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A Computational Approach to Measuring Thermal Demand in Jordanian Greenhouses

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Abstract: This research provides an in-depth analysis of the thermal equilibrium in a greenhouse, taking into account variables such as the greenhouse's geographical position, the variety of crops grown, the type of covering material, heating techniques, and the overall size of the structure. A computerized tool has been crafted to aid farmers, agricultural engineers, and those interested in greenhouse management, offering a significant resource for optimizing greenhouse operations.

In Jordan, energy consumption in plastic greenhouses is of utmost importance for agriculture, especially in regions with harsh weather conditions. Effective management requires an understanding of climatic factors to improve heating systems, which are costly but vital for crop quality and quantity. This study developed a computer program to assess heating needs and revealed that Jordan requires 1.97 megawatts for agricultural greenhouses. The highest consumption was in the Al-Aghwar at 1.00 megawatt. Looking at areas like Shooneh Janobiyeh and Deir Alla, we find consumption levels of 0.59 and 0.35 megawatts, respectively. Optimal heating control led to energy consumption of 1.77, 0.971, 0.61, and 0.221 megawatts for eggplant, tomatoes, peppers, and cucumbers, respectively, contributing to food security and reducing the need for imports. Despite the very successful results of this research, we recommend expanding it to cover the entire territory of the Hashemite Kingdom of Jordan.

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1.Introduction

Understanding the energy dynamics within greenhouses in Jordan is pivotal for several reasons: it influences energy management, cost-effectiveness, and environmental conservation. Given Jordan's energy constraints and commitment to resource optimization, precise assessment of greenhouses' energy requirements is a cornerstone for strategic planning, informed decision-making, and enhancing greenhouse operations (Mansour et al., 2014; Shqiarat, 2019).

Heating is a critical aspect of energy management in greenhouses, particularly during the colder seasons. Jordan's diverse climate poses a threat to crop viability through low temperatures, making adequate heating provision essential. The calculation of heating needs entails a thorough analysis of the greenhouse's architecture, insulation quality, temperature differentials, heat dissipation, and the specific requirements of the crops (Mansour et al., 2014). Accurate estimations enable farmers to select appropriate heating solutions, utilize energy efficiently, and reduce expenses. These calculations are not only vital for energy conservation but also offer economic and ecological advantages. By understanding their energy needs, farmers can better forecast expenses, allocate funds effectively, and explore renewable energy options to decrease reliance on fossil fuels. Moreover, proficient energy management contributes to the reduction of greenhouse gas emissions, bolstering environmental sustainability and aligning with Jordan's climate change mitigation strategies (Chou et al., 2004a).

(Ghaly et al., 2024) devised a software tool to compute the heating demands of greenhouses in Egypt. This tool takes into account variables such as geographic location, crop type, covering material, heating system type, and greenhouse area. Findings indicated that Dakahlia and Al-Buhayrah provinces required the most heating, with energy needs for strawberries and peppers reaching 37.31 kilowatts and 27.8 kilowatts in Dakahlia, and 50.89 kilowatts and 40.62 kilowatts in Al-Buhayrah, respectively.

(Dimitropoulou et al., 2023) introduced a refined method to predict thermal energy needs for European greenhouses. Their model computes annual heating requirements, peak heating power, and the duration of heating and zero-energy periods. It integrates factors like greenhouse design parameters, crop cultivation conditions, and climatic data, all adjusted to the specific geographic location. The study underscored the significance of latitude in determining heating needs, with lower latitudes (40 to 50 degrees) requiring between 250 to 430 kWh/m^2/year and higher latitudes (50 to 60 degrees) necessitating 430 to 650 kWh/m^2/year.

(van der Salm et al., 2023) developed a specialized greenhouse model for optimal yields in Algiers' coastal areas. They evaluated two cultivation strategies: winter cultivation with heating and summer cultivation with air-conditioning and CO_2 enrichment. The study revealed that while yields were similar in both seasons, summer production costs were 30% higher, although summer cultivation benefited from lower water and energy usage.

(Morshed et al., 2022) implemented a tubular heat exchanger in a Syrian greenhouse to provide an economical and environmentally friendly heating solution. The system, featuring 20-meter-long pipes buried a meter deep, significantly influenced heating efficiency. Soil temperatures remained between 18 and 19 degrees Celsius, with indoor air temperatures averaging 11 to 12 degrees Celsius. Extending the pipe length improved heating efficiency by 56%.

(Hainoun et al., 2010) initiated a two-year project to develop a strategic energy plan for Syria, focusing on reducing greenhouse gas emissions cost-effectively. The plan included building a 100 MW wind farm and exploring the installation of 1.2 million solar water heating systems by 2030. The wind farm is expected to produce 275 GWh of electricity per year, cutting greenhouse gas emissions by 190 kt CO_2 eq annually, totaling 3.8 Mt CO_2 over its lifetime. The solar project aims to save 19.33 TWh of electricity and reduce CO_2 emissions by about 11 million tons.

(Al Miaari et al., 2023) presented the design and thermal efficiency of a novel solar greenhouse with a humidification-dehumidification unit, water-cooled heat exchanger, and adjustable mixing ratio, suitable for the Mediterranean climate. This greenhouse maintains ideal microclimates for plant growth, generates fresh water, and saves energy using semi-transparent photovoltaic panels. On average, it can lower temperatures by 11.14°C compared to conventional greenhouses, maintain appropriate humidity levels, and produce 70 liters of fresh water daily.

(Attar et al., 2013) reported significant savings in heating costs by using a flat plate solar collector with a capillary polypropylene heat exchanger in Tunisian greenhouses. This system increased the internal air temperature by 5°C but was insufficient to meet all heating requirements. Lower temperatures were found to impact plant growth, and reducing the heating set point could delay the initial harvest (Kläring et al., 2015).

In Jordan, approximately **4000 hectares** are dedicated to plastic greenhouses, primarily catering to the domestic demand for vegetables and decorative plants. These structures are increasingly favored for the early-season production of vegetables, fruits, and flowers, thanks to their polyethylene makeup. Greenhouse cultivation typically surpasses open-field farming in yield per unit area and consistently delivers higher quality products. Effective climate regulation within these greenhouses is essential to attain substantial crop yields and quality that align with consumer expectations and cost-efficiency standards (Baeza Romero et al., 2019).

This research provides an in-depth analysis of the thermal equilibrium in a greenhouse, taking into account variables such as the greenhouse's geographical position, the variety of crops grown, the type of covering material, heating techniques, and the overall size of the structure. A computerized tool has been crafted to aid farmers, agricultural engineers, and those interested in greenhouse management, offering a significant resource for optimizing greenhouse operations.

2.Material And Method

A compting program in Visual Basic 6.0 has been developed for calculation of heating capacities for greenhouses in Jordan. The software is available on request at ggurdil@omu.edu.tr

The materials used in greenhouses in the research were regulated according to the thickness of some material's conduction resistances in Table **1**.

Tabel 1: Coverage materials used in greenhouses

Type of cover material	Thickness (mm)	Thermal conductivity (W/m^2 K)
Glass	3.18	6.3
A layer of fiberglass	1.02	5.7
Ultraviolet stabilized polyethylene film, PE	0.0003	6.3
Polyethylene film IR absorbing	0.0003	5.7
Polyvinyl fluoride film PVF	0.0008	5.7
Glass-double pane	25.40	3.0
Polycarbonate structured sheets	6.80	3.5

Some meteorological data that can be used in calculating the heating loads of greenhouses that can be established given in Table **2**.

Table 2: The geographical distribution of greenhouses in Jordan (2010).

Location	Product	Cultivated area (km^2)
Al-Aghwar	Tomato	9.730
	Cucumber	0.502
	Pepper	0.927
	Eggplant	9.800
Shooneh Janobiyeh	Tomato	1.230
	Cucumber	0.100
	Pepper	0.220
	Eggplant	5.528
Dair Alla	Tomato	3.560
	Cucumber	0.280
	Pepper	0.302
	Eggplant	2.975
Total		35.172

Source: Ministry of Agriculture and Land Reclamation (In Arabic 2010).

Tabel 3: Average temperature, wind speed, and solar energy for some Jordanian locations:

Location	Average Temp. (°C)	Average Wind Speed (m/s)	Solar Energy MJ/m^2.day	Solar Energy kW/m^2.day
Al-Aghwar	11	3.2	5.96	69.19
Shooneh Janobiyeh	10	3.1	6.09	66.99
Dair Alla	10	2.6	5.91	65.01

Average Temperature and average wind speed data are available: https://weatherspark.com

Solar Energy data is available (Global horizontal irradiation is chosen): https://globalsolaratlas.info

Figure 1: Geographical distribution of Jordan's regions (Shqiarat, 2019)

Table 4: Climate requirements for selected greenhouse crops in hot and arid regions.

Crops	Optimal T (°C°)		Optimal RH (%)	Reference
	Day	Night		
Pepper	21-30	18-20	50-70	(Belanger et al., 1995)
Tomato	23-27	13-16	50-80	(Ponce et al., 2014)
Cucumber	25-30	16-18	70-90	(Perry et al., 1986)
Eggplant	26-32	20-26	50-65	(Gajewski et al., 2009)

The calculation of heating capacities in greenhouses and the flowchart of the program have been developed as shown in Figure **2**.

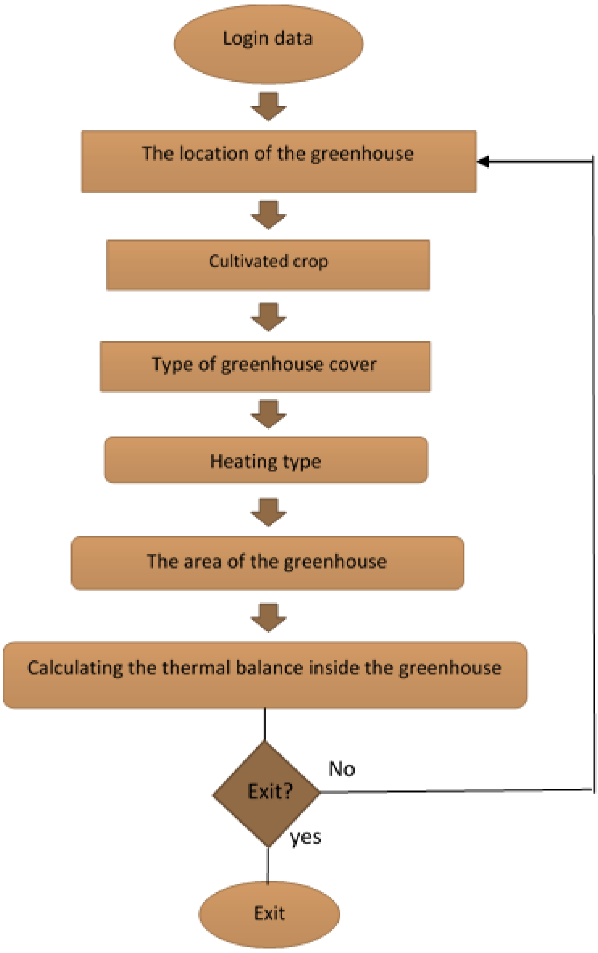

Figure 2: Flowchart of the calculation program.

The program adjusts the greenhouse heating capacity as follows: calculations according to equations (Yavuzcan, 1995). The current requirements for greenhouse heating are determined by assessing the heat losses and gains within the greenhouse, and this calculation is based on the disparity between these factors.

$$Q = Q_1 - Q_2 \quad (1)$$

Where:

Q = Greenhouse heat current requirement (W)

Q_1 = Total heat flow lost from the greenhouse (W)

Q_2 = Heat gained from solar energy in the greenhouse (W)

The heat loss from the greenhouse can be quantified using the following equation:

$$Q_1 = A * K * (T_i - T_d) \quad (2)$$

Where:

A = Total area of glass or plastic (m^2)

K = The coefficient of the total heat transfer (W/m^2. K)

T_i = Temperature inside the greenhouse (K)

T_d = External temperature (K)

The cumulative heat transfer coefficient from the greenhouse to the atmosphere, encompassing both the total heat transfer and ventilation heat, is the summation of convection coefficients.

$$K = K_1 + K_2 \tag{3}$$

$$K_1 = \frac{1}{\frac{1}{\alpha_i} + \frac{d}{\lambda} + \frac{1}{\alpha_d}} \tag{4}$$

$$K_2 = 0.19 * v \tag{5}$$

Where:

K_1 = Total heat transfer coefficient from the greenhouse to the atmosphere (W/m^2. K)

K_2 = Heat convection that meets the ventilation temperature coefficient (W/m^2. K)

α_i = Heat transfer coefficient inside the greenhouse (W/m^2. K)

d = Thickness of the used cover material (m)

λ = Thermal conduction coefficient of the used cover material (W/m. K)

α_d = External heat transfer coefficient from the cover surface to the atmosphere (W/m^2. K)

In Jordanian, greenhouses commonly employ pneumatic and tubular heaters. Nonetheless, when considering the initial investment and operational expenses, particularly in the context of higher energy costs and central heating systems, air-type heaters are typically the preferred choice for greenhouse heating.

$$\alpha_i = \alpha_h + \alpha_{tö} \tag{6}$$

$$\alpha_{tö} = \frac{Q_{tö}}{A_{tö} * (T_i - T_{öi})} \tag{7}$$

$$Q_{tö} = C_t * A_t * \left[\left(\frac{T_t}{100} \right)^4 - \left(\frac{T_{öi}}{100} \right)^4 \right] \tag{8}$$

Where:

α_h = Heat transfer coefficient between hot air and greenhouse air (W/m^2. K)

$\alpha_{tö}$ = Heat transfer coefficient of the heat carried from the soil to the inner surface of the cover (W/m^2. K)

$Q_{tö}$ = Heat flow radiating from the soil to the inner surface of the cover (W)

$A_{tö}$ = Greenhouse cover surface area hitting the soil surface (m^2)

$T_{öi}$ = Inner surface temperature of the greenhouse cover (K)

C_t = Thermal radiation coefficient of the upper surface of the soil (W/m^2. K^4)

A_t = Top surface area of soil (m^2)

T_t = Temperature of the upper soil surface (K)

The inner surface temperature of the greenhouse cover can be determined using the following equation:

$$T_{öi} = 0.43 * (T_i - T_d) + T_d \tag{9}$$

When calculating the total heat transfer coefficient from the greenhouse to the atmosphere, the convection coefficient for external heat transfer from the cover surface to the atmosphere is determined as follows.

$$\alpha_d = \alpha_{rü} + \alpha_{öt} \tag{10}$$

Where:

$\alpha_{rü}$ = External heat transfer coefficient caused by wind (W/m^2. K)

$\alpha_{öt}$ = Heat transfer coefficient from the cover surface to the atmosphere (W/m^2. K)

The amount of heat gained in the greenhouse environment can be calculated from the equation:

$$Q_2 = I_0 * A_{ça} * \eta \tag{11}$$

Where:

I_0 = Average daily solar radiation intensity (W/m^2. day)

$A_{ça}$ = The surface area of the greenhouse (m^2)

η = The percentage (%) of solar energy coming to the greenhouse that is converted into useful form in the greenhouse.

3. Results

The results of the study were given in tables, below.

Table 5: The total amount of required heat for greenhouses in some regions in Jordan.

Regions	Al-Aghwar				Shooneh Janobiyeh				Dair Alla			
	Tomato	Cucumber	Pepper	Eggplant	Tomato	Cucumber	Pepper	Eggplant	Tomato	Cucumber	Pepper	Eggplant
Cultivated area (km^2)	9.730	0.502	0.927	9.800	1.230	0.100	0.220	5.528	3.560	0.280	0.302	2.975
Solar Energy MJ/m^2.day	5.96	5.96	5.96	5.96	6.09	6.09	6.09	6.09	5.91	5.91	5.91	5.91
ir velocity (m/s)	.2	.2	.2	.2	.1	.1	.1	.1	.6	.6	.6	.6
Area of the greenhouse (m^2)	9730	502	927	9800	1230	100	220	5528	3560	280	302	2975
Indoor air temp. (°C)	16	18	20	26	16	18	20	26	16	18	20	26
Outdoor air temp. (°C)	11	11	11	11	10	10	10	10	10	10	10	10
Q_1 (kW)	426.68	30.91	73.64	1310.2	64.21	6.98	19.26	782.16	178.80	18.81	25.44	404.88
Q_2 (kW)	90.4	0.14	7.20	93.3	7.79	.88	.54	14.7	34.2	0.55	1.38	12.1
Q (kW)	36.28	10.77	36.62	916.90	16.42	3.10	10.72	567.46	44.60	8.26	14.06	292.78

Table 6: The required amount of heat for greenhouses by region

Location	Al-Aghwar	Shooneh Janobiyeh	Dair Alla	Total
The required amount of heat (kW)	1000.38	597.61	359.60	1957.59

Table 7: The required amount of heat for greenhouses by product

Product	Tomato	Cucumber	Pepper	Eggplant	Total
The required amount of heat (kW)	97.19	22.12	61.22	1777.06	1957.59

4 . Discussion

In the study that covered 88% of the cultivated lands in greenhouses, it was found that Jordan requires 1.957 megawatts of energy. This energy consumption is primarily distributed among the following vegetables: eggplant, tomato, pepper, and cucumber.

The crop with the highest energy consumption in terms of heat energy is eggplant. This is due to its need for higher temperatures compared to other plants, especially because of its dense production, particularly in the Al-Aghwar. The country's energy requirements for eggplant cultivation amount to 1.77 megawatts. Tomato cultivation requires 0.97 megawatts, pepper 0.61 megawatts, and finally, cucumber 0.22 megawatts. The warm climate of the "Al-Aghwar" makes it an ideal location for eggplant cultivation due to its high-temperature requirements.

The regions with the highest energy demand for protected agriculture are the Jordan Valley, mainly because of its low elevation below sea level. It is fertile land containing 51.2% of the agricultural greenhouses in Jordan, thus requiring 1 MW of energy. Following the Al-Aghwar are Shooneh Janobiyeh and Dair Alla, with energy consumption of 0.60 and 0.34 MW, respectively.

From the data, it is evident that the Al-Aghwar has higher energy needs for two reasons: its large area of protected agricultural land and its cultivation of eggplant, which requires high temperatures.

5.Conclusion

In Jordan, energy consumption in plastic greenhouses is of utmost importance for agriculture, especially in regions with harsh weather conditions. Effective management requires an understanding of climatic factors to improve heating systems, which are costly but vital for crop quality and quantity. This study developed a computer program to assess heating needs and revealed that Jordan requires 1.97 megawatts for agricultural greenhouses. The highest consumption was in the Al-Aghwar at 1.00 megawatt. Looking at areas like Shooneh Janobiyeh and Deir Alla, we find consumption levels of 0.59 and 0.35 megawatts, respectively. Optimal heating control led to energy consumption of 1.77, 0.971, 0.61, and 0.221 megawatts for eggplant, tomatoes, peppers, and cucumbers, respectively, contributing to food security and reducing the need for imports. Despite the very successful results of this research, we recommend expanding it to cover the entire territory of the Hashemite Kingdom of Jordan.

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