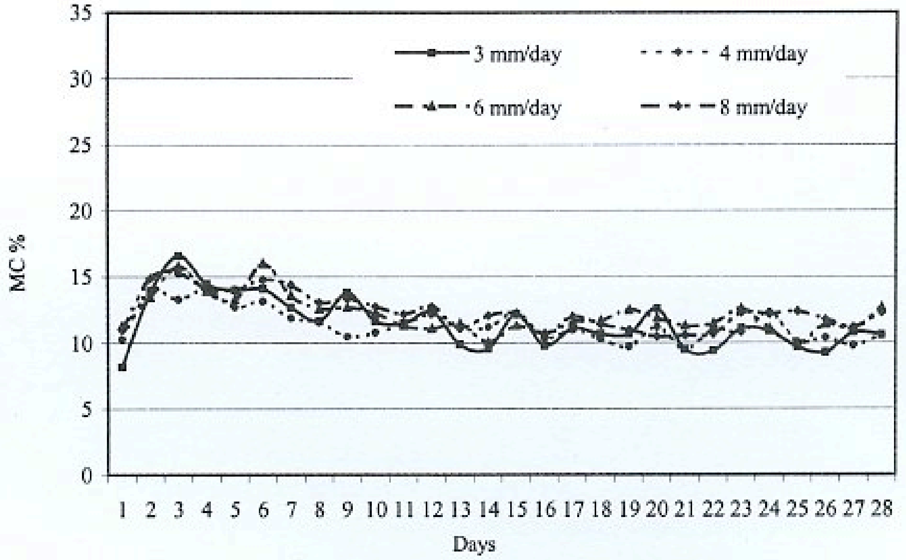

Figure 4. Field soil moisture content with time as affected by application rates.

experiment 2 mm/day application optimized yields, whereas the 3 mm/day application maximized yields of greenhouse cucumbers, with no significant difference being observed from the 2 mm/day applications.

For the open field treatments, the yield (Y) increased linearly ($R^2 = 0.92$) as the irrigation water (X) increased from 3 mm/day to 8 mm/day according to the relationship:

$$Y = 7.72\,X + 9.84$$

There was no significant difference between the 6 and 8 mm/day applications, both being significantly higher than the 3 or 4 mm/day application ($p < 0.05$) as shown in Table 1. The 3 mm/day treatment had the lowest yield ($p < 0.05$). When irrigation was increased from 3 mm/day to 4, 6 and to 8 mm/day the yield increased by 35, 95 and 125 %, respectively. The 6 mm/day treatment had 44 % higher yield than the 4 mm/day treatment. But as irrigation was increased from 6 to 8 mm/day, the yield increased by only 15 %, which indicated that yields were optimized at 6 mm/day and maximized at 8 mm/day. It was clear that the 2 mm/day treatment in the greenhouse produced a better yield than the 6 mm/day for open field treatment. Optimum yields were obtained at an average crop factor ($K_c = Et_p/Et_o$)

TABLE 1

Yield, number, length and diameter of greenhouse and field cucumbers.

Depth mm/d	Yield (t/ha^{-1})		Number		Length (cm)		Diameter (cm)	
	G/H	Field	G/H	Field	G/H	Field	G/H	Field
1 (1.3)	26.88 b	-	237 b	-	15.5 b	-	11.2 b	-
2 (2.2)	52.94 a	-	444 a	-	16.5 ab	-	11.8 a	-
3 (3.1)	63.06 a	17.81 c	482 a	181 c	17.0 ab	12.7 c	119 a	10.8 c
4 (4.0)	51.81 a	24.06 b	402 a	239 b	17.9 a	13.4 b	12.1 a	11.3 b
6 (6.0)	-	34.69 a	-	328 a	-	14.6 a	-	11.4 b
8 (7.7)	-	40.00 a	-	367 a	-	15.0 a	-	11.7 a
LSD	19.30	5.50	152		1.71	0.61	0.54	0.31

Figures in parenthesis are actual application rates as measured.

of 0.58 and 1.55 in the greenhouse and the field respectively. This indicates that water requirements for greenhouse cucumber are about one third of the water requirement in open field.

NUMBER OF CUCUMBERS: The number of cucumbers followed the same trends as that of the weight of cucumbers for both greenhouse and open field treatments (Table1). For the greenhouse treatments, the number of fruits (N) increased quadraticly ($R^2 = 0.69$) as irrigation water quantity (X) increased from 1 mm/day to 4 mm/day:

$$N = -71.72X^2 + 412.03X - 100.78$$

It is clear that the number of fruits increased up to 3 mm/day then they decreased. The greatest numbers were obtained at 3 mm/day with no significant difference between 2, 3 and 4 mm/day ($p < 0.05$).

For the field treatments the number of fruits (N) increased linearly ($R^2 = 0.89$) as the irrigation water quantity (X) increased from 3 mm/day to 8 mm/day.

$$N = 64.31X + 118.13$$

There was no significant difference in the number of fruits between 6 and 8 mm/day ($p < 0.05$), but both were significantly more than the 3 and 4 mm/day application. The 3 mm/day had the lowest number of fruits. With 8 mm/day the number of field fruits were lower than the number in the 2 mm/day greenhouse application.

LENGTH AND DIAMETER OF CUCUMBERS: Length and diameter of fruits increased linearly as the amount of irrigation water increased for both the greenhouse and field treatments (Table 1). For the greenhouse treatments there was no significant difference in the length of the fruits between the 2 and 3 mm/day applications ($p < 0.05$). There was, however, a significant difference between the 1 and 4 mm/day applications. Treatment 2, 3 and 4 mm/day cucumbers had significantly larger diameter than 1 mm/day treatment. As for the field treatments, there was no significant difference in the fruit length ($p < 0.05$) between the 6 and 8 mm/day but both were significantly longer than the 3 and 4 mm/day applications. Shorter fruits were obtained from the 3 mm/day application. The diameters of the field fruits were larger with 8 mm/day than 3, 4 or 6 mm/day treatments.

The large size fruits obtained from the field treatment at 8 mm/day was obtained from the 2 mm/day green-house applications. These results give a clear indication that the fruits reached marketable size more quickly as the irrigation water increased. Greenhouse fruits reached marketable size with one third the irrigation water quantities as compared to the open field.

EVAPORATIVE COOLING PAD WATER USE: Pad water use was measured throughout the experiment. The measurements were determined every other day by using a water meter. The average water use was calculated to be 79.1 $l\ d^{-1}\ m^{-2}$ of the pad. The higher water use (107.1 $l\ d^{-1}\ m^{-2}$) was noticed at the beginning of the experiment on 10 December, then it decreased to 63.2 $l\ d^{-1}\ m^{-2}$ on 10 January. Humidity and temperature had an effect on the water use, with the relative humidity being more effective in reducing water use (Fig. 5).

WATER USE EFFICIENCY (WUE): In agriculture, water use efficiency is a concept indicating crop output per unit of water added. It is an important criterion for assessing the benefit of irrigation on crop productivity. Water use efficiency can be defined in various ways, depending on the nature of the inputs and outputs considered (Hillel, 1988). The ratio of the yield (kg) to the amount of water (m^3) used to produce that yield was taken as an indicative measure.

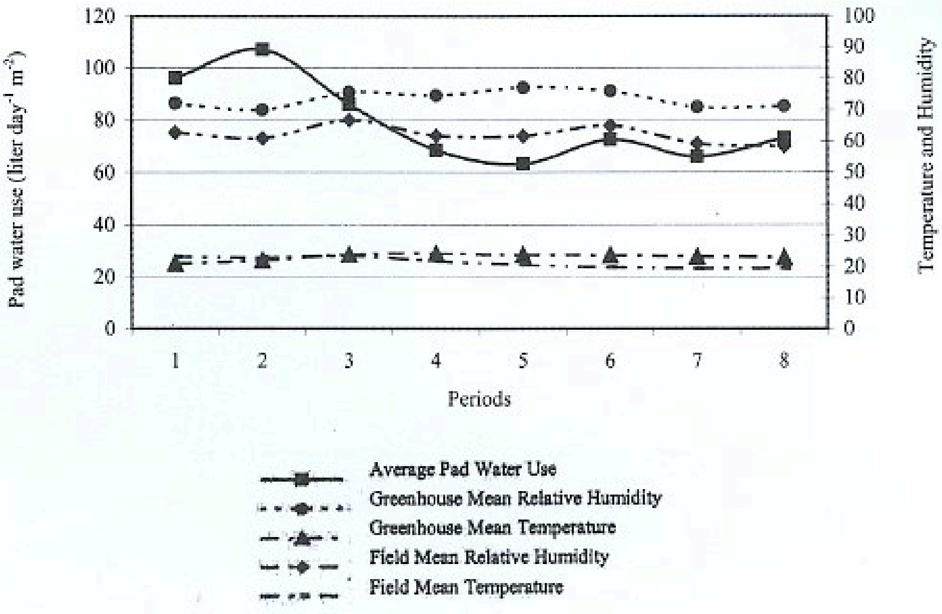

Figure 5. Pad evaporation as affected by greenhouse conditions.

The results shown in Table 2 indicate that the Irrigation Water Use Efficiency was higher in the greenhouse than in the open field because of the lower water requirements and higher yield of cucumbers in the greenhouse. But the Total Water Use Efficiency of the greenhouse (irrigation plus cooling water) approached that of the field as irrigation water was maximized to 4 mm/day. For the greenhouse treatments, Irrigation Water Use Efficiency was significantly higher with the 2 mm/day treatment (31.3 kg/m^3) than the 4 mm/day treatment (17.0 kg/m^3), but not significantly different than the 1 or 3 mm/day applications, which yielded 27.7 and 26.7 kg/m^3, respectively. When irrigation was increased from 1 to 2 mm/day, IWUE increased by 13 % but decreased by 15 % and 46 % when irrigation water was increased to 3 and 4 mm/day, respectively. The Total Water Use Efficiency was significantly higher for the 2 and 3 mm/day treatments than the 1 or 4 mm/day treatments. The average IWUE of the greenhouse was increased by 30% over the average TWUE, due to water used in cooling the greenhouse.

For the open field treatments, irrigation water use efficiencies (equal to the total water use efficiency) was about the same for all treatments (7.2 kg/m^3) on the average, with no significant difference among them. The average Irrigation Water Use Efficiency attained in the greenhouse was higher by 257 % than that obtained from the open field, but the average Total Water Use Efficiency was only 10% higher.

TABLE 2

Irrigation and total water use efficiency of greenhouse and field cucumbers.

Depth	Yield (T/ha)		Irrigation Water Use (m^3/ha)		Total Water Use (m^3/ha)		Irrigation water use efficiency (kg/m^3)		Total water use efficiency (kg/m^3)	
	G/H	Field	G/H	Field	G/H	Field	G/H	Field	G/H	Field
1 (1.3)	26.88 b	-	971	-	5029	-	27.7 ab	-	5.3 b	-
2 (2.2)	52.94 a	-	1690	-	5748	-	31.3 a	-	9.2 a	-
3 (3.1)	63.06 a	17.81 c	2363	2572	6421	2572	26.7 ab	6.9 a	9.8 a	6.9 a
4 (4.0)	51.81 a	24.06 b	3045	3240	7103	3240	17.0 b	7.4 a	7.3 ab	7.4 a
6 (6.0)	-	34.69 a	-	4593	-	4593	-	7.6 a	-	7.6a
8 (7.7)	-	40.00 a	-	5834	-	5834	-	6.9 a	-	6.9a
LSD	19.30	5.500					12.26	1.34	2.90	1.34

Figures in parenthesis are actual application rates as measured.

TABLE 3

Total yield return, total water cost and net return for the greenhouse and field trials (Omani Rials† per hectare).

Depth	Greenhouse				Field		
	Yield return* (RO/ha)	Irrigation water** (RO/ha)	Total water** (RO/ha)	Net return (RO/ha)	Yield return* (RO/ha)	Total water** (RO/ha)	Net return (RO/ha)
1 (1.3)††	4,570	21.362	110.638	4,459	-	-	-
2 (2.2)	9,000	37.180	126.456	8,873	-	-	-
3 (3.1)	10,720	51.986	141.262	10,579	3,028	56.554	2,971
4 (4.0)	8,808	66.990	156.226	8,651	4,090	71.280	4,019
6 (6.0)	-	-	-	-	5,897	101.046	5,796
8 (7.7)	-	-	-	-	6,800	128.348	6,672

†1 RO = $2.58 †† Actual application rates as measured. *At the rate of RO 170/ton. **At the rate of RO 0.022/m^3.

WATER COST AND YIELD RETURN ANALYSIS: The results obtained from this experiment showed an asymptotic increase of greenhouse cucumbers and a linear increase for field treatments as the irrigation water increased. The irrigation water used was higher in the field as compared to the greenhouse, but the total water used (including water used for cooling) was higher in the greenhouse. Norman *et al.* (1998) calculated the cost of irrigation water in northern Oman in 26 farms. They found that the average cost of irrigation water was 0.022 Omani Riyal/m^3 (0.0568 \$/m^3 since 1 OR = \$ 2.58) including fixed, operating and labor costs for water pumping. This value was used to calculate irrigation and total water cost in this experiment (Table 3). For the field experiments, the irrigation water cost was the total water cost, but for the greenhouse experiment the total water cost included the cost of water used in cooling the system. Yield return was also calculated by taking an average selling value of 170 OR/ton ($ 438.6/ton fresh weight) of cucumbers.

For the greenhouse experiments, maximum yield returns and profits were obtained at the third level of irrigation, i.e. 3 mm/day treatment (Fig. 6), where marginal water use profits were maximized. As for the field experiment, the maximum yield return was obtained at the highest level of irrigation, i.e. 8mm/day (Fig. 7), but marginal profits from water use remained constant. Even when based on the total water use, greenhouse returns outprofited those of the field at all levels of water applications above 1mm/day. The maximum net profit from the greenhouse (10,579 OR) was higher by about 60% than that of the field (6,672 OR). This analysis does not include other fixed and running costs, of which assets and electricity would be of significance.

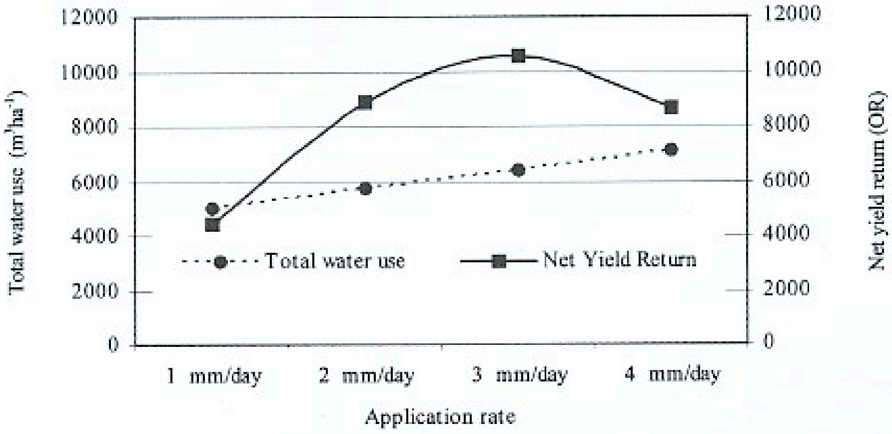

Figure 6. Total water use and net yield return of greenhouse cucumbers.

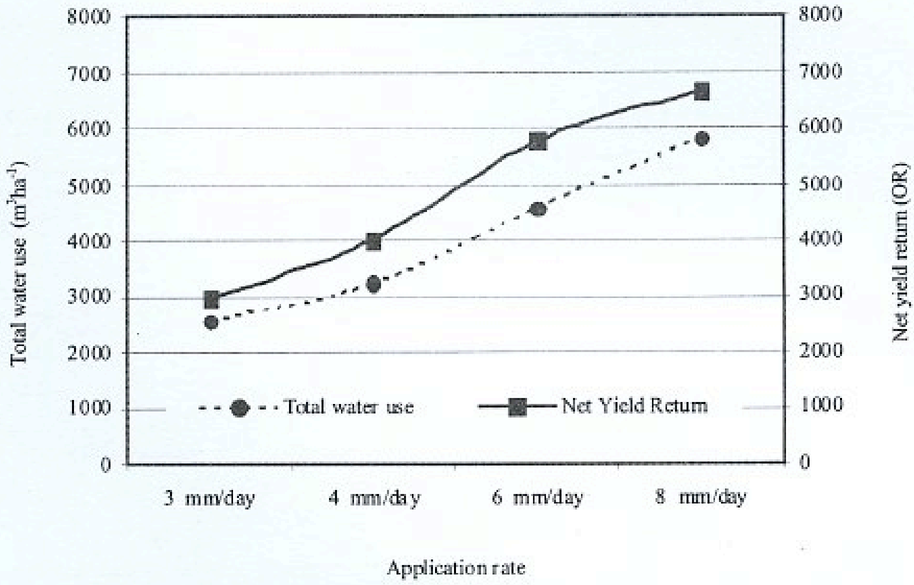

Figure 7. Total water use and net yield return of field cucumbers.

Conclusions

Experiments indicated that a 2 mm/day water application in the greenhouse optimized cucumber yields. The yield increased by 135 % when irrigation was increased from 1 mm/day (27 t/ha) to 3 mm/day (63 t/ha^{-1}). The results also showed that 2 mm/day in the greenhouse produced better yields than 6 mm/day, which optimized cucumber yields in the field. Optimum yields were obtained at an average crop factor K_c of 0.58 ET_o and 1.55 ET_o in the greenhouse and the field respectively, indicating that water requirements for the greenhouse cucumber were about one third of that required in the open field. Irrigation water use efficiency was higher in the greenhouse than in the open field, but the total water use efficiency approached that of the field as irrigation water was maximized to 4 mm/day because of the high quantity of water used in evaporative cooling of greenhouse. The average water use for cooling was calculated to be 79.1 Ld^{-1} m^{-2} of pad area.

Even at times when outside field conditions were most favorable for cucumber production, husbandry practices within the greenhouse made the application of irrigation to cucumbers profitable at all levels as indicated the marginal cost benefit analysis. Thorough analyses of cost-benefits need to be investigated to include all fixed and running costs. Although treatments close to the cooling pads in the greenhouse were irrigated by less water, they had a higher soil moisture content but lower yields, which could be attributed to high soil salinity being washed from the pads and probably the chilling effect of lower temperatures at night. This needs to be further investigated.

Acknowledgements

The authors would like to acknowledge Sultan Qaboos University and the Ministry of Agriculture and Fisheries in the Sultanate of Oman for funding this project.

References

Al-Ajmi, H. and H.A. Abdel-Rahman. 2001. Water management intricacies in the Sultanate of Oman: the augmentation – conservation conundrum. *Water International* 26(1):69-79.

Abdel Rahman, H.A. 1996. Traditional systems and application of modern irrigation techniques in Oman. *Agricultural Mechanization in Asia, Africa and Latin America*, Tokyo, Japan 27(1):41-45.

Ayers, R.S. and D.W. Westcot. 1985. Water quality for agriculture. *Irrigation and Drainage Paper 29*. FAO, Rome.

Blanco, F.F. and M.V. Folegatti. 2000. Greenhouse soil salinity reclamation by leaching. *ASAE. Annual International Meeting*, Milwaukee, Wisconsin, p 1-6.

Chartzoulakis, K.S. 1991. Effect of saline irrigation water on germination, growth and yield of greenhouse cucumber. *Acta Horticulture* 287:327-334.

Chartzoulakis, K. and N. Michelakis. 1990. Effect of different irrigation systems on the root growth and yield of greenhouse cucumber. *Acta Horticulture* 278:237-243.

Doorenbos, J. and W.O. Pruitt. 1977. Guidelines for Predicting Crop Water Requirements. FAO Irrigation and Drainage Paper 24. Rome, Italy.

Eliades, G. 1988. Irrigation of greenhouse-grown cucumbers. *Journal of Horticulture Science* 63(2):235-239.

Hillel, D. 1988. The efficient use of water in irrigation . principles and practices for improving irrigation in arid and semiarid regions. World Bank Technical Paper No. 64, Washington, D.C. USA.

Komamura, M., A. Karimata, A. Mizuta, T. Takasu and A. Yoneyasu. 1990. Fundamental studies on the water requirement irrigation for greenhouse horticulture (Part 1). *Irrigation Method, Water Requirement and Effect of Irrigation for Greenhouse Cucumber* 35(2):93-103.

Limbulkar, C.S., G.R. More and S.N. Suryawanshi. 1998. Yield Response of Cucumber to Microirrigation. Maharashtra Agricultural University 23(1):77-78.

McCollum, J.P. 1980. *Vegetable Crops.* The Interstate Printers & Publishers Inc., U.S.A.

Ministry of Water Resources (MWR). 1991. National Water Resources, Master Plan (Volume 1). Exclusive Summary. Mott MacDonald International Ltd in association with Watson Hawksley.

Merkle, F.G. and E.C. Dunkle. 1944. Soluble salt content of greenhouse soil as a diagnostic acid. *Journal of American Society in Agronomy*, Washington 36(1):10-19.

Muhamadain, S.A. 1997. Report About the Greenhouses in the Sultanate of Oman. Ministry of Agriculture and Fisheries.

Norman, W.R., W.H. Shayya and A.S. Al-Ghafry. 1998. Irrigation water costs and management practices among farms in Northern Oman. *SQU Journal for Scientific Research – Agricultural and Marine Sciences* 3:1-8.

Novak, J. and P. Milotay. 1995. Water consumption and yield dynamics of the cucumber cultivars. *Kecskemeti Livme* 55-70.

O' Sullivan, J. 1980. Irrigation spacing and nitrogen effects on yield and quality of pickling cucumbers grown for mechanical harvesting. *Canadian Journal of Plant Science.* 60(3):923-928.

Richards, L.A. 1954. Diagnosis and Improvement of Saline and Alkali Soils. Agricultural Handbook 60. USDA, Washington, D.C.

SAS. 1993. SAS/STAT User's Guide. Volume 2, Version 6. Statistical Analysis System, Cary, N.C.

Williams, C.N., J.O. Uzo and W.T.H. Peregrine. 1991. *Vegetable Production in the Tropics.* Malaysia, Vinlin Press Sdn.

Received February 2004.
Accepted September 2004.