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Developing a Passive Energy Consumption Reduction Solution

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Abstract. This study focuses on optimizing the energy efficiency of polyethylene tunnel greenhouses in Mediterranean climates using Design Builder and EnergyPlus software. The research examines the impact of different greenhouse orientations and opening configurations on energy consumption for heating and cooling. The east-west (90°) orientation was found to be the most effective in reducing cooling needs during summer while slightly increasing winter heating requirements. Various opening configurations were tested, including 0%, 20%, 40%, 60%, 80%, and 100%, with openings positioned at the bottom on one side and the top on the opposite side. The 20% opening configuration was identified as optimal for annual energy management. However, a monthly adaptive planning strategy was developed to further enhance energy efficiency. This planning involves keeping the greenhouse closed during winter, using 100% openings in summer, and 20% openings during transitional months. The proposed monthly planning resulted in a significant reduction in energy consumption, decreasing daytime usage by 27.3%, night time usage by 29%, and overall annual energy consumption by 27.6%. This research demonstrates that strategic orientation and adaptive opening management can substantially improve the energy efficiency of greenhouses in Mediterranean climates.

1 Introduction

Mediterranean climates present significant challenges to agriculture due to the intensity of solar radiation and environmental variations. Greenhouse cultivation emerges as an effective solution, allowing the creation of controlled microclimates that improve the quality and yield of crops throughout the year.

The orientation of greenhouses is essential for optimizing their environment. According to Gheyrati et al. [1], during the cold season in Hemmatabad, Iran, the study of N-S, E-W, and NE-SW orientations showed that the E-W orientation is optimal for maximizing solar energy capture.

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Natural ventilation is crucial for optimizing the yield and quality of greenhouse crop. This requires precise optimization of the size and placement of openings [2-3]. Recent studies, such as those by Lyu et al. [4], examined the impact of vent openings, wind speed, and crop height on the microenvironment within a naturally ventilated three-span arched greenhouse. Senhaji et al. [5] studied the aerodynamic environment inside greenhouses for tomato cultivation. Additionally, research like that of Lee et al. [6] investigated the natural ventilation rate induced by wind in a mono-span greenhouse, considering wind speed and direction, as well as different greenhouse shapes and aeration openings.

Moreover, research such as that by Ouazzani Chahidi et al. [7] evaluated passive solutions for the six climatic zones of Morocco, using advanced models in the EnergyPlus environment to improve the energy efficiency of greenhouses.

Using Design Builder for energy modelling, this research focuses on improving the energy efficiency of polyethylene tunnel greenhouses in Mediterranean climates. The optimal orientation was selected, followed by an analysis of the impact of crossed side openings, varying symmetrically from 0% to 100%, with two openings at the top on one side and two at the bottom on the other side, and vice versa. This initial study was followed by a monthly analysis of the most effective configuration, with a monthly trial planning developed to optimize the use of openings based on daytime and night time conditions. The objective is to reduce energy consumption for heating and cooling, thereby promoting sustainable and efficient management of greenhouse agricultural environments in Mediterranean regions.

2 Materials and Methods

2.1 Greenhouse Description

The greenhouse to be studied is a tunnel-type mono-span structure, as depicted in Fig. 1 (3D representation). Its dimensions are 20 m long, 11 m wide, 6 m high at the gutter and 7.5 m high at the ridge. The greenhouse is equipped with eight side openings located on the long sides (four on each side). The openings will be operated in a crossed manner: two openings will be opened at the top on one side while two are opened at the bottom on the opposite side, and vice versa. These openings will be opened to the same degree. The roof remains closed.

The supporting structure is made of galvanized steel, with cross-sectional dimensions of 30 mm x 30 mm. The cover is made of a commercial polyethylene, 215µm in thickness. The transparent surface area of the greenhouse (roof and side) is 617. 3 m^2.

All simulations take place in Larache (35°11'00" N, 6°09'00"W).

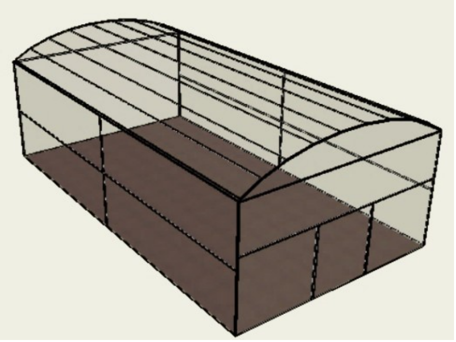

Fig.1. The greenhouse geometry.

2.2 Simulation Model Description

The simulations use EnergyPlus with graphical user interface Design Builder, incorporating the specific climatic data for Larache for the year 2023. These data are derived from measurements taken by weather stations, including temperature, ambient humidity, solar radiation, and wind velocity recorded hourly throughout the year. This represents the typical climatic conditions of the region. Energy calculations are performed with a temporal resolution of six iterations per hour, allowing for a detailed analysis of heating and cooling needs throughout the day and seasons.

To model the greenhouse materials in Design Builder, we employed the integrated materials library. The structure of the greenhouse is made of galvanized steel with a thickness of 0.03 m. Due to its flexibility and robustness, steel is ideal for large greenhouses. The galvanization protects the steel from rust, increasing its durability.

The greenhouse cover is made of commercial polyethylene with thickness of 215µm. The thermal and optical properties of this cover, as detailed in Table 1, were manually entered in the "external windows" section of Design Builder.

As for the greenhouse floor, it is modelled with the material "Earth, common (0.5 m)" available in the Design Builder library and covers an area of 220 m^2.

Table 1. Properties of polyethylene cover used in the model [8].

Property	Value
Thickness (µm)	215
Thermal conductivity (W/m.K)	0.33
Solar transmittance	0.80
Outdoor solar reflectance	0.17
Inside solar reflectance	0.17
Visible transmittance	0.85
Outdoor visible reflectance	0.12
Inside visible reflectance	0.12
Infra-red transmittance	0.00
Outdoor emissivity	0.70
Inside emissivity	0.70

Airflows resulting from natural ventilation and infiltration are calculated based on the sizes of openings, cracks, buoyancy, and wind pressure, using the calculated ventilation option in Design Builder. Air infiltration has also been accounted for. Natural ventilation was simulated with symmetric cross openings, varying from 0% to 100%.

Tomatoes, as the reference crop in this study, require specific temperature conditions for optimal growth: between 18°C and 25°C during the day, and between 10°C and 20°C at night [9]. These temperature ranges were used to determine the heating and cooling needs of the greenhouse. A natural gas heating system is employed, featuring a boiler with a coefficient of performance (COP) of 0.96 and a maximum air supply temperature of 35°C.

Meanwhile, an electric cooling system with a coefficient of performance of 3.5 and a minimum air supply temperature of 7°C maintains the optimal conditions [7].

3 Results and Discussion

3.1 Determination of Optimal Greenhouse Orientation

Fig.2 shows the monthly energy consumption for heating and cooling of greenhouses oriented at 0°, 45°, and 90°. For the 0° orientation, heating needs peak at 1. 85 kWh/m² in January and are zero in summer, while cooling needs are highest in August at 20. 97 kWh/m². With the 45° orientation, heating needs are slightly higher in January (1. 94 kWh /m²), and cooling needs decrease slightly.

For the 90° orientation, heating needs are even higher in January (1.88 kWh/m²) and close to zero in summer, while cooling needs are reduced, peaking in July at 19.10 kWh/m². This greater difference for cooling is due to increased solar exposure in summer, raising cooling demands, while winter solar gains are insufficient to significantly reduce heating needs. These results, supported by Stanciu et al. [10] and Choab et al [11], indicate that an East-West (90°) orientation is more effective in reducing cooling energy consumption, despite a slight increase in heating needs during winter

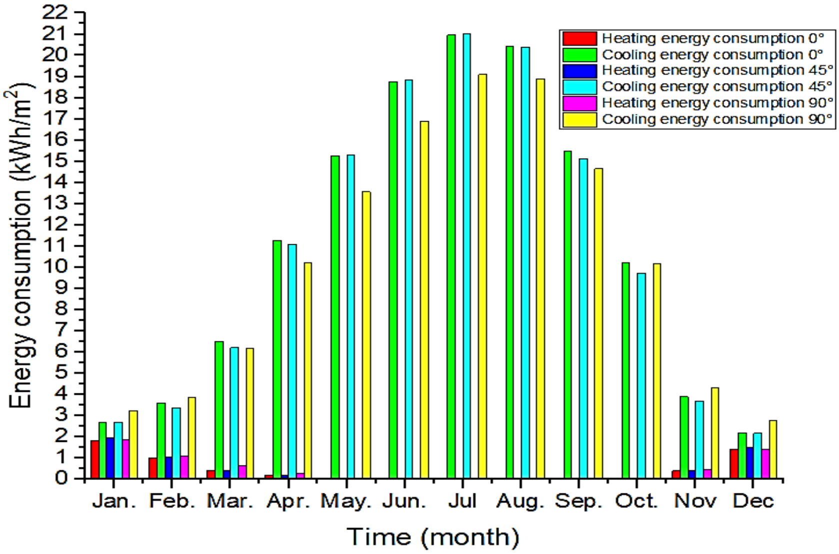

Fig.2. Monthly energy consumption for different greenhouse orientations.

3.2 Impact of opening configurations on annual energy consumption in the greenhouse

The simulations conducted for the mono-span greenhouse, oriented at 90° (east-west) as recommended in Section 3-1, reveal notable variations in annual energy consumption depending on the opening configurations. In this study, we altered the positioning of the lateral openings and the opening rates to assess their impact on energy consumption. The results, shown in Fig.3, demonstrate that the BN TS (Bottom-North, Top-South) configuration consistently performs better than the TN BS (Top-North, Bottom-South) configuration. Specifically, at a 20% opening rate, BN TS exhibits the lowest annual energy consumption at 156.30 kWh/m^2, compared to 159.31 kWh/m^2 for TN BS. This trend is consistent across all tested opening rates. Senhaji et al. [5] indicated that the aerodynamics of the greenhouse is affected by the positioning of the lateral openings, which supports the observed advantages of the BN TS configuration.

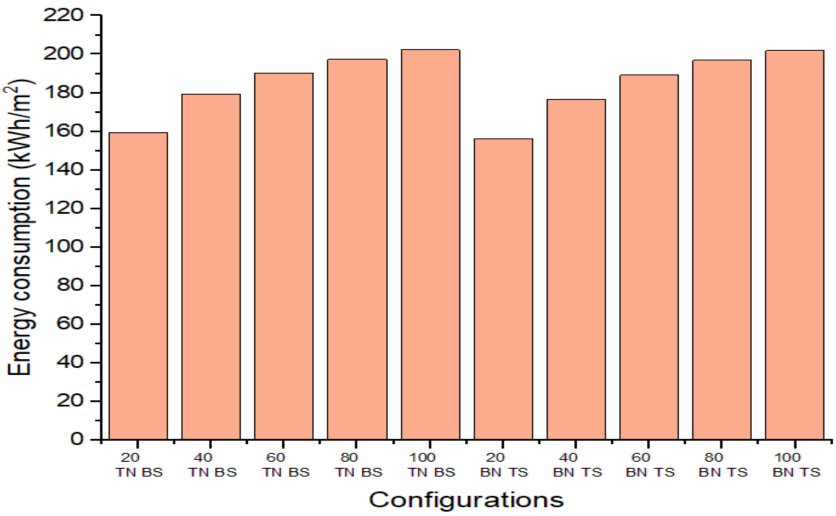

Fig.3. Annual energy consumption for various opening rates and positions.

3.3 Planning

Fig.4 presents the monthly energy consumption for the greenhouse simulation 20 BN TS (Bottom-North, Top-South), which has the lowest annual combined energy consumption for heating and cooling. During the winter, heating is predominant, reaching up to 16.78 kWh/m^2 in January, with very low cooling consumption. In summer, cooling becomes essential and reaches a peak of 18.88 kWh/m^2 in July, while the need for heating is minimal. In September, cooling consumption is 14.56 kWh/m^2, decreasing from the summer peak in July, while heating remains negligible. In November, heating consumption increases to 6.54 kWh/m^2, while cooling is low at 0.73 kWh/m^2.

During the transitional months of March, April, and May, cooling consumption gradually increases, reaching 9.4 2 kWh/m^2 in May, while heating consumption decreases. In October, the trend shifts from the previous months: heating consumption increases to 0.49 kWh/m^2, while cooling consumption decreases to 7.79 kWh/m^2.This analysis highlights the need to adjust energy management strategies, optimizing heating during the winter and regulating cooling during the hot summer periods.

For the next phase of the work, we aim to reduce energy consumption. By comparing the results from different greenhouse configurations, we make the following observations:

The closed greenhouse (Fig. 5) is advantageous during the winter months, with relatively low heating consumption, ranging from 1.88 kWh/m^2 in January to 0.28 kWh/m^2 in April. However, it requires high cooling consumption in the summer, reaching a peak of 19. 10 kWh/m^2 in July, with almost no heating needed during this period.

The 100% BN TS open greenhouse (Fig. 6) shows high heating consumption in winter, reaching up to 28.51 kWh/m^2 in January. In the summer, cooling consumption is also significant, with a peak of 17.81 kWh/m^2 in August. Although it is more effective in reducing cooling consumption during the summer, it remains less optimal due to its high heating consumption in winter.

To optimize energy consumption:

- The closed greenhouse is the best option for January, February, March, November, and December due to its low heating consumption.
- The 20% BN TS configuration is the most balanced for April and May, providing a good compromise between heating and cooling.
- The 100% BN TS open greenhouse is the most suitable for June, July, August, September, and October, as it minimizes cooling consumption.

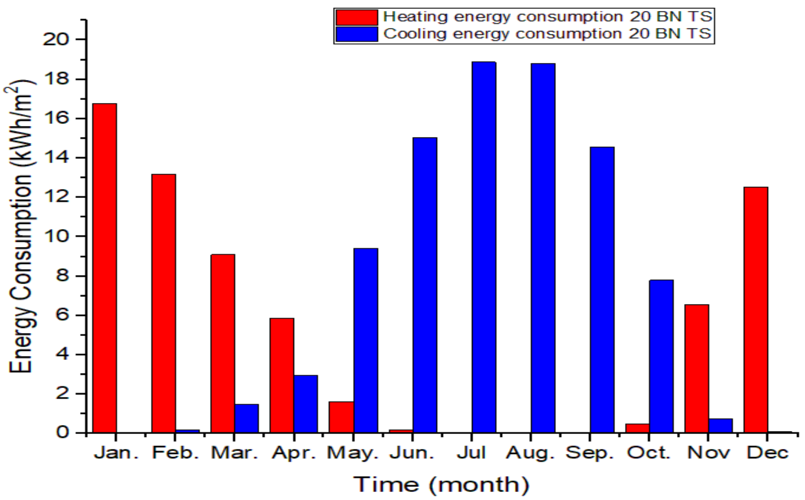

Fig.4. Monthly energy consumption for the most effective configuration.

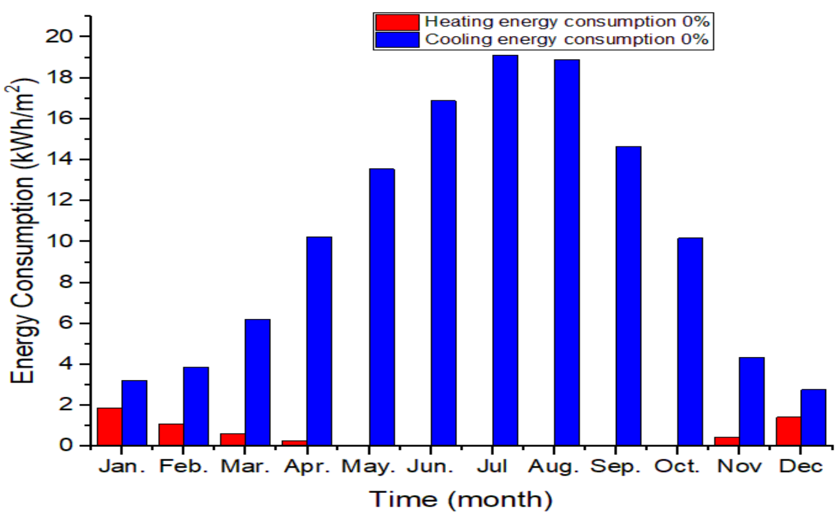

Fig.5. Monthly energy consumption for a closed greenhouse.

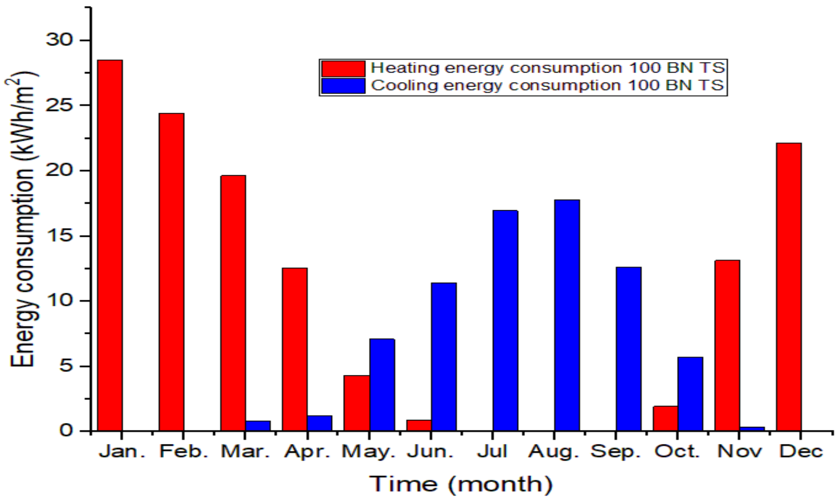

Fig.6. Monthly energy consumption for a greenhouse with 100% openings at north bottom and south top.

For the next part of our work, we will further analyse energy consumption by distinguishing between daytime and night time periods, given that the temperature set points for tomatoes range between 18°C and 25°C during the day and between 10°C and 20°C at night [9].

According to Fig. 7, the closed greenhouse is most advantageous for January, February, March, November, and December, with relatively low consumption. In April and May, a 20% BN TS opening is preferable, showing lower consumption compared to both the closed and 100% BN TS opening configurations. For the remaining months, a 100% BN TS opening is generally the best option, offering lower consumption.

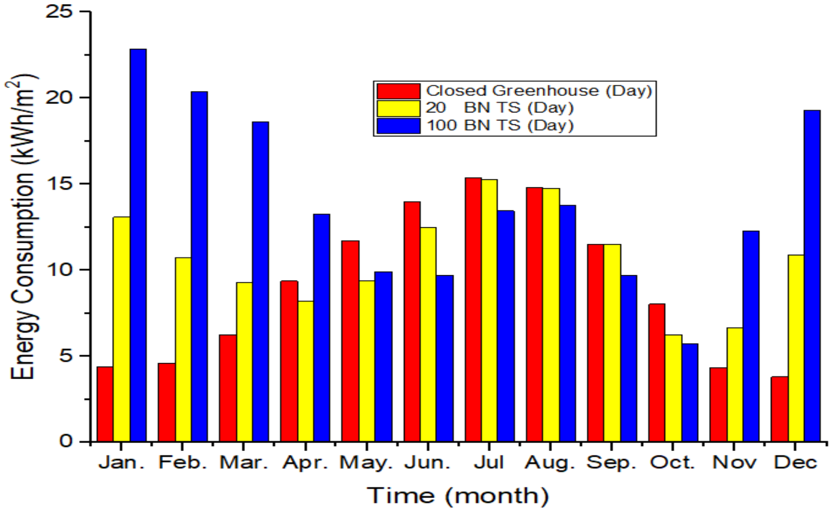

Fig.7. Monthly daytime energy consumption: Closed greenhouse, 100% BN TS openings, and 20 BN TS (effective).

Fig. 8 shows that for night time periods, the closed greenhouse is also optimal for January, February, March, November, and December, with low consumption. For the other months, a 100% BN TS opening is generally preferable, providing more balanced night time consumption values.

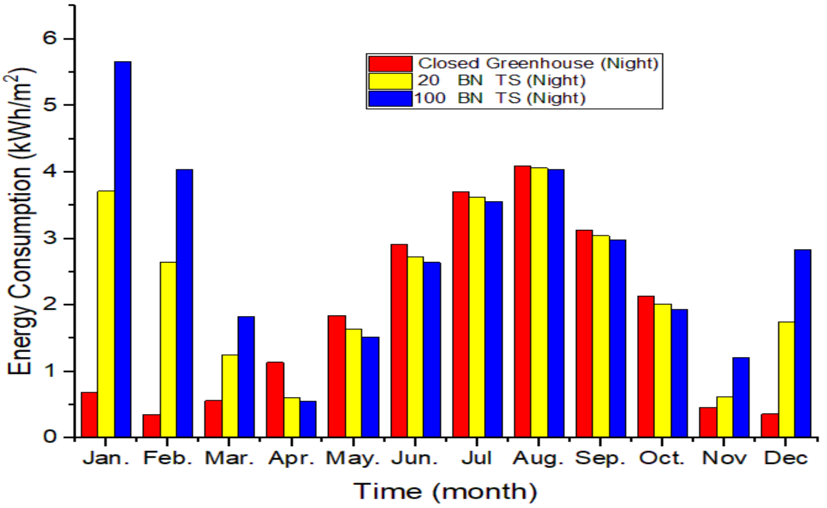

Fig.8. Monthly Night time energy consumption: Closed greenhouse, 100% BN TS openings, and 20 BN TS (effective).

When comparing the annual optimal configuration at 20% BN TS with the proposed schedule, there is a significant reduction in energy consumption. According to Fig.9, the schedule decreases daytime consumption by 27.3 %, from 128.615 kWh/m^2 to 93.477 kWh/m^2. For night time consumption, the reduction is 29%, dropping from 27.68 kWh/m^2 to 19.656 kWh/m^2 combining both daytime and night time periods, the overall reduction in total energy consumption with the schedule is 27.6%

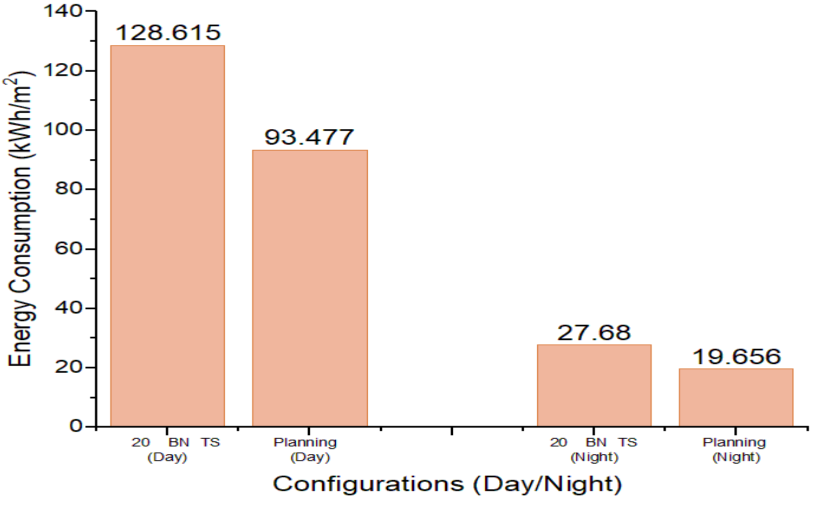

Fig.9. Annual day and night energy consumption: comparison of effective configuration (20 BN TS) with planning (Day/Night).

4 Conclusion

This study on the energy optimization of polyethylene tunnel greenhouses in Mediterranean climates reveals several key conclusions:

Greenhouse Orientation: The east-west (90°) orientation is the most effective for reducing cooling needs in the summer, while slightly increasing heating requirements in the winter. This orientation outperforms the 0° and 45° orientations in terms of overall energy consumption.

Opening Configuration: The 20% opening configuration (BN TS) is optimal for annual energy management, but the monthly planning proves to be even more effective.

Monthly Planning and Energy Consumption Reduction: The monthly planning, which recommends keeping the greenhouse closed in winter, using 100% BN TS openings in summer, and 20% openings during transitional months, significantly reduces total energy consumption. Compared to the annual optimal configuration with 20% BN TS, the planning reduces daytime consumption by 27.3%, night time consumption by 29%, and overall annual energy consumption by 27.6%.

In summary, an adaptive management of opening configurations based on seasonal needs, combined with strategic orientation choices, is essential for maximizing greenhouse energy efficiency. The proposed monthly planning offers an optimized solution, leading to a substantial reduction in total energy consumption.

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References

1. M. Gheyrati, A. Akram, H. Ghasemi-Mobtaker, Optimum Orientation of the Multi-Span Greenhouse for Maximum Capture of Solar Energy in Central Region of Iran, JREE, **9**, No 3, 65-74, (2022).
2. P.-E. Bournet, and T. Boulard, Effect of ventilator configuration on the distributed climate of greenhouses: A review of experimental and CFD studies. Computers and Electronics in Agriculture, **74**, 195-217, (2010)
3. S. Benni, P. Tassinari, F. Bonora, A. Barbaresi, D. Torreggiani, Efficacy of greenhouse natural ventilation: Environmental monitoring and CFD simulations of a study case, Energy and Building, **125**, 276-286, (2016)
4. X. Lyu, Y. Xu, M. Wei, C. Wang, G. Zhang , S. Wang, Effects of vent opening, wind speed, and crop height on microenvironment in three-span arched greenhouse under natural ventilation, Computers and Electronics in Agriculture, **201**, 107326, (2022)
5. A. Senhaji, M. Mouqallid, H. Majdoubi, CFD Assisted Study of Multi-Chapels Greenhouse Vents Openings Effect on Inside Airflow Circulation and Microclimate Patterns, Open Journal of Fluid Dynamics, **9**, 119-139, (2019)
6. S. Lee, I. Lee, R. Kim, Evaluation of wind-driven natural ventilation of single-span greenhouses built on reclaimed coastal land, Biosystems Engineering, **171**, 120-142, (2018)
7. L. Ouazzani Chahidi, A. Mechaqrane, Energy and economic analysis for the selection of optimal greenhouse design: a case study of the six Morocco's climatic zones, Energy and Buildings **289**, 113060, (2023)

8. B. Lebre, P.D. Silva, L.C. Pires, P.D. Gaspar, Computational Modeling of the Thermal Behavior of a Greenhouse. Appl. Sci. **11,** 11816 , (2021)
9. FAO. Food and Agriculture Organization of United Nations. Accessed: 2024. [Online]. Available: http://www.fao.org/land-water/ databases-and-software/crop information/tomato/en/
10. C. Stanciu, D. Stanciu, A. Dobrovicescu, Effect of greenhouse orientation with respect to E-W axis on its required heating and cooling loads, Energy Procedia, **85**, 498–504, (2016)
11. N. Choab, A. Allouhi, A. E. Maakoul, T. Kousksou, S. Saadeddine, A. Jamil, Effect of Greenhouse Design Parameters on the Heating and Cooling Requirement of Greenhouses in Moroccan Climatic Conditions, IEEE Access, **9**, 2986–3003, (2021)