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Parameters Affecting Water Consumption for Greenhouse Cooling in a Hot Arid Region

S. Ayyash and M. Rasas

Energy Department, Kuwait Institute for Scientific Research
P.O. Box 24885, Safat 13109, Kuwait

ABSTRACT. Crop production in greenhouses in Kuwait is constrained in summer by the prevailing harsh weather conditions, characterized by high solar irradiance and ambient temperature, and scarce fresh water resources. The harsh weather conditions and inefficient evaporative cooling systems cause excessive water consumption for greenhouse cooling. It is shown that the ambient temperature has a particularly significant effect on water consumption, which varies exponentially with temperature. The efficiency of the cooling system has also a significant effect on water consumption. It is argued that substantial water saving can be achieved by improving the efficiency of the cooling system and controlling solar irradiance transmitted into the greenhouse.

The greenhouse industry in Kuwait and neighbouring countries has expanded noticeably over the past few years. Statistics show that the area of greenhouses in Kuwait, termed protected agriculture houses, has increased from 47.08 hectare in 1983/84 to 273.85 hectare in 1985/86 (MOP 1987). Crop production in greenhouses in Kuwait is, however, constrained by adverse weather conditions in summer and scarcity of water resources. In summer, solar irradiance reaches 1000 W/m^2 and ambient dry bulb temperature rises to the upper forties. For seven months of the year, April to October, crop production in greenhouses can be maintained only with the help of cooling. Evaporative cooling systems of the pad-fan type are commonly used. Poor greenhouse design and inefficient evaporative cooling systems make it difficult to maintain indoor conditions appropriate for crop production, especially during the period from June to August, inclusive. It is during this period of the year that most of water consumption for cooling takes place and indoor conditions are least appropriate for crop production. That is why many farmers terminate production during this period of the year. Those who sustain production in summer complain of excessive water consumption and low productivity.

Fresh water is rather scarce and is usually bought at a relatively high cost. To conserve fresh water and reduce cost farmers use brackish water, which is readily available, for greenhouse cooling. Brackish water causes a problem of salt deposits and necessitates annual replacement of the pad and costly maintenance.

The thermal performance of greenhouses has been extensively researched (Kimball 1986, Cooper and Fuller 1983). Available literature tend to address, mostly, greenhouses in colder climates, where heating is of particular interest. Extensive research has been conducted on reducing the cost of heating greenhouses in cold climates (Bailey 1988, Staley *et al.* 1986). Where greenhouses in hot climates, such as parts of Australia and the U.S., are concerned there seems to be little concern for water consumption for cooling purposes (Cooper and Fuller 1983, Garlozi and Blackwell 1973). This makes the situation in the countries of the Arabian peninsula rather unique because of the prevailing harsh weather conditions in summer and the scarcity of water resources.

In this paper we investigate water consumption for greenhouse cooling to identify the parameters of importance and assess their effect on consumption. We realize that crops respond differently to the environmental conditions and this response may have a bearing on the operation mode of greenhouses and, in effect, water consumption. However, this interesting aspect of greenhouse management is outside the scope of the paper.

Weather conditions of Kuwait

Although Kuwait is situated on the northwestern tip of the Gulf, it has a dry climate, however, because of the dominant northwesterly wind. It has a long hot summer and short mild winter. Figure 1 shows the patterns of monthly mean daily solar irradiance, mean monthly maximum dry bulb temperature and monthly mean diurnal temperature range. It is seen that during June to September, inclusive, the maximum temperature is above 40°C and mean daily solar irradiance is more than 23 MJ/m^2. The combination of high solar irradiance and ambient temperature increase the indoor temperature drastically. Stagnation temperature inside uncooled and unventilated greenhouses can reach as high as 70°C.

Analysis

Figure 2 shows a typical greenhouse of the type commonly used in Kuwait. The cover material is a polyethylene sheet or corrugated reinforced fiberglass. The cooling pad is fixed at one side of the greenhouse and propeller fans are installed on the opposite side. Air is drawn through the pad, where it is cooled, and flows along the house to be exhausted at the other end. The pad is kept wet by water recirculated between the pad and a water tank.

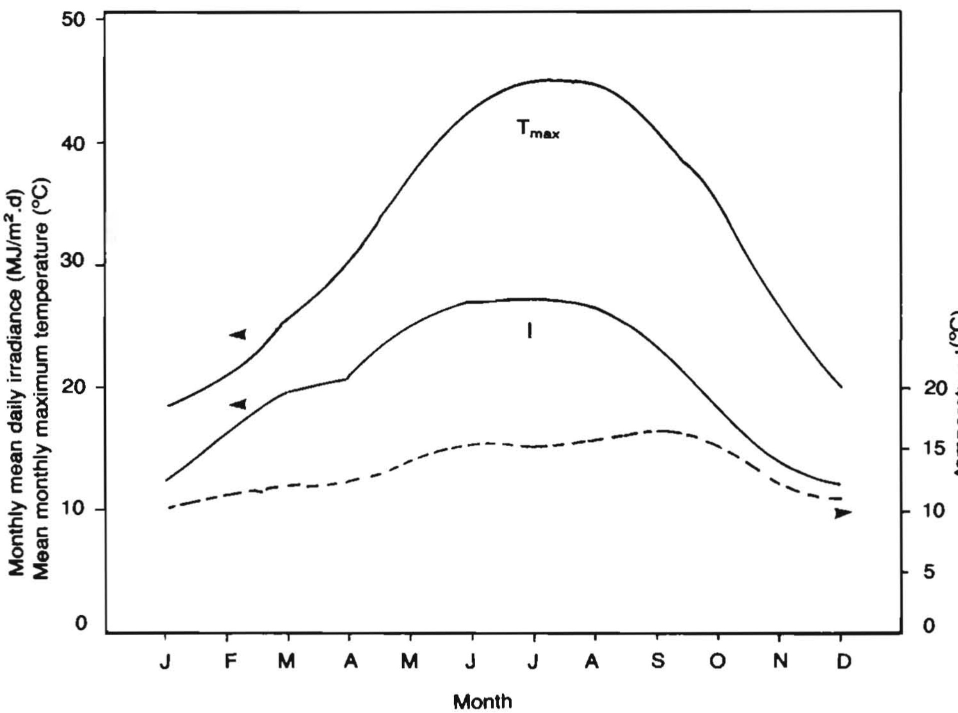

Fig. 1. Patterns of monthly mean daily solar irradiance, maximum by bulb temperature and diurnal temperature range.

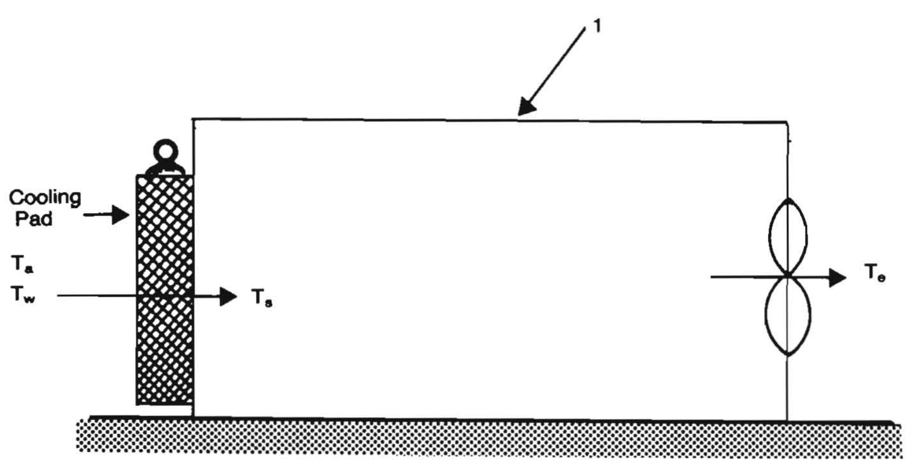

Fig. 2. Greenhouse with evaporative cooling system.

The common practice in the country is to operate the cooling system manually during the day time and switch it off at night, or to use an on-off thermostat to control system operation. The airflow rate is kept constant and the indoor temperature fluctuates accordingly. In our analysis we fix the exhaust air temperature and allow air flow to change accordingly. A comparative assessment of the two modes of operation is being investigated independently.

A simplified model of the sensible cooling load of a greenhouse can be expressed as:

$$Q = UA_c (T_a - T_m) + \tau \alpha I A_r \tag{1}$$

The model is particularly valid for a well-sealed greenhouse with a crop at an early stage of development, where the transmitted solar irradiance is converted, almost all, into sensible heat.

The cooling load per unit floor area is:

$$Q_u = U x (T_a - T_m) + \tau \alpha I \tag{2}$$

Where x is the ratio of cover to floor areas.

The mean temperature in the greenhouse is calculated as:

$$T_m = \frac{T_s + T_e}{2} \tag{3}$$

To maintain T_e at a set value the evaporative cooling system should deliver enough air flow rate at a temperature T_s such that

$$Q_u = m C_p (T_e - T_s) \tag{4}$$

Since T_s varies in relation to the ambient dry and wet bulb temperatures and the humidification efficiency of the evaporative cooling system, it is assumed that m varies accordingly to maintain T_e at the set value. T_s is calculated as

$$T_s = T_a - \eta (T_a - T_w) \tag{5}$$

Investigation of temperature data at a desert site in Kuwait has shown that T_w can be expressed as a constant ratio of T_a. In fact, the data showed that T_w during summer months varies within a narrow range about 0.45 T_a. For convenience, T_w is assumed as a fixed ratio of $T_a (T_w = f\,T_a)$. Equation 5 becomes

$$T_s = (1 - \eta\, y)\, T_a \tag{6}$$

where $y = 1 - f$

Combining eqs. 3 and 6 gives

$$T_m = \frac{T_a(1-\eta\, y)+T_e}{2} \tag{7}$$

Water consumption in the evaporative cooling system is

$$W = m(w_s - w_a) = m\,\triangle w \tag{8}$$

Since air is cooled adiabactically the increase of water vapor content, $\triangle w$, can be expressed as

$$\triangle w = K(T_a - T_s) \tag{9}$$

Combining eqs. 6, 8 and 9 together gives

$$W = \eta y K\ m\ T_a \tag{10}$$

and combining eqs. 2, 4, 6, 7 and 10 gives

$$W = \frac{\eta y K\ (U \times (T_a - \frac{(1-\eta)T_a+T_e}{2}) + \tau\alpha I]T_a}{C_p\ (T_e - (1-\eta\ y)\ T_a)} \tag{11}$$

Equation 11 shows that water consumption for greenhouse cooling is strongly dependent on T_a. In fact, whereas W varies linearly with I it varies exponentially with T_a. The extent of challenges of greenhouse cooling in hot arid lands is exacerbated by the fact that T_a is an independent variable and is normally associated with large values of I. The combination of high solar radiation and high ambient temperature increases water consumption significantly and stretches the cooling systems beyond their capacity to maintain appropriate indoor conditions. No wonder that many farmers in this part of the world terminate production during the hot summer months.

The other parameter of interest in eq. 11 is η, the humidification efficiency of the evaporative cooling system. An increase of η causes T_s to drop further and increases the amount of water vapour gain of air. On the other hand, as T_s drops it increases the utilizable cooling potential of air as $(T_e - T_s)$ becomes larger. This, in turn, reduces the air flow rate required to maintain T_e at the set value. But since the percentage increases of water vapour gain is smaller than the percentage reduction of air flow rate, the increse of η causes a net reduction of water consumption. This effect is more pronounced at higher, than lower, ambient temperature as is shown below.

The third parameter of importance I has a linear effect on water consumption. Though this parameter is an independent variable its contribution to the magnitude of cooling load and, in consequence, water consumption can be controlled by changing τ through controlled shading. It is realized that such an approach affects the rate of photosynthesis and, potentially, crop yield.

Results and Discussion

Results of the effect of ambient temperature and evaporative cooling system efficiency on water consumption are presented in this section. As an illustrative example the parameters of eq. 11, except for T_a and η, are assumed to have the following values:

I = 800 W/m^2 (2.88 MJ/m^2 h)
K = 0.0004 Kg (water)/Kg (air) °C. (From Psychrometric chart)
T_e = 32°C
U = 5.2 W/m^2 °C
x = 1.5
f = 0.45
τ = 0.6
α = 0.8
C_p = 1.01 KJ/Kg (air) °C

1. Effect of T_a

The effects of variation of ambient temperature on water consumption, cooling load and air flow rate are presented in Fig. 3. It is shown that the increase of T_a from 34 to 46°C, at a constant η of 0.70, increases the cooling load by 18% but it increases water consumption by about five fold. T_a has also a significant effect on the air flow rate, which increased about 3.5 times. This causes a significant increase of power consumption, especially that power consumption varies with the cube of airflow rate. As shown in Fig. 1 the mean maximum temperature in Kuwait during the peak summer months falls within the middle forties. This fact, coupled with poor greenhouse design and inefficient evaporative cooling systems, makes it difficult to maintain indoor environmental conditions appropriate for crop production. Given the prevailing temperature conditions and existing state-of-affairs in the greenhouse industry it seems that, aside from terminating production, controlling solar radiation transmittance to the greenhouse is probably the only solution left to help maintain appropriate indoor conditions. Such a practice is not uncommon. Greenhouse roofs are usually covered with anexternal shading or painted with a washable paint.

2. Effect of η

The effect of variation in the efficiency of the evaporative cooling system on water consumption is presented in Fig. 4. It is shown that improving η has a small

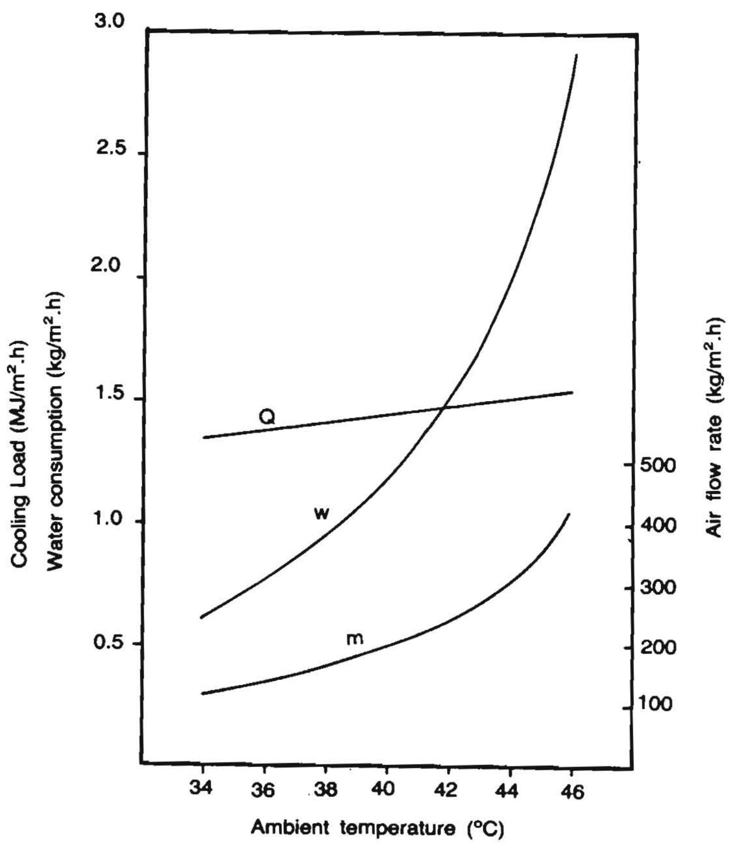

Fig. 3. Effect of ambient temperature on cooling load, water consumption and air flow rate.

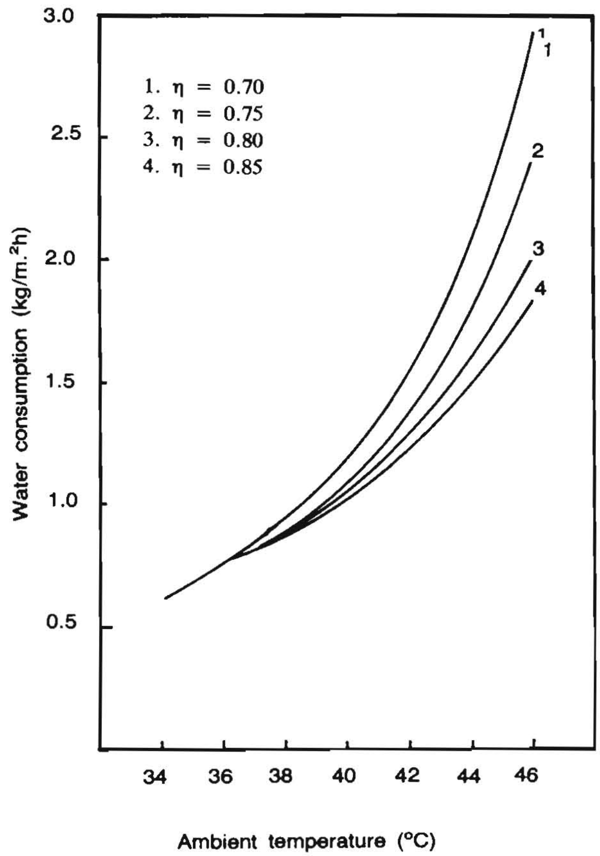

Fig. 4. Effect of cooling system efficiency on water consumption.

effect on water consumption at ambient temperature below 40°C. As T_a rises above 40°C η shows a significant effect on water consumption. At 46°C the increase of η from 0.7 to 0.85 reduces water consumption by 38%, a water saving of 1.33 Kg/m^2.h. The saving is caused mainly by the reduction of air flow rate from 492 to 250 Kg/m^2.h. Ofcourse, the air flow rate decreases because the increase of η decreases T_s and, in turn, increases $T_e - T_s$ (eq. 4). In general, the improvement of η results in more prounoured water saving as the difference between T_a and T_e increases.

Experience tells that the vast majority of greenhouse evaporative cooling systems in the country has an efficiency below 75%. This leaves a room for further research in this area. It should be mentioned that evaporative cooling systems are recommended to bring air temperature to within 2°C of the wet bulb temperature

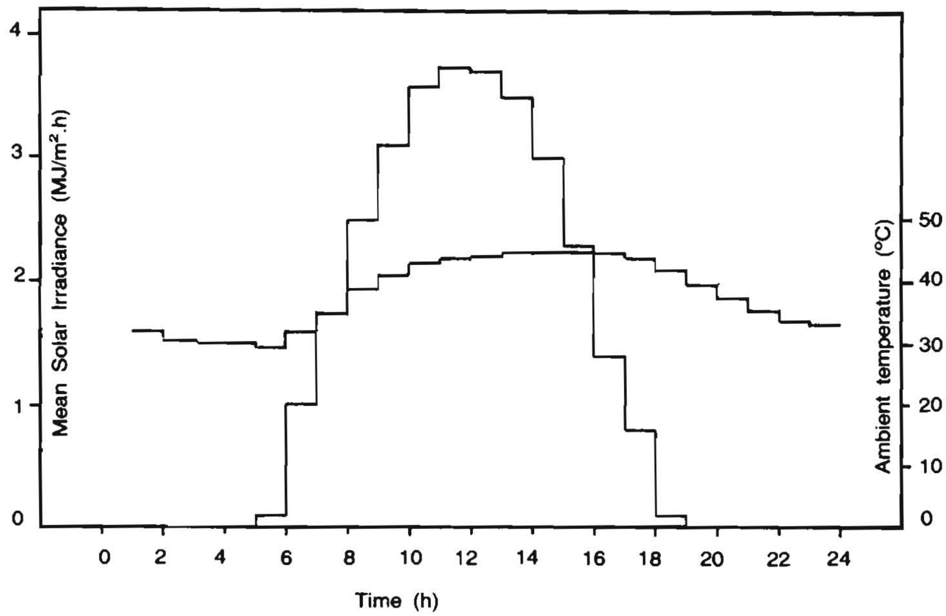

Fig. 5. Hourly solar irradiance and ambient temperature on a typical summer day.

(ASAE 1987), which implies an efficiency of 0.9 or better.

Since most of water consumption takes place during hours of the day when both solar irradiance and temperature are high the improvement of η would still show an appreciable water saving on daily basis, eventhough ambient temperature falls below 40°C for 12 hours of the day even in peak summer months. The effect of η on daily water consumption was investigated using the data of a typical summer day (Fig. 5). The results are presented in Fig. 6, where it is shown that an increase of η from 0.7 to 0.9 results in 28% water saving, equivalent to 7 Kg (of water)/m^2.day. Even a modest rise from 0.7 to 0.8 results in 19% saving, equivalent to 4.8 Kg (of water)/m^2.day.

Conclusion

Crop production in greenhouses in Kuwait is constrained in summer by the prevailing harsh weather conditions and scarcity of fresh water resources. It is shown that the high ambient temperature has a significant effect on water consumption for greenhouse cooling. In fact, water consumption varies exponentially with ambient temperature. To maintain indoor conditions appropriate for crop production in summer it is essential that the efficiency of the evaporative

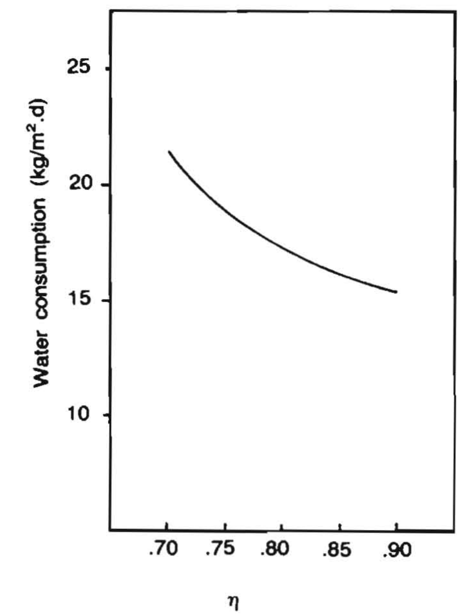

Fig. 6. Effect of cooling system efficiency on water consumption on a typical summer day.

cooling system is improved to the level of 0.85 to 0.9 and solar irradiance transmission to the greenhouse is controlled to reduce the magnitude of cooling load.

Notation

A	area; m^2
C	specific heat; KJ/Kg °C
I	solar irradiance; W/m^2 or KJ/m^2 h
K	constant
m	air flow rate; Kg/m^2 h
Q	cooling load; W/m^2 or KJ/m^2 h
T	temperature; °C
U	overall coefficient of heat transfer; W/m^2 °C
W	water consumption; Kg/m^2 h
w	humidity ratio; Kg(water)/Kg(dry air)
x	ratio of cover to floor areas
f	ratio of wet bulb to dry bulb temperatures
α	absorptance of greenhouse crop and floor
τ	transmittance of cover material
η	efficiency of evaporative cooling system

Subscriptions

a	ambient dry bulb
c	cover
e	exhaust air
m	mean
p	constant pressure
w	wet bulb
r	floor
s	supply air to the greenhouse
u	unit floor area

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العوامل المؤثرة على استهلاك المياه لتبريد بيوت الزراعة المحمية في منطقة حارة قاحلة

سعود عياش و مي رصاص

إدارة الطاقة ـ معهد الكويت للأبحاث العلمية ـ ص. ب: ٢٤٨٨٥ ـ الصفاة ١٣١٠٩ ـ الكويت

يتطلب انتاج المحاصيل في بيوت الزراعة المحمية توفير ظروف من درجة الحرارة والرطوبة النسبية الملائمة لنمو المحاصيل. وفي المناطق الحارة القاحلة يمكن توفير هذه الظروف داخل البيوت أثناء فصل الصيف فقط باستخدام نظم التبريد. والأمر الشائع في تبريد بيوت الزراعة المحمية هو استخدام نظم التبريد البخرية، التي تستهلك كميات كبيرة نسبياً من الماء وكمية قليلة من الكهرباء.

تستقصي الورقة أهمية العوامل المؤثرة على استهلاك المياه لتبريد بيوت الزراعة المحمية. وتبين الورقة أن كمية الماء المطلوبة لتبريد بيت زراعي تعتمد على مقدار حمل التبريد ودرجة الحرارة الخارجية وكفاءة نظام التبريد. ويمكن التعبير عن الحمل التبريدي بدلالة درجة الحرارة الخارجية وشدة الاشعاع الشمسي. هذا، وقد تم التوصل في الورقة إلى معادلة رياضية تعبر عن استهلاك الماء لأغراض التبريد بدلالة درجة الحرارة وكفاءة نظام التبريد وشدة الاشعاع الشمسي.

تقدم الورقة أمثلة حسابية لتبيان تأثير درجة الحرارة وكفاءة نظام التبريد على استهلاك الماء. ويبين أحد الأمثلة أنه في الوقت الذي لا يزداد فيه الحمل التبريدي بأكثر من ١٨٪ نتيجة ارتفاع درجة الحرارة الخارجية من ٣٤ إلى ٤٦ مئوية فان استهلاك الماء يتضاعف خمس مرات. ويبين مثال آخر أن تحسين كفاءة نظام التبريد من ٠,٧ إلى ٠,٨٥ عند درجة حرارة خارجية تبلغ ٤٦° مئوية يؤدي إلى خفض استهلاك الماء بنسبة ٣٨٪. وتبين الحسابات الخاصة

بتأثير كفاءة نظام التبريد على الاستهلاك اليومي من الماء لأغراض التبريد أن زيادة الكفاءة من ٠,٧ إلى ٠,٩ يؤدي إلى خفض الاستهلاك اليومي بمقدار ٪٢٨.

تخلص الورقة إلى نتيجة بأن ظروف الصيف المناخية القاسية وندرة المياه تشكل تقييدات على انتاج المحاصيل في بيوت الزراعة المحمية في الكويت وغيرها من المناطق الحارة القاحلة. ان توفير ظروف ملائمة لانتاج المحاصيل في البيوت المحمية أثناء الصيف في المناطق الحارة القاحلة يتطلب تحسين كفاءة نظم التبريد والحد من كمية الاشعاع الشمسي النافذة إلى داخل البيت.