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Development and Application of a Mathematical Simulation Model to Evaluate Environmental Performance of Greenhouses Using Physical and Climatic Indicators

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Abstract: This study was conducted to determine and apply a mathematical model to simulate the environmental and climatic parameters to evaluate the performance of different greenhouses in three areas within the Khartoum North – Sudan (Date Palm Technology Company., Abu Halima Center and Khartoum University). The assessment method depends on development of a computer simulation model to generate from house physical characteristics and climate data ten environmental performance evaluation indicators (Relative moisture efficiency; Cooling effectiveness, Moisture saturation efficiency; Water consumption rate; House overall efficiency; House ventilation rate, Optimum internal temperature and internal relative humidity).The result of application of the evaluation model for nine greenhouses in three different locations in Khartoum North reveals that there is no significant differences (P = 0.05) in evaluation indicators between the three studied areas. The study concluded that additional work is needed to upgrade the mode of running greenhouse crop cultivation system with regards to: using sustainable and energy efficient cooling and ventilation technologies, adopting new techniques to conserve water and its efficient utilization, introducing properly adapted materials for high temperatures and strong solar radiation, and accessibility of technologies such as automation systems. In the current system moisture use efficiency in particular found to be lower than expected and measures to improvement are critically needed. With respect to the system efficiency and utility of fan and pad greenhouse the effectiveness of cooling system is function of internal environmental parameter (temperature and relative humidity with negative relation). The evaluation model shows that cooling efficiency tends to go up in the areas with low relative humidity.

Keywords: Tropical Greenhouse, Environmental Performance, Evaporative Cooling, Moisture and Energy Efficiencies

1. Introduction

The general objective of this study is to develop and apply analytical, user- friendly computer evaluation model to generate indicators of greenhouses performance to aid farmer, managers, agricultural engineers and decision-makers for formulating improvement actions. The study is directed to assess greenhouses farming system due to its recent spread in Sudan dry zone and around capital cities such as Khartoum North. In this type of farming system environment inside the greenhouse is controlled mainly to cultivate commercially off-season vegetables and ornamental plants. The on-farm environment in Sudan is characterized by its long and hot summers and short and mild winters. Such climatic conditions put great strain on the types of crops that could be successfully grown. Many attempts were made to adapt to such climatic status including the use of different types of evaporative cooling pads to reduce the temperature and alter relative humidity in greenhouses. However, their performance was reported to be lower than expected. The control of the environment inside a greenhouse is dependent on many factors including the house physical characteristics, the external temperature, the season of the year, the amount and duration of natural sunlight, the relative humidity, the size and type of equipment, and structure used and the type of plants growing in the house. Total solar radiation received by a greenhouse at a particular time and locations depends upon its shape as well as orientation, which ultimately determines the inside air temperature. Air temperature is one of the most dominant parameters affecting the plant growth. It is already established that inside air temperature of a passive greenhouse directly depends upon the ambient air temperature, the solar radiation intensity, the overall heat transfer coefficient, the cover material, and the wind velocity [1]. Performance evaluation of three different types of local evaporative cooling pads in 1greenhouses in Sudan is studied by in Tree Palm company site in Khartoum North and in Wad Medini in central Sudan by [2,3]. Mohammed Ahmed Egbal *et al.,* claimed that the reason for using fan and pad cooling method was to let plants in the greenhouse reach the temperatures that they need with artificially controlled environment which require labor and energy inputs and the more energy used the more reduction in temperature compared to the one outside is maintained [2]. However, more energy consumed more cost is incurred resulting in reduced the economic benefits of the plant production system.

Protected Agriculture (PA) is defined as “modification of the natural environment to achieve optimal growth [4]. It is being viewed by several countries within the region as a viable technology to attain a level of self-sufficiency in vegetable production and as a potential adaptation option to address the vagaries of climate change on food supply. Greenhouses provide a suitable environment for the intensive production of various crops. They are designed to control solar radiation, temperature, and humidity and carbon dioxide levels in the aerial environment. [4] Claimed that the availability and distribution of solar radiation has a great influence on crop productivity and quality. This is because the transmitted solar radiations through the greenhouse cover have vital effects in modifying air temperature mainly. However, solar radiations itself depends on shape and size of greenhouse, motion of the sun and weather conditions [5]. Furthermore, stated that the amount of light transmitted into the structure affect house design, orientation and type of glazing [6]. The ability to control the internal environment of greenhouse depends upon the climatic conditions and plants requirement [7].

Crop cultivation in modern greenhouses represents economic sectors that can mainly benefit from technology innovation and it is significantly becoming more and more technological and automated to improve the quality and efficiency of crop production. New remote sensors, devices, networking communication, and control strategies can make available real-time information about crop health, soil, temperature, humidity, and other indoor parameters. Fundamental path towards sustainability of the production is to frequently monitor and evaluate its performance and consequently make improvements by installing these new devices and are equipped the house with forefront IoT- and ICT-based control systems. To arrive to this end, require development of application of a computerized evaluation model.

Dynamic models are important for simulating the greenhouse response on a small timescale, which requires the proper representation of the heat exchange processes between the interacting components. The heat and mass transfer coefficients are functions of the system variables, and it is important that they are formulated under relevant conditions of the greenhouse situation [8].

Llao *et al.,* Studied the thermal heating of controlled environment greenhouse using a transient analysis [9]. In their design, north wall is used as a thermal storage and the ground air collector was also integrated with the greenhouse. In addition, the prediction of moisture content, drying rate, and crop temperature were explained by transient analytical model, Indicators used to express performance of greenhouse is reported by [10] to looked at several environmental elements including Relative moisture efficiency; Cooling effectiveness, Moisture saturation efficiency; Water consumption rate; House overall efficiency; House ventilation rate, Optimum internal temperature and internal relative humidity.

1.1. Indicators Standard Values

[11] Reported that the internal and external temperatures play the most influential role in the evaluation of the design’s thermal performance. The temperature acts on the vital functions of the plant and is generally critical above 70° C and below 0° C. Outside these limits cultures die or hibernate. The amount of water vapor in the air has effects in growth, transpiration, fertilization of plants and in the case of high values, in the development of diseases or in the induction of physiological stress. Conversely a low value of humidity increases the transpiration impeding photosynthesis. Some values of temperature and humidity for optimal type of culture are shown in table 1 [11].

Table 1. Temperature and humidity for optimal type of culture

Cultivation	Optimum temperature range	Optimum Humidity range	Cultivation	Optimum temperature range	Optimum Humidity range
Lettuce	14°C-18°C	60-80%	pepperoni	20°C-25°C	50-60%
Peas	16°C-20°C	65-75%	Cucumbers	20°C-25°C	70-90%
Beets	18°C-22°C	60-70%	Eggplant	22°C-27°C	50-60%
Celery	18°C-25°C	65-80%	Watermelon	23°C-28°C	65-75%
Beans	18°C-30°C	60-75%	Zucchini	25°C-35°C	65-80%
Tomatoes	20°C-25°C	50-60%	Melon	25°C-30°C	60-70%

Previously many authors claimed that both inner temperature and humidity have upper effect in expressing performance of greenhouse compared to other indicators [3, 7, 12]. Chiara Bersani *et al.,* reported that other efficiency indicators including moisture saturation utilization efficiency and energy efficiency plays a key role in the context of management of indoor microclimate condition under an energy-saving approach, and both are thus, the most important fundamental path towards sustainability of the production [13]. Hanan stated that the standard pad and fan system efficiency is about 85% and at low relative humidity conditions of less than 20 % the greenhouse is capable of cooling air below 10°C [14]. As such these studies focus on monitoring and predicting the indicators of both internal temperature and humidity and efficiency indicators in greenhouse systems to enhance sustainable crop production. Based on this review it is assumed that the status utilization of moisture is to be predicted by Relative moisture efficiency; Moisture saturation efficiency; Water consumption rate with standard values of 55%, 75%, and 150 respectively. While the status of Energy efficiency is to be indicated through Cooling effectiveness, and House ventilation rate with standard values of 70%, and 0.9 respectively. However, it is planned that prediction of system overall efficiency with minimum standard value of 75% indicates acceptable overall system performance [3, 7, 12, 11, 13, 15]. This architectural evaluation research study is conducted in pursuit of simulating conditions to reflect the reality of fan and pad greenhouse design. Its intention is to learn about the construction operation and behavior of single-story greenhouses to apply the theories and techniques to rehabilitate and modernize them.

The quantification of the impacts of different energy saving techniques is essential and critical parameter of design, and operation. Therefore, the outcomes of the study investigations and conclusions could reflect insight into the subject. The quantitative evaluation process is assumed to generate comparative results from the real and simulated environments, which contribute to the validity of computer models as a valid decision-aid tool in general.

2. Materials and Methods

Greenhouses assess depends on collecting climate data, inside and outside the Greenhouses, calculate the assessment indicators and optimizing indicators using linear programming approach.

2.1 Data collection

The climatic data used to run the computer model, collected from three study areas within Khartoum North (15.40 N Latitude, 32.32 E Longitude and altitude 380 m above "msl"). Three greenhouses were selected from each area giving a total of nine houses with double layers of polyethylene cover, and galvanized frames, and each with its own specifications.

Table 2. Greenhouses physical data from the three study areas

Greenhouse data	Abu Halima **House 1**	Abu Halima **House 2**	Abu Halima **House 3**	Palm Co. **House 1**	Palm Co. **House 2**	Palm Co. **House3**	Khr. Univ. **House 1**	Khr. Univ **House 2**	Khr. Univ **House 3**
Greenhouses direction	North-south	North-south	North-south	North-south	North-south	North-south	North-south	North-south	North-south
Greenhouses dimensions (L, W, H)	(20*12*4)	(12*6*3)	(17*5*2.3)	(38*8.5*2.5)	(38*10*4.1)	(30.4*7.4*2.64)	(20*9*3)	(20*9*3)	(38*8.5*2.5)
Door dimensions (L, W)	(2*2.7)	(2*2.7)	(2*2.7)	(2*2.7)	(2*2.7)	(2*2.7)	(2*2.7)	(2*2.7)	(2*2.7)
Window dimensions (L, W)	(1.35*1.35)	(1.35*1.35)	(1.35*1.35)	(1.35*1.35)	(1.35*1.35)	(1.35*1.35)	(1.35*1.35)	(1.35*1.35)	(1.35*1.35)
Number of windows	2	2	2	2	2	2	2	2	2
Number of doors	1	1	1	1	1	1	1	1	1
Resistant material of window	3	3	3	3	3	3	3	3	3
Resistant material of door	6.57	6.57	6.57	6.57	6.57	6.57	6.57	6.57	6.57
Resistant material of Walls	2	2	2	2	2	2	2	2	2

Table 3. Climatic and Greenhouses data from the three study areas

Climatic data	Abu Halima	Abu Halima	Abu Halima	Palm Co.	Palm Co.	Palm Co.	Khr. Univ.	Khr. Univ	Khr. Univ
	House 1	**House 1**	**House 1**	**House 1**	**House 2**	**House 3**	**House 1**	**House 2**	**House 3**
Temperature outside (C^o)	36.5	36	34	40.5	32.7	36.2	40.5	20	24.3
Temperature inside (C^o)	25.7	25.6	25.2	26.3	24.9	20.5	23.7	23.5	23.3
Relative humidity outside (%)	18	18	18	35	22.5	28.35	69.4	77.2	79
Relative humidity inside (%)	59	70	69	30	45	30	44	16	30
Specific heat of air	1.013×10^{-3}	1.013×10^{-3}	1.013×10^{-3}	1.013×10^{-3}	1.013×10^{-3}	1.013×10^{-3}	1.013×10^{-3}	1.013×10^{-3}	1.013×10^{-3}
Air speed (m /sec)	1.4	1.4	1.4	36	31	30	0.8	0.8	0.9
Specific volume of air	0.89	0.88	0.88	0.91	0.87	0.85	0.86	0.87	0.87
Air moisture content outside	0.005	0.006	0.010	0.017	0.008	0.015	0.016	0.015	0.017
Air moisture content inside	0.077	0.0696	0.745	0.0678	0.0160	0.016	0.094	0.0938	0.927

Each house is equipped with a cooling pad and a water system components source of water, pump, pipes, gutter and tank. As given in table 3 and 4 the data collected from each greenhouse includes physical characteristics "direction, dimensions and structural material" and climate and environmental data. Exhaust fans were located on the greenhouse walls to draw out the greenhouse air, thus allowing fresh air to pass through the pads and into the greenhouse. Relative humidity and temperature meter were used to measure the relative humidity and temperature inside and outside of the greenhouse. Pipe of irrigation system is 3/4 in. in diameter and 35 m length was used for the irrigation of the test crop in the greenhouses the pipe has 70 nozzles 50 cm apart and is connected with the water source pump. As recommended by [3] all experiments were conducted in steady state and all of the tests were achieved in triplicate.

The experimental works involve measurement of climate and environmental parameters inputs to determine the evaluation indicators (Table 2 and3). For measuring inside and outside climate data: the dry-bulb and wet-bulb temperature were measured by Ordinary thermometer (with range of -20 to 50 °C) located horizontally at the pad, in the mid, and at the end of the greenhouse and vertically at one meter interval upwards in each one of the three horizontal measuring point. The air relative humidity (RH %) was measured using Digital Tri-Sense Model No. 3700-0 (a device for sensing temperature, relative humidity, and air velocity) and these measurements are authenticated by calculation using psychometric chart [16].

Analysis of collected data was carried out by Statistical Package for the Social Sciences (SPSS) software version 16. One-way ANOVAs and descriptive statistics were carried out to determine the level of significance and the combined effect of the evaluation parameters on the house efficiency.

2.2. Model Development

The mathematical model is structured and coded using Excel software. The scope of the software allows for full integration of elements and their customization. The software can specify an incredible amount of detail, down to a custom house physical specification, product construction and all climate elements.

The model processes the variables according to the sequential modular approach so that the output data of a component are used as input to the next component. To start the simulation, the user must specify the input data as given in table 3 and 4. The solar cooling model built was developed by connecting the various components which in turn were created based on physical equations related to their operation

The basic mathematical structure of the model based on calculating the evaluation indicators: Relative moisture efficiency; Cooling effectiveness, Moisture saturation efficiency; Water consumption rate; House overall efficiency; House ventilation rate, Optimum internal temperature and internal relative humidity as described by [17] and Wang, and [18].

1. **Optimum internal temperature (T_{av}):** The overall average temperature (Tav) inside the Greenhouse is obtained by:

$$T_{av} = \frac{T_p + T_c + T_f}{3} \quad (1)$$

Where: Tp : average temperature at pads, Tc: average temperature at the center of the green house, Tf : average temperature at the end of the greenhouse.

2. **Relative humidity:** To obtain the average relative humidity in greenhouse, an average relative humidity at pads and center of greenhouse must be consider as:

$$\mathrm{R_{ha}} = \frac{\mathrm{R_{hap}} + \mathrm{R_{hac}} + \mathrm{R_{han}}}{3} \quad (2)$$

Where: $\mathrm{R_{hap}}$ = The relative humidity at pads, $\mathrm{R_{hac}}$ = the relative humidity at center of greenhouse, $\mathrm{R_{han}}$ = the relative humidity at the end of greenhouse

3. **Cooling efficiency (C_f %):** this is defined as the ratio of the actual dry bulb temperature reduction to the theoretical maximum at 100% saturation [19]. It is calculated as per the following equation:

$$\mathrm{C_f} = (\mathrm{T_o} - \mathrm{T_p})/(\mathrm{T_{in-st}}) \times 100 \quad (3)$$

Where: To = Temperature outside of the greenhouse, $\mathrm{T_{in-st}}$: Difference between the internal temperature and air temperature at saturation,

4. **The Saturation Efficiency (SE %**): can be calculating from average temperature at pads and overall average temperature as:

$$\mathrm{SE\%} = 100 \times (\mathrm{T_o} - \mathrm{T_{av}})(\mathrm{T_p}) \quad (4)$$

The mass balance (Wgh) equation for the greenhouse air [20] could be written as:

$$\mathrm{W_{gh}} = 0.622 \times \emptyset \times \frac{\mathrm{P_{sg}}}{\mathrm{P} - \mathrm{P_{sg}}} \quad (5)$$

Where: Ø = the relative humidity inside the greenhouse, P = Vapors pressure of outside air, Psg = Vapors pressure inside greenhouse.

Deviation from optimum temperature (TOP) can be calculated from the following equation:

$$\mathrm{T_{op}}(\%) = 100 \times \frac{\mathrm{T_{av}} - \mathrm{T_c}}{\mathrm{T_c}} \quad (6)$$

5. **The ventilation rate**(Q): The outgoing ventilation flux $(\theta_{v,1})$ per unit length of the window and door through the upper part is:

$$\theta_{v,1} = \int_0^{h_1} v(z)dz \quad (7)$$

Where: V (z) = velocity in the opening at distance z, [m.s-1]; h1 = height of the window or door. The ventilation rate (Q) to balance the overall air through the greenhouse can be calculated by using equation 7 as:

$$\mathrm{Q} = \frac{\mathrm{vo} \times \mathrm{qb_d}}{(60 \times \mathrm{qvo})(\mathrm{to} - \mathrm{ti})} \quad (8)$$

$$\mathrm{Qt} = \mathrm{A} \times 0.0067 \times \frac{\mathrm{h_A}}{2} \times (\mathrm{to} - \mathrm{ti}) + 0.023 \times ((\mathrm{s})^2)^{\frac{1}{2}} \quad (9)$$

$$\mathrm{Qw} = \frac{(\mathrm{vo}/60)(0.55)}{(\mathrm{wi} - \mathrm{wo})} \quad (10)$$

$$\mathrm{ECF\%} = 100 \times (\mathrm{to} - \mathrm{tHAv})(\mathrm{twbd}) \quad (11)$$

$$\mathrm{tdot\%} = 100 \times \frac{\mathrm{thav} - 26}{26} \quad (12)$$

$$\mathrm{HE\%} = \frac{100 \times \emptyset\mathrm{hav}}{70} \quad (13)$$

$$\mathrm{tgpf} = \mathrm{tfav} - \mathrm{tpav} \quad (14)$$

6. **Water consumption rate (Wc)**

$$Wc = \frac{Q}{vo}((we - wo) \quad (15)$$

Where: Wc = Water consumption rate; Q = Aeration rate m^3/s ; vo = Air specific volume m^3/kg. we = in house moisture content Kg/s, and wo= out house moisture content

7. **House overall efficiency (HOE)**

$$(HOE) = (RHe)(Cf)(SE)^{1/3)} \quad (16)$$

Where: SE = Saturation Efficiency; RHe = Relative humidity efficiency, and Cf = Cooling efficiency.

3. Results and Discussions

Abu Halima Site: Table 4 shows the achieved evaluation indicators scores for Abu Halima Site. It indicates significant differences using t-student test for internal temperature only and other indicators do not differ between the replicated houses inside the site. In all house the overall pattern of the temperatures follows a natural and typical diurnal swing, with higher temperatures during the day and lower ones in the evening. This result of rise in temperature is consistent with the finding of [21] and [2] who reported that the temperature outside the greenhouse at 8 am in the morning was relatively high due to the fact that the greenhouses conserve their coolness during the night and protects them inside from the short-wave radiations in the morning.

Cooling effectiveness and House ventilation rate are rather low resulting in higher temperature. This call for revision of the operation parameters of the fan system (speed mainly) and removal of salt accumulated in the pads. This is also noted by [3]. In contrast moisture efficiency is better resulting in acceptable relative humidity.

3.1 Date Palm Site

Table 5 shows the achieved evaluation indicators scores for Date Palm Site. Using t-student test there is no significant differences between the replicated houses in Date Palm site for all measured evaluation indicators reflecting their homogeneity. The good performance of moisture saturation efficiency, the Cooling system and maintenance of the pads resulted in Acceptable temperature [3].

3.2 Khartoum University Site

Table 6 shows the achieved evaluation indicators scores for Khartoum University Site. The table indicates that the high cooling efficiency and moisture saturation efficiency resulted in reduced temperature inside the houses.

Table 4. Achieved evaluation indicators scores for Abu Halima Site

No.	Indicator	Abu Halima				
		R1	R2	R3	Average	Standard Value
1	Internal Temperature	25.7	25.6	25.2	25.5	22.9
2	Internal relative humidity	59	70	69	66	62.8
3	Cooling effectiveness,	73	72	69	71.3	70
4	House ventilation rate	1	0.8	0.9	0.9	0.9
5	Relative moisture efficiency;	42	48	47	45.7	55
6	Moisture saturation efficiency	78	80	64	74	75
7	Water consumption rate	75.4	22.4	24	40.6	150
8	House overall efficiency	62.6	65.1	63.8	63.8	75

*=t-test significant difference

Table 5. Achieved evaluation indicators scores for Date Palm Site

No.	Indicator	Date Palm				
		R1	R2	R3	Average	Standard Value
1	Internal Temperature	26.3	24.9	20.5	23.9	22.9
2	Internal relative humidity	30	45	30	35	62.8
3	Cooling effectiveness,	77	66.1	57.2	66.8	70
4	House ventilation rate	0.8	0.7	0.6	0.7	0.9
5	Relative moisture efficiency;	35.3	35.3	28.2	32.9	55
6	Moisture saturation efficiency	80	80	64	74.7	75
7	Water consumption rate	73.6	206.6	112.1	130.8	150
8	House overall efficiency	58.2	57.1	46.1	53.8	75

*=t-test significant difference

Table 6. Achieved evaluation indicators scores for Khartoum University Site

No.	Indicator	Khartoum University Site				
		R1	R2	R3	Average	**Standard Value**
1	Internal Temperature	23.7	23.5	23.3	23.5	22.9
2	Internal relative humidity	44	16	30	30	62.8
3	Cooling effectiveness,	39.8	77	20.6	45.8	70
4	House ventilation rate	0.4	0.8	0.3	0.5	0.9
5	Relative moisture efficiency;	56	32	74.8	54.3	55
6	Moisture saturation efficiency	85	87	64	78.7	75
7	Water consumption rate	44	41.4	42.9	42.8	150
8	House overall efficiency	56.3	49.9	49.8	52	75

*=t-test significant difference

Table 7. Indicators of the overall performance of nine greenhouses in Khartoum North

No	Indicator	Abu Halima	Date Palm	Khartoum University	Khartoum Overall Average	Standard Value
1	Internal Temperature	25.5	23.9	23.5	24.3	22.9
2	Internal relative humidity	25.5	35	30	30.2	62.8
3	Cooling effectiveness,	71.3	66.8	45.8	61.3	70
4	House ventilation rate	0.9	0.7	0.5	0.7	0.9
5	Relative moisture efficiency	45.7	32.9	54.3	44.3	55
6	Moisture saturation efficiency	74	74.7	78.7	75.8	75
7	Water consumption rate	40.6	130.8	42.8	71.4	150
8	House overall efficiency	63.8	53.8	52	56.5	75

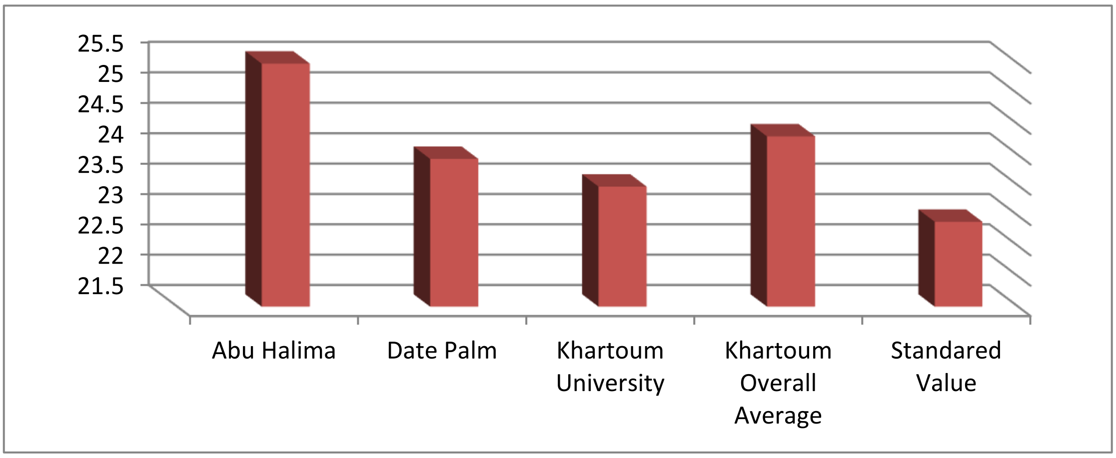

Figure 1. The internal Temperature for nine greenhouses in Khartoum North in relation to target level

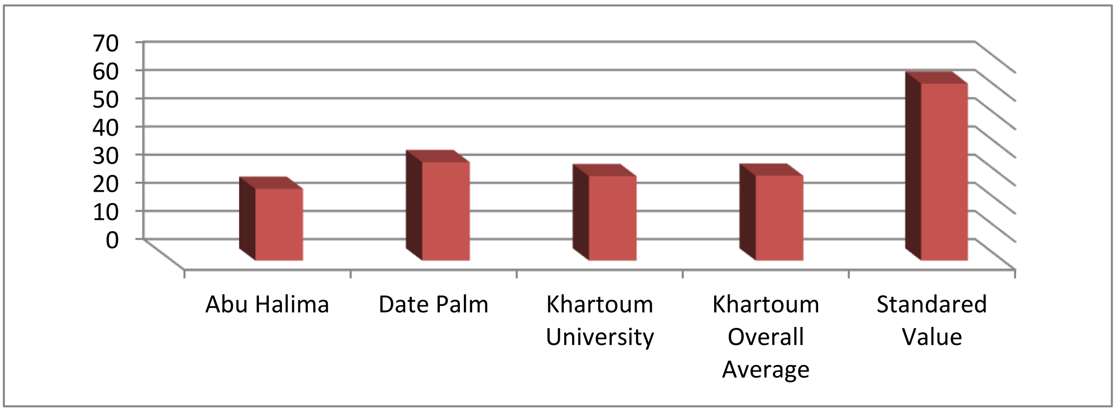

Figure 2. Internal Relative humidity for nine greenhouses in Khartoum North in relation to target level

Overall performance of Khartoum North: The results of the indicators of the overall performance of the nine greenhouses installed in the area of Khartoum north is depicted in table7. T-test analysis at 0.05 and 0.01 levels of significance shows that there are no significant differences between the averages of the indicators of each site and the standard values.

Internal Temperature: As given in table 7 the internal temperature values in shown in Figure 1 for the nine houses in relation to standard values low and almost same as the target level except for Abu Halima which rather a little higher due to the reduction in the efficiency of the cooling system. Likewise, the overall pattern of all the temperatures follows a natural diurnal attitude, with higher temperatures during the day morning and lower towards the evening.

Internal Relative humidity: Table 7 shows the overall range of relative humidity is 25.5 to 35 %. [2] Reported that the results obtained for relative humidity from the greenhouses with different types of evaporative cooling pads, showed that the range of relative humidity is 39.56% followed by 42.75% and reached 51.16%. They attributed these values to higher relative capability of those pads in reducing the temperature at that time of the day, and their ventilation efficiency. These results are in line with the finding of [21]. Figure 2 shows that the relative humidity in the three sites is the same but they are all below the target level. This result is in agreement with results given by [22] and [23]. As stated by [21] and [2] indicated that maintaining proper relative humidity in the greenhouse or growing area can be very difficult during hot, dry summer days.

Cooling effectiveness: Figure 3 shows the cooling effectiveness of the nine greenhouses in Khartoum North in relation to target level. Although the cooling efficiency in the site of Khartoum University is low but the cooling efficiency do not differ significantly from the other sites or in comparison to the target level. This low performance could be attributed to the increased relative humidity coupled with plant evapotranspiration and reduced ventilation efficiency (Table7). This is in agreement with [3] who attributed the performance of the cooling effectiveness to be direct function of internal environmental parameters that include temperature, relative humidity, water quantity, and pressure drop and air velocity. The much better performance of both Abu Halima and Date Palm sites could be attributed to the well-designed properly installed and operated evaporative cooing system. These results are in line with the finding of [21] and [19].

House ventilation rate: Figure 4: give the house ventilation rate for the nine greenhouses in Khartoum North in relation to target level. From figure 4 it is clear that in the Date Palm Co site and Khartoum university site are lower than the target rate while that maintained in Abu Halima is equivalent to the standard level. [15] Stated that ventilation rate depends on airflow velocity through cooling Pads (material and maintenance from clogging), fans capacity, horizontal location distance of fans and cooling pads.

Relative moisture efficiency: Figure 5: depicted the relative moisture efficiency for the nine greenhouses in Khartoum North in relation to target level. It shows that the overall average for all houses is almost typical to the target level. However, the data of the Palm site exhibit the lowest level. This may be attributed to its low ventilation rate in the studied houses (Figure 4).

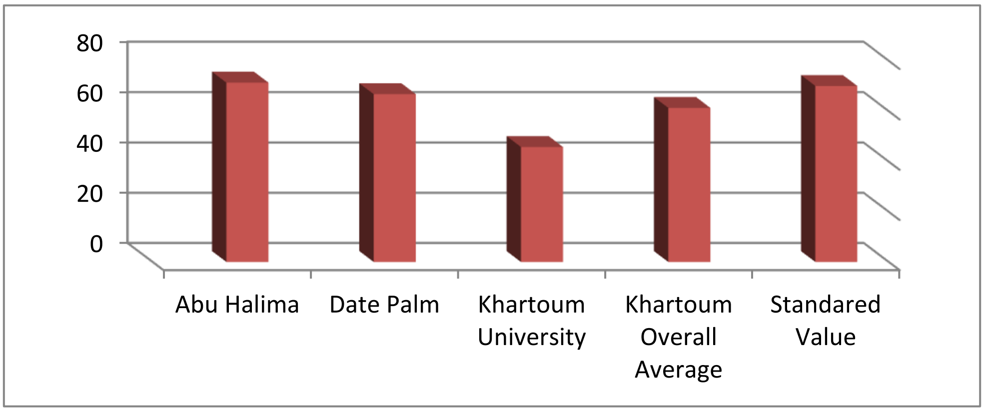

Figure 3. Cooling effectiveness of nine greenhouses in Khartoum North in relation to target level

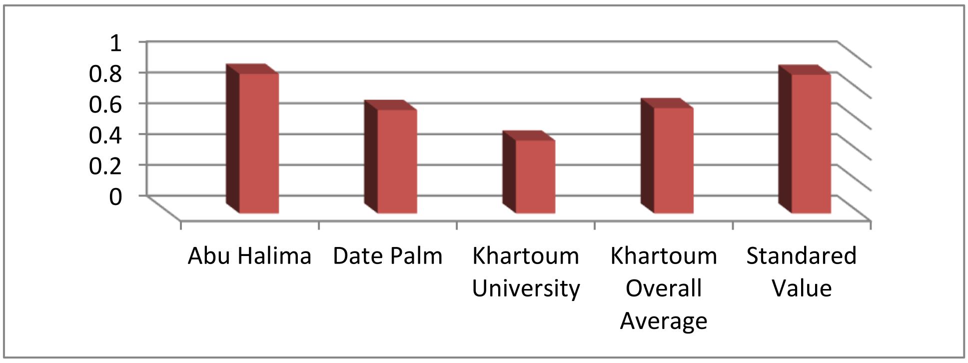

Figure 4. House ventilation rate of nine greenhouses in Khartoum North in relation to target level

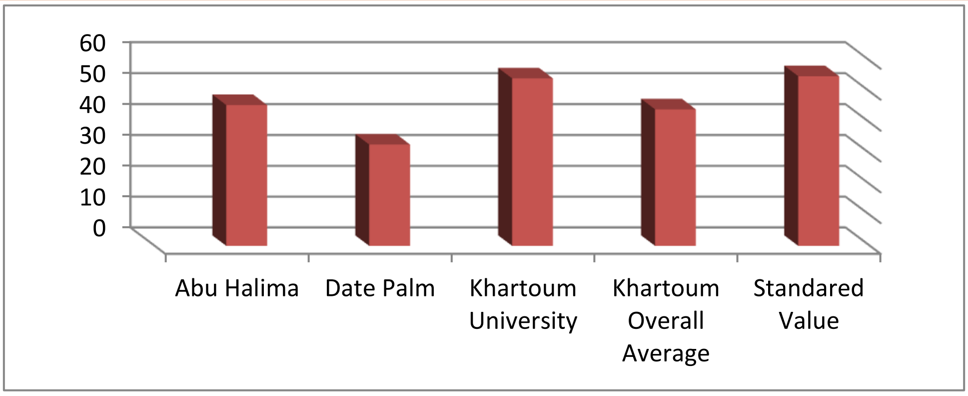

Figure 5. Relative moisture efficiency of nine greenhouses in Khartoum North in relation to target level

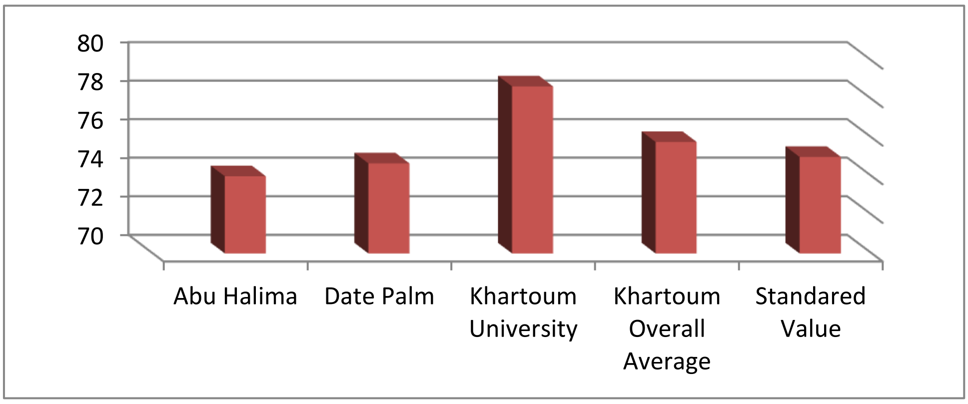

Figure 6. Moisture saturation efficiency of nine greenhouses in Khartoum North in relation to target level

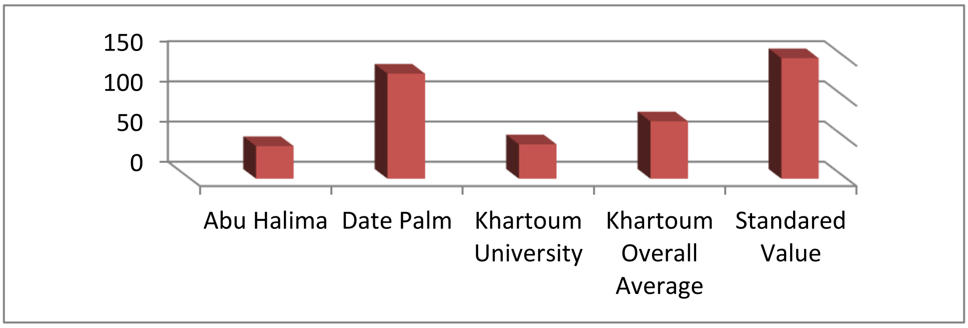

Figure 7. Water consumption rate of nine greenhouses in Khartoum North in relation to target level

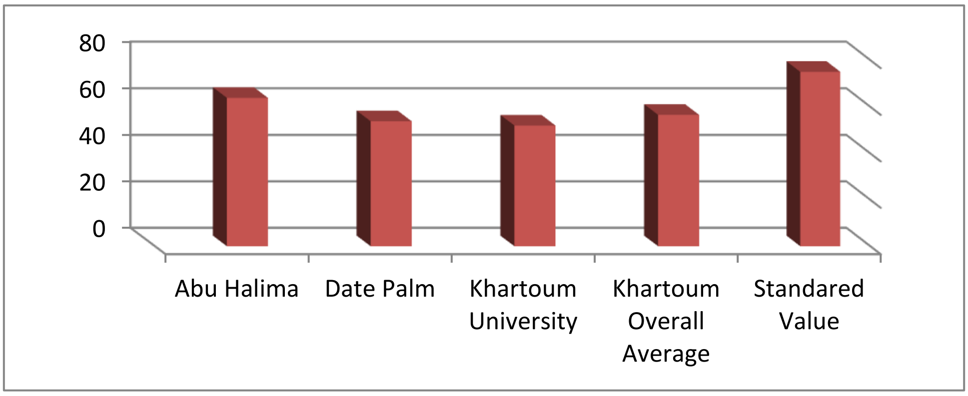

Figure 8. Overall efficiency of nine greenhouses in Khartoum North in relation to target level

Moisture saturation efficiency: The values of the saturation efficiency for the nine greenhouses in Khartoum North in relation to target level are shown in Figure 6. It indicates high level of moisture saturation efficiency in Khartoum university site due to its high relative moisture efficiency compared to other sites. In contrast Data Palm site shows the lowest level of moisture saturation efficiency due to its lowest relative moisture efficiency.

Water consumption rate: Figure 7 which give the water consumption rate of the nine greenhouses in Khartoum North in relation to target level. It is evident from the figure that the Date Palm site consumed largest amount of water and this water is not properly used and it is wasted as losses (With low moisture saturation efficiency "figure 5" low Relative moisture efficiency "figure 4").

House overall efficiency: The overall efficiency that reflects combined of moisture saturation efficiency, relative humidity efficiency, and Cooling efficiency is illustrated in Figure 8 for the nine greenhouses in Khartoum North in relation to target level. However, the overall efficiency of the study areas is rather less that needed and indicate more efforts is required to improve both the design and operation parameters. This includes reduction of cooling energy, use of optimum air flow rate and clean pads to upgrade ventilation level and conserve water and improve its utilization.

4. Conclusions

From the results of this quantitative evaluation study in tropical and arid climate protected agriculture in dry land in general and in Sudan in particular (Khartoum North areas), work still remains to upgrade the mode of running greenhouse crop cultivation system with regards to: Sustainable and energy efficient cooling and ventilation technologies Sustainable and efficient water use methods. Properly adapted materials for high temperatures and strong solar radiation Accessibility of technologies Automation of systems. With respect to the system efficiency and utility of fan and pad greenhouse the effectiveness of cooling system is function of internal environmental parameter (temperature and relative air humidity). The system cooling efficiency tends to go up in the areas with low relative air humidity. This because of the negative relation between the temperature and relative air humidity.

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Conflict of interest

The Authors has no conflicts of interest to declare that they are relevant to the content of this article.

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Yes