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Calculating Greenhouse Heating Capacities under Egypt's Climate Conditions: Using a Computational Program

Sera Isıtma Kapasitelerinin Mısır İklim Koşullarında Hesaplanması: Bir Bilgisayar Programı Kullanımı

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ABSTRACT

According to recent projections, the world's population is anticipated to reach 9.8 billion by 2050, posing significant challenges to global food security and the availability of freshwater resources. The sector of protected cultivation in Egypt plays a pivotal role in ensuring food security, as it supplies wholesale markets with fresh leafy vegetables and fruits during the winter season, offering adequate quantities at reasonable prices. The effective management of greenhouses and protected cultivation necessitates a thorough understanding of climate dynamics and the optimal environmental conditions for cultivated crops. To implement sound management practices for greenhouses, it is imperative to comprehend the influence of climate variables on plant growth and production throughout various seasons. Heating and cooling systems represent significant expenses in greenhouse production. The inadequacy of heating systems has detrimental consequences on the quality, yield, cultivation duration, and quantity of greenhouse products. Therefore, the accurate calculation of the heating costs is critical to decrease the operating costs. In this study, a computer program was developed to calculate heating requirements for glasshouses according to geographical location, product type, cover material, heating system type, and the greenhouse's ground area size. The results reveal that Dakahlia and Behara governorates exhibited the highest heating requirements, with values of 37.31 kW for strawberry, 27.8 kW for pepper, 50.89 kW for strawberry, and 40.62 kW for pepper, respectively. Conversely, Giza, Gharbia, Nubaria, Sharkia, Ismailia, Menoufia, Damietta, Kafr El-Sheikh, and Suez governorates did not require heating inside the greenhouses.

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ÖZET

Son nüfus projeksiyonlarına göre, dünya nüfusunun 2050 yılına kadar 9,8 milyara ulaşması ve bunun da küresel gıda güvenliği ve tatlı su kaynaklarının mevcudiyeti açısından önemli zorluklar yaratması beklenmektedir. Mısır'daki korumalı yetiştiricilik sektörü, kış mevsiminde toptan satış pazarlarına taze yapraklı sebze ve meyve tedarik ederek makul fiyatlarla yeterli miktarda ürün sunduğu için gıda güvenliğinin sağlanmasında çok önemli bir rol oynamaktadır. Seraların ve korumalı yetiştiriciliğin etkin yönetimi, iklim dinamiklerinin ve yetiştirilen ürünler için en uygun çevre koşullarının tam olarak anlaşılmasını gerektirir. Seralarda sağlam yönetim uygulamalarının hayata geçirilmesi için iklim değişkenlerinin çeşitli mevsimler boyunca bitki büyümesi ve üretimi üzerindeki etkisinin anlaşılması zorunludur. Isıtma ve soğutma sistemleri sera üretiminde önemli giderleri temsil etmektedir. Isıtma sistemlerinin yetersizliği, sera ürünlerinin kalitesi, verimi, yetiştirme süresi ve miktarı üzerinde zararlı sonuçlara yol açmaktadır. Bu nedenle, ısıtma maliyetlerinin doğru bir şekilde hesaplanması, işletme maliyetlerinin azaltılması için kritik öneme sahiptir. Bu çalışmada, seranın coğrafi konumu, ürün tipi, örtü malzemesi, ısıtma sistemi tipi ve seranın toprak alanı büyüklüğü gibi çeşitli faktörler dikkate alınarak seraların ısıtma taleplerini belirlemeyi amaçlayan bir bilgisayar programı geliştirilmiştir. Sonuçlar, Dakahlia ve Behara valiliklerinin sırasıyla çilek için 37.31 kW, biber için 27.8 kW ve çilek için 50.89 kW, biber için 40.62 kW olmak üzere en yüksek ısıtma ihtiyaçlarına sahip olduğunu ortaya koymaktadır. Bununla birlikte, Giza, Gharbia, Nubaria, Sharkia, Ismailia, Menoufia, Damietta, Kafr El-Sheikh ve Suez valiliklerinde sera içinde ısıtma gereksinimi bulunmamaktadır.

1. INTRODUCTION

The rise in global population and energy consumption has prompted researchers and scientists to explore alternative sources for meeting the demand for both food production and energy generation. Additionally, the challenges posed by climate change and limited water resources underscore the increasing preference for protected greenhouse cultivation as a means of advancing the agriculture sector. Greenhouse production optimizes favorable environmental conditions, such as air temperature, and relative humidity (Beyhan et al., 2013).

Protected cropping was introduced in Egypt as a production technique in 1980 and has experienced significant growth over the past three decades. The primary objectives behind this expansion were to augment off-season production of vegetables and fruits, achieve earlier harvests compared to open field crops, and enhance both the yield and quality of agricultural products (Abdrabbo et al., 2019).

Greenhouses serve as a vital component of contemporary agriculture, enabling the cultivation of crops within controlled settings independent of external weather conditions. Nevertheless, the operation of greenhouses entails substantial energy consumption, particularly in heating, cooling, and artificial lighting. Modern greenhouse structures, in particular, are characterized by limited thermal mass and inadequate insulation, frequently resulting in heightened energy requirements for heating and increased emissions of greenhouse gases (Munoz et al., 2022).

Energy expenditure is the most substantial operational cost in cultivating greenhouse crops in temperate climates. Furthermore, the initial expenses of fossil fuels and conventional energy sources have significantly escalated. Given the adverse environmental consequences, finite fossil fuel reserves, and elevated energy demand in both the agricultural and food sectors, there has been a surge in the quest for solar energy as an environmentally responsible and sustainable alternative (Hassanien et al., 2016).

Solar energy stands out as a primary renewable energy source, offering worldwide availability during daylight hours and sustainability. Nevertheless, the management of greenhouse environments necessitates energy input to ensure the provision of optimal growth conditions for plants (Gorjian et al., 2021).

In greenhouse operations, the primary energy consumers are the cooling and heating systems. CO_2 emissions and heating expenses can be decreased by using solar energy for greenhouse heating (Hassanien et al., 2018).

Energy expenses typically account for approximately 15% to 40% of the total production costs in commercial greenhouse operations, with heating costs representing roughly 30% of the greenhouse's overall operational expenditures (Heidari and Omid, 2011).

The design of greenhouses in Egypt must address the challenge of coping with elevated daytime temperatures in summer, low nighttime air temperatures in winter, and consistently low air humidity, particularly in the southern regions of Egypt, which experience higher temperatures throughout the year (El-Afandi and Abdrabbo, 2015).

The practice of protected cultivation for horticultural crops in Egypt has undergone substantial advancements in various domains. The ambitious national initiative aimed at establishing 100.000 greenhouses has played a pivotal role in driving enhancements within the protected cultivation sector in recent years. Furthermore, extensive trials have been conducted in both the commercial and research sectors, focusing on the enhancement of greenhouse production and the integration of innovative technologies, including large-scale adoption of soilless cultivation methods (Abdrabbo et al., 2019).

Research has validated that the growth, yield, and quality of greenhouse plants are influenced when exposed to temperatures below 12°C or above 30°C. The most favorable temperature range for greenhouse plants lies between 22 to 28°C during the daytime and 15 to 20°C at night (Castilla and Hernandez, 2006).

The expansion of greenhouse cultivation has resulted in a combination of advantages and disadvantages concerning food security and the environment. On the positive side, greenhouse production has brought about enhanced efficiency and increased yields due to its capacity to control the microclimate and reduce the risk of excessive insect and pest infestations. This enhanced efficiency and higher yields have been particularly evident in the cultivation of crops such as capsicum, tomatoes, and various other vegetables (Hossard et al., 2014; Zhao et al., 2021). Multiple interconnected factors can impact the environmental control system within greenhouses. These factors include the greenhouse's dimensions, geographical location, choice of covering materials, heat retention techniques, materials' quantity and quality, cultivation method, target day and night temperature, as well as external environmental conditions. Sustainable energy sources, such as heat pumps, solar collectors, and energy storage, have proven effective in heating and cooling systems (Yıldız et al., 2012).

The primary objective of agricultural greenhouses is to enhance crop yield during off-seasons by consistently maintaining optimal temperatures throughout each growth stage (Sethi et al., 2008).

Heating is typically achieved through the combustion of fossil fuels like diesel, fuel oil, and liquid petroleum, resulting in increased emissions of carbon dioxide (CO_2), or by employing electric heaters, which exhibit higher energy consumption (Chai et al., 2012).

Attar et al. (2013) stated that the implementation of a flat plate solar collector (FPC) combined with a capillary polypropylene heat exchanger for greenhouse heating in Tunisia resulted in a substantial 51.8% reduction in heating costs for a 1000 m^3 greenhouse during April. Furthermore, this system was found to elevate the internal air temperature of the greenhouse by 5°C. Nonetheless, the accumulated solar energy alone proved insufficient to fully satisfy the heating demands (Attar and Farhat, 2015). It was observed that the influence of reduced temperatures has a significant impact on plant growth, and adjusting the heating temperature set point downward could potentially postpone the initial harvest (Kläring et al., 2015).

In Egypt, there are approximately 1350 hectares of polyethylene greenhouses, 50000 hectares of walk-in tunnels, and an additional 10 hectares dedicated to hydroponic systems. The utilization of these greenhouse systems serves the purpose of fulfilling domestic market demands for both vegetables and ornamental plants. Beyond catering to local needs, it is essential to underscore the significant value of greenhouse production for its export potential, as it plays a pivotal role in contributing to the foreign trade balance of numerous national economies in Egypt (El-Gayar et al., 2019). The geographical distribution of greenhouses, cultivated area (km^2), production (ton), and the percentage for all governorates in Egypt (2016-2019) is shown in Table 1.

In Egypt, there is an expanding use of polyethylene greenhouses for the early cultivation of warm-season vegetables, fruits, and flowers, making it an effective application of solar energy for space heating and plant cultivation. Furthermore, greenhouse production typically outperforms field production in terms of productivity per unit area, consistently delivering the highest product quality. In general, maintaining climate control is of paramount significance in greenhouse agriculture to achieve both high crop yields and top-quality produce that aligns with consumer demands while also ensuring cost-effective production (Gao, 2012).

Table 1. The geographical distribution of greenhouses in Egypt (2016-2019)

Location	***Cultivated area (km²)***	***Percentage (%)***	***Production (ton)***	***Number of Greenhouses***
Dakahlia	13.20	49.0	104 849	39 705
Giza	2.00	7.30	23 600	6 024
Gharbia	1.50	5.80	20 833	4 752
Nubariya	1.70	6.40	25 174	3 438
Sharkia	2.00	7.40	14 462	3 171
Ismailia	1.20	4.40	13 792	3 083
Menoufia	0.98	3.30	7 423	2 579
Damietta	0.87	3.30	6 876	2 244
Kafr ElSheikh	0.53	2.00	6 983	1 661
Suez	0.57	2.10	3 869	1 507
Behara	1.10	3.80	19 923	1 307
Other governorates	1.40	5.20	8 891	3 449
Total	27.05	100	256 675	72 920

Source: Ministry of Agriculture and Land Reclamation (In Arabic 2019).

Heating in greenhouses is a critical and indispensable element for optimal growth, particularly during the coldest periods, such as chilly nights. However, in composite climates characterized by the need for greenhouse heating during winter nights and cooling during hot summer days, a single system is insufficient to address the demands of such climatic variations. Therefore, the concept and implementation of an air conditioning system have been proposed to directly manage the meteorological conditions encountered. Furthermore, greenhouse heating can be achieved through either passive or active methods (Sethi and Sharma, 2008).

In this research, the heat balance within a greenhouse can be determined through a comprehensive analysis, which considers various parameters including the greenhouse's geographical location, the type of crops cultivated, the material used for the greenhouse cover, the heating technique employed, and the dimensions of the greenhouse. A computer program has been created, with the expectation that it will offer utility to farmers, agricultural engineers, and individuals interested in these matters.

2. MATERIALS AND METHODS

The materials used in greenhouses in the research were regulated according to the thickness and conduction resistances of some materials as shown in Table 2.

Table 2. Thermal conduction resistances of some materials used in greenhouses, arranged according to their thickness (EP, 2004)

Type of cover material	*Thickness (mm)*	*Thermal conductivity (W m^{-2} °C^{-1})*
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	25.4	3.0
Polycarbonate structured sheets	6.8	3.5

Some meteorological data that can be used in calculating the heating loads of greenhouses that can be established in various regions of Egypt are given in Table 3 (Abdelaty, 2015; Noreldin et al., 2016; Rizk, 1987; Maheswara et al., 2014).

Table 3. Long term average climatical parametrs (temperature, average wind speed, and solar energy) in some governorates of Egypt

Location	*Average Temperature (°C)*	*Average Wind Speed (m s^{-1})*	*Solar Energy (kW m^{-2}.day^{-1})*
Dakahlia	16.90	2.30	5.5-6.3
Giza	21.25	2.65	7.0-7.3
Gharbia	21.70	2.68	6.3-6.6
Nubariya	19.15	3.57	5.5-6.3
Sharkia	21.81	2.61	6.6-7.0
Ismailia	21.30	3.70	6.6-7.0
Menoufia	21.80	2.61	6.3-6.6
Damietta	21.30	3.29	5.5-6.3
Kafr ElSheikh	21.01	2.61	5.5-6.3
Suez	21.08	2.50	7.3-7.7
Behara	20.99	2.72	6.3-6.5

The optimal temperature ranges for promoting plant growth within greenhouse environments are outlined in Table 4.

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

Crops	***Optimal T (°C)***		***Optimal RH (%)***	***Reference***
	Day	**Night**		
Lettuce	24-28	13-16	60-80	(Ponce et al., 2014)
Pepper	22-30	14-16	50-70	(Rabbi et al., 2019)
Cabbage	15-16	2	70-80	(Tazawa, 1999)
Tomato	23-27	13-16	50-80	(Ponce et al., 2014)
Cucumber	25-30	16-18	70-90	(Somerville et al., 2014)
Strawberry	20-26	13-16	50-65	(Soussi et al., 2022)

The calculation of heating capacities in greenhouses and the flowchart of the program have been developed as shown in Figure 1.

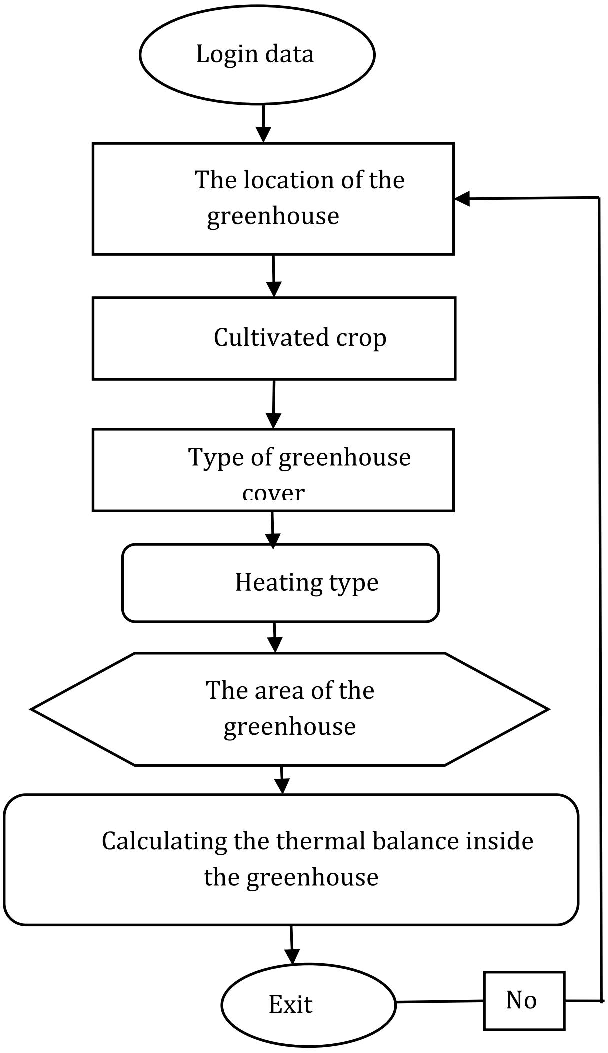

Figure 1. Diagram of the calculation program

The program adjusts the greenhouse heating capacity as follows: calculations according to equations (Yavuzcan, 1995; Anonymous, 2009).

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 (Eqs. 1, 2).

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

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, ($W\ m^{-2}\ K^{-1}$)

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 (Eqs. 3-8).

$$K = K_1 + K_2 \quad (3)$$

$$K_1 = \frac{1}{\frac{1}{\alpha_i} + \frac{d}{\lambda} + \frac{1}{\alpha_d}} \quad (4)$$

$$K_2 = 0.19 * v \quad (5)$$

Where:

K_1 : Total heat transfer coefficient from the greenhouse to the atmosphere, ($W\ m^{-2}\ K^{-1}$)

K_2 : Heat convection that meets the ventilation temperature coefficient, ($W\ m^{-2}\ K^{-1}$)

α_i : Heat transfer coefficient inside the greenhouse, ($W\ m^{-2}\ K^{-1}$)

d : Thickness of the used cover material, (m)

λ : Thermal conduction coefficient of the used cover material, (W m-1 K-1)

α_d : External heat transfer coefficient from the cover surface to the atmosphere, (W m-2 K-1)

In Egypt, 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.

$$\alpha_i = \alpha_h + \alpha_{tö} \quad (6)$$

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

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

Where:

α_h : Heat transfer coefficient between hot air and greenhouse air, (W m-2 K-1)

$\alpha_{tö}$: Heat transfer coefficient of the heat carried from the soil to the inner surface of the cover, (W m-2 K-1)

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

$A_{tö}$: Greenhouse cover surface area hitting the soil surface, (m2)

$T_{öi}$: 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, (m2)

T_t : Temperature of the upper soil surface (K)

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

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

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.

$\alpha_d = \alpha_{rü} + \alpha_{öt}$	(10)

Where:

$\alpha_{rü}$: External heat transfer coefficient caused by wind, (W m-^{2} K^{-1})

$\alpha_{öt}$: Heat transfer coefficient from the cover surface to the atmosphere (W m-^{2} K^{-1})

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

$Q_2 = I_0 * A_{ça} * \eta$	(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 (%).

The calculation of heating capacities in greenhouses is performed through a computer program developed using MS Visual Basic 6.0 programming language.

3. RESULTS AND DISCUSSION

During cold seasons, maintaining specific internal temperatures within greenhouses is essential for optimal plant growth. Nonetheless, this practice leads to escalated heating expenses attributable to the surge in global energy prices. The heating demands for greenhouses across numerous Egyptian governorates have been calculated, given their extensive utilization for cultivating both winter and summer crops.

Using the developed computer program, the required heating quantity for strawberry and pepper greenhouses in the selected governorates was calculated. The obtained results are presented in Table 5. Through result analysis, it became evident that governorates such as Giza, Gharbia, Nubaria, Sharqia, Ismailia, Menoufia, Damietta, Kafr El-Sheikh, and Suez do not require heating inside the agricultural greenhouses. Instead, they require ventilation, attributed to the high daytime temperatures.

Table 5. The total amount of required heat for strawberry and pepper greenhouses in some regions in Egypt

Location	Product	Q_1 (kW)	Q_2 (kW)	Q (kW)
Dakahlia	Strawberry	69.61	31.9	37.71
	Pepper	58.98	31.9	27.08
Giza	Strawberry	6.41	40.60	-34.18 Ventilation required
	Pepper	40.87	40.60	0.27
Gharbia	Strawberry	2.57	36.54	-33.96 Ventilation required
	Pepper	37.10	36.54	0.56
Nubariya	Strawberry	26.04	31.90	-5.86 Ventilation required
	Pepper	62.99	31.90	31.09
Sharkia	Strawberry	1.619	38.28	-36.66 Ventilation required
	Pepper	35.95	38.28	-2.33 Ventilation required
Ismailia	Strawberry	6.46	38.28	-31.83 Ventilation required
	Pepper	43.66	38.28	5.38
Menoufia	Strawberry	1.70	36.54	-34.84 Ventilation required
	Pepper	36.04	36.54	-0.50 Ventilation required
Damietta	Strawberry	6.28	31.90	-25.62 Ventilation required
	Pepper	42.46	31.90	10.56
Kafr ElSheikh	Strawberry	8.44	31.90	-23.46 Ventilation required
	Pepper	42.79	31.90	10.89
Suez	Strawberry	7.77	42.34	-34.57 Ventilation required
	Pepper	41.80	42.34	-0.53 Ventilation required
Behara	Strawberry	87.43	36.54	50.89
	Pepper	77.16	36.54	40.62

Based on the climate data for Dakahlia, where the average temperature during December, January, February, and March was recorded as 16.90 °C (Table 3), it becomes evident that temperatures often drop below the critical threshold of 16°C during these months. Consequently, there arises a necessity to implement heating systems within greenhouses, particularly during daylight hours, in order to maintain conducive growing conditions for crops. As a result, greenhouse growers are inclined to utilize heating systems to ensure optimal growth conditions for their plants. Moreover, the computer program developed has provided illustrative sample calculations, as shown in Figures 2 and 3.

Figure 2 shows a specific case study involving a glass-covered strawberry house covering an area of 1000 m^2 in the Dakahlia region of Egypt, wherein a heating capacity of 37.71 kW was determined. Additionally, the program conducted another computational example focusing on pepper plants with similar specifications, revealing a heating capacity requirement of 27.8 kW for greenhouses in the same region (Fig. 3).

Figure 2. The calculation of the heating capacity required for a 1000 m^2 fiberglass greenhouse for strawberries in the Dakahlia region

Figure 3. The calculation of the heating capacity needed for a pepper greenhouse established in the Dakahlia region

Using identical specifications as the computer program applied for strawberry and pepper plants, the amount of heating required for an agricultural greenhouse covered with fiberglass in Behara

Governorate was 50.89 kilowatts for strawberries and 40.62 kilowatts for pepper plants as shown in Figures 4 and 5 this is attributed to the low temperatures during the daytime.

The main reason why greenhouse cultivation does not develop in these regions is that greenhouse cultivation is no longer a profitable production branch due to high heating costs. In many regions, low winter temperatures pose a significant challenge to agricultural productivity. Therefore, utilizing heating within greenhouses serves as a means to ensure productivity continuity and achieve desired crop yields regardless of external weather fluctuations. Hence, there is a belief that accurately and practically calculating the costs associated with greenhouse heating using this developed program will benefit individuals engaged in this sector.

Figure 4. The calculation of the heating capacity required for a greenhouse for strawberries in the Behara region

Figure 5. The computation of the heating capacity required for a greenhouse for pepper in the Behara region

4. CONCLUSION

Determining the heat energy requirements is essential for conducting greenhouse feasibility studies, designing heating systems, and strategizing production plans. These requirements vary based on factors such as the type of greenhouse, cultivated plants, greenhouse components, and climatic conditions. Focusing on the location of greenhouse production, the governorates that need the highest values for heating requirements are Dakahlia (37.31 kW for strawberry and 27.8 kW for pepper) and Behara (50.89 kW for strawberry and 40.62 kW for pepper) respectively. Whereas the governorates that do not need heating inside greenhouses are Giza, Gharbia, Nubaria, Sharqia, Ismailia, Menoufia, Damietta, Kafr El-Sheikh, and Suez, due to the high temperatures during the day. The proposed program was found to be effective in calculating the heat requirements for greenhouses in certain regions of Egypt. More specifically, the most important factors affecting annual greenhouse heating requirements are, in order of importance: the average temperature during plant growth, the type of greenhouse covering, and the crop type under cultivation. The expansion of greenhouse cultivation represents a burgeoning segment within the agricultural industry. Minimizing energy consumption in greenhouses is intricately linked to mitigating production expenses and the impact of greenhouse farming on the environment.

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