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Article

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Numerical modeling and simulation of pitched and curved-roof solar greenhouses provided with internal heating systems for different ambient conditions

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Abstract

During the past few years, the plant nursery sector has drastically minimized its carbon footprint by using geothermal systems for heating rather than fossil fuel. This study aims to define the temperature range inside a greenhouse by means of a multiparametric analysis, with regard to several inner and external conditions imposed. In detail, it has been used the Finite Element Method (FEM), contained in the modules for the thermal analysis of the COMSOL Multiphysics (CM) software. The greenhouse structures considered are the most common in the north of Italy and Europe. Through the development of a stationary study, it has been possible to choose the suitable design solution for the heating standard required for both the floriculture and the horticulture. A 2D study of the transitory has been implemented with the intent to consider as influential factors the irradiation and the daily temperature throughout the year. The temperature trend over horizontal direction is investigated to detect any non-uniformity on the temperature distribution to which floriculture and horticulture plants are exposed. This study aims to be a starting point for the development of a system to be exploited during the design phase of these kind of greenhouses, to enhance the functioning relatively to inner and external conditions fluctuations, maximizing the thermal performance.

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Keywords: Heat transfer; COMSOL multiphysics; Solar greenhouses; Temperature distribution; Numerical simulation

1. Introduction

Greenhouse cultivation is the most common way to recreate the microclimate conducive to plant growth throughout the year [1]. The greenhouses are confined environments in which, both as a result of direct solar radiation and air conditioning systems, the ideal thermo-hygrometric conditions for different crops growing-up are maintained [2]. The most commonly used materials for wall covering are glassy or rigid plastic films [3], such as polycarbonate or polymethylmethacrylate. The latter are used especially in horticulture and for ornamental plants with less restrictive thermal needs. For crops that do not need regular temperature control, their survival is guaranteed

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in a much wider thermal range. The peculiar characteristics that distinguish a greenhouse from other systems of simple protection are given by the using of air conditioning and heating systems, more than human and machines accessibility [4–6]. These factors require certain height and width, which are volume per unit of covered surface; in fact, we can talk about greenhouses starting from unit volumes of $1.8 \div 2 \text{ m}^3$ per square meter of covered area [7]. The territorial distribution of the various types of greenhouses is strictly influenced by climatic factors. In the regions of Northern and Central Europe, where winters are cold and summers are characterized by low solar radiation, there are almost exclusively glass greenhouses [8,9]. In recent years many companies have started to use polymethylmethacrylate, that is plexiglass [10]. In the regions of the Mediterranean basin, characterized by mild winters and hot summers with high solar radiation, the most widespread type of greenhouse is characterized by a curved roof, often tunneled [8–11]. The greenhouse influences the microclimate parameters and consequently the growth and physiology of the plants placed inside it. The main influences are due to temperature, solar radiation, air humidity, wind conditions and CO_2 concentration in the air. The air temperature in protected plant systems is related to thermal fluxes due to radiation, convection, conduction and air exchange, which take place by the external environment through the walls of the greenhouse and by the ground. Depending on the materials used, the dispersions could be reduced [12]. The optimal temperature for the type of plant chosen, in this case flower, varies between $17 \text{ }^\circ\text{C}$ and $27 \text{ }^\circ\text{C}$ [7]; for extended periods exceeding temperatures $27 \text{ }^\circ\text{C}$ [6], artificial cooling is necessary to maintain a suitable microclimate for the vegetable correct growth. Although other parameters as those aforementioned have to be considered, the study is focused mainly on the thermal exchange between the air inside the greenhouse and the environment [6], once fixed some heating system configurations. The heating considered for the study takes place by means of underground or vertical pipes located close to the plants. The fluid flowing through the pipelines should be heated by exploitation of geothermal energy sources, to reduce emission of pollutants due to fossil-based fuels usage [13–17]. The implemented geometry models are those of the pitched and curved roof, referring to Northern and Central Europe conditions [8].

2. Materials and methods

The numerical simulation scenario has been implemented in COMSOL Multiphysics (CM) [18], a finite element method solver which allows the user to set multi-physical conditions, taking into account different equation phenomena, simultaneously [19,20]. For the simulation analysis a 2D green house model was considered, focusing on a vertical section considerably distant from the anterior façade located at $x = 0$ and from the posterior one in $x = L$. The section is then positioned in the middle-located plane, that is at $x = L/2$. These assumptions were also justified by the high level of symmetry that should be noticed for the heat transfer phenomena, once both external and internal conditions are imposed, uniformly. Anyway, a 3D approach has been also implemented to confirm the previous hypothesis. A remarkable symmetry on heat transfer phenomena was noticed, so a 2D geometry model has been chosen to reduce computational resources requirements. A parametric sweep has been also implemented for every scenario, highlighting the influence on internal temperature once varying boundary conditions such as the incoming radiation flux, due to the solar radiation, and the ambient temperature for each of the considered months are varied. The thermal features and properties of the materials have been manually initialized by the user in CM interface. In this case, it was possible to select each domain's material by choosing it from the built-in material library of CM: PMMA, also known as plexiglass, or PVC are two of the most used materials as an alternative to the glass for greenhouse walls and roofs structures; high density polyethylene (PE 100) for heating systems pipelines, where an out-of-plane high temperature fluid flow is forced. The reason why PMMA is considered as an alternative to glass is that the last one is both much heavy and fragile than the plexiglass [21]. The solving procedure applied to each one of the scenarios allows to compute the temperature at different distances from the ground level inside the greenhouse confined environment (constituted by an air volume) along the horizontal direction. The reason why the focus was placed on this kind of temperature distribution is that every horizontal gradient should provoke a different growth condition for every family of plants within the greenhouse in the same period. Indeed, non-uniform temperature could negatively affect the plants growth. In Table 1, are reported the optimal development temperatures of two different plant species [7].

Table 1. Plant survival temperatures for optimal growth.

Species		Temperature [°C]
Horticultural	Tomato	21 – 26
	Lettuce	17 – 22
	Melon	22 – 28
Floricole	Rose	20 – 24
	Chrysanthemum	17 – 21
	Gerbera	21 – 27

Finally, [Table 2](#) shows the physical and chemical characteristics of the materials used.

Table 2. Coefficient values.

Parameter	Soil	Air	PMMA	PVC	Polyethylene	Description
k [W/(m K)]	2,5	0,026	0,19	0,1	0,38	Thermal conductivity
ρ [kg/m ³]	2650	1,225	1190	1760	959	Density
C_p [J/(kg K)]	870	1420	1420	900	1850	Heat capacity at constant pressure

2.1. Definition of external environment and boundary conditions

For parametric sweeps, average outdoor temperatures [22] and radiation [12] values were considered for each month of the year, as reported in [Table 3](#).

The results of the summer months (May, June, July, August) will not be reported as thermometric conditions inside the greenhouse are met at this time of year even with heating system disabled. For the underground pipelines heating system, the number is decreased from 20 to 11 tubes while for the vertical pipeline configuration is varies from 4 for each series to 3 (considering 7 series). The choice lies in the fact that, after several hypotheses, with this decrease in the number of vertical tubes it is possible to have an appropriate thermal exchange with plants, not allowed with a lower or higher number of pipes: indeed, it was not possible to ensure an approximately uniform temperature on every x -direction and y -direction coordinate.

Table 3. Values of ambient temperature and radiation during the year.

Months	$T_{amb,ext}$ [°C]	Irr [W/m ²]
January	10	290
February	12	420
March	15	530
April	18	705
May	22	810
June	26	770
July	30	795
August	30	800
September	27	650
October	21	500
November	16	320
December	11	250

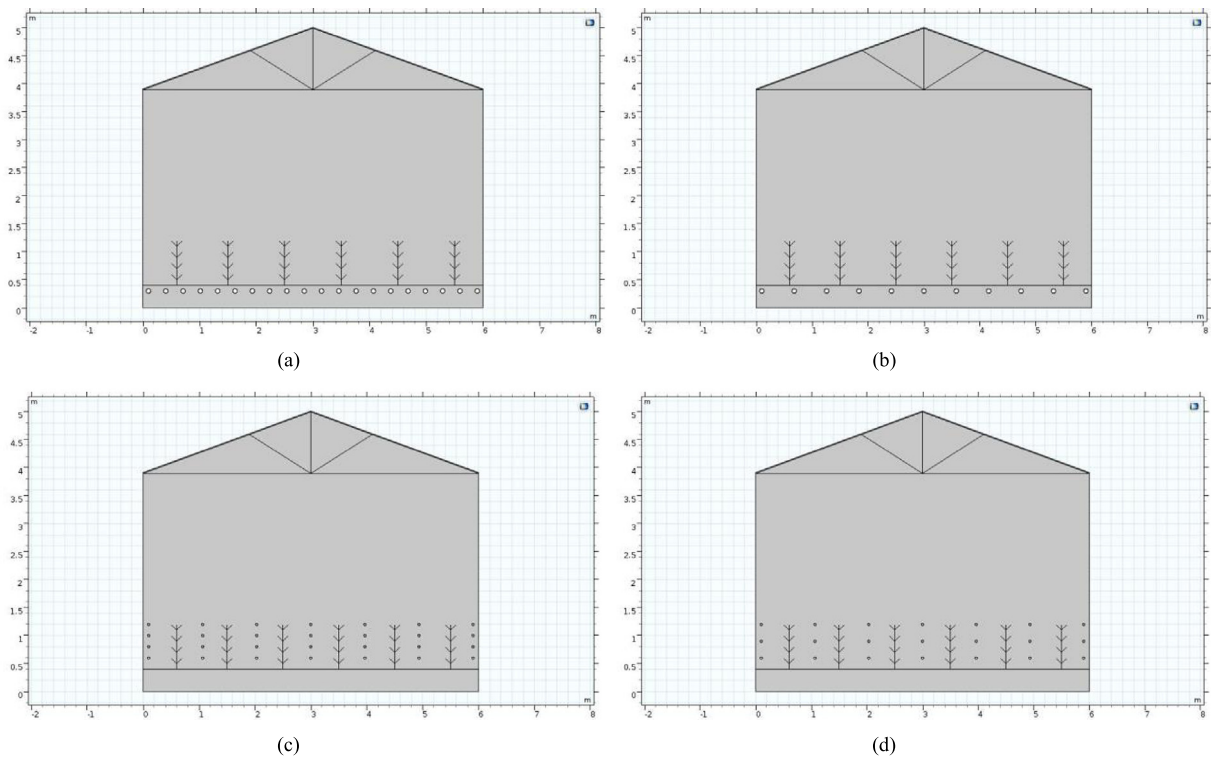
2.2. Definition of pitched roof greenhouse numerical scenario

The implementation of the pitched roof greenhouse scenario has required the definition of both geometric [12] and environmental parameters, as reported by [Table 4](#). The values shown are the typical ones of the most common configurations of solar greenhouse in the reference territory (Northern and Central Europe) [8].

Four simulations were carried out by modifying the number of vertical tubes of the internal heating system, while the in-ground pipelines number was also varied, as shown by [Fig. 1](#).

Table 4. Implemented parameters for the pitched roof greenhouse.

Parameter	Value	Description
T_{ri}	30 °C	Underground pipe temperature
T_{rv}	25 °C	Vertical tube temperature
R_{ri}	40 mm	Underground pipe beam
R_{rv}	20 mm	Vertical tube radius
H_{pl}	3,5 m	Sidewall Height
L_s	6 m	Length of the greenhouse
H_{gnd}	0,4 m	Ground height
L_{gnd}	6 m	Ground length
dy_{ri}	0,1 m	Distance from the surface of the underground pipes
dy_{rv}	20 cm	Distance between vertical tubes

**Fig. 1.** Implemented geometry configurations for the pitched roof solar greenhouse: (a) n. 20 underground pipelines available; (b) n. 11 underground pipelines available; (c) n. 4 × 7 vertical pipelines available; (d) n. 3 × 7 vertical pipelines available.

Each scenario has been solved to obtain the temperature horizontal distribution at fixed distances (10 cm, 30 cm, 50 cm and 70 cm along vertical direction, respectively) from the soil level in the inner structure. This kind of investigation has been applied to highlight the constancy and uniformity of the temperature which the plants are exposed to. Evidently, a major thermal overhang could negatively affect the growth of the plant.

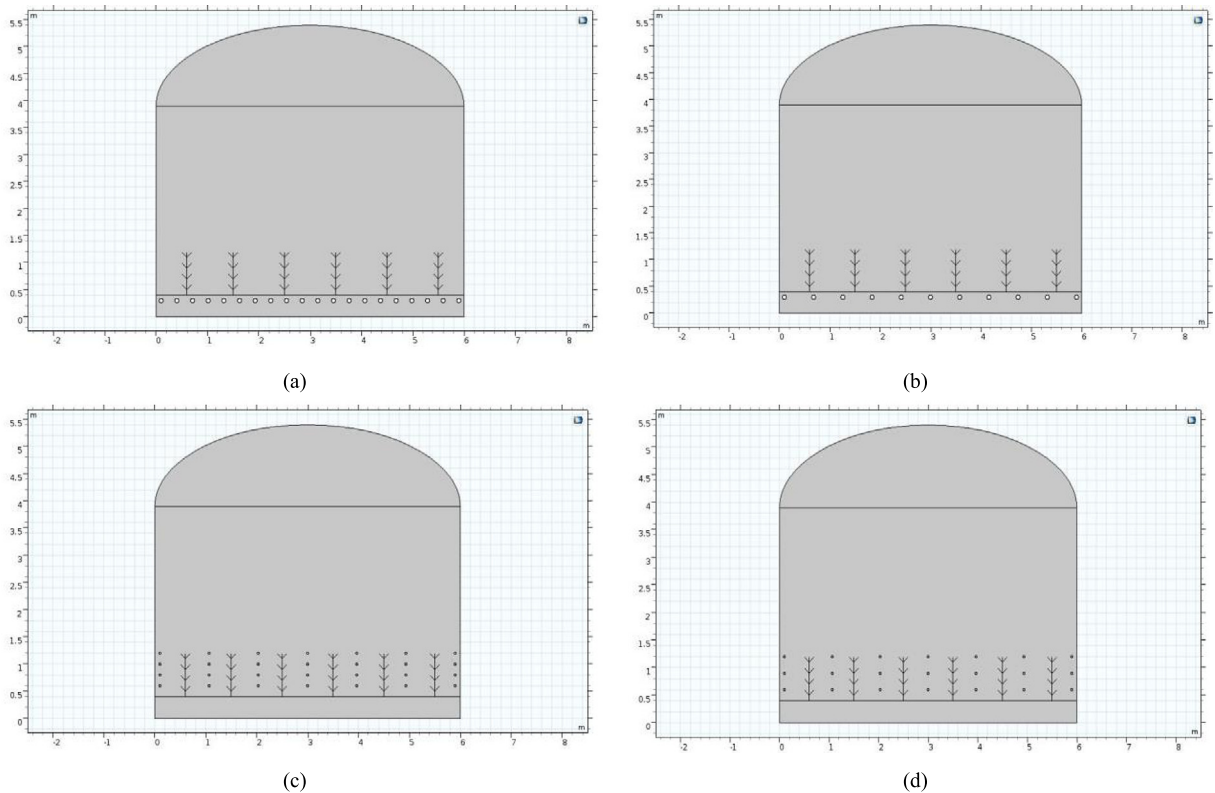
2.3. Definition of curved roof greenhouse numerical scenario

The parameters implemented for the curved roof solar greenhouse scenario are shown in Table 5. Additional parameters such as semi-axis and sector corner angle are related to the construction of the curved roof [3].

An analogue study to the previous conducted for the pitched roof greenhouse has been implemented for the curved roof structure, investigating the horizontal distribution of temperature for every one of the heating system configurations reported by Fig. 2.

Table 5. Implemented parameters for the curved roof greenhouse.

Parameter	Value	Description
T_{ii}	30 °C	Underground pipe temperature
T_{iv}	25 °C	Vertical tube temperature
R_{ii}	40 mm	Underground pipe beam
R_{iv}	20 mm	Vertical tube radius
H_{pl}	3,5 m	Side wall height
L_s	6 m	Length of the greenhouse
H_{gnd}	0,4 m	Ground height
L_{gnd}	6 m	Ground length
dy_{ti}	0,1 m	Distance from the surface of the underground pipes
dy_{tv}	20 cm	Distance between vertical tubes
a	3 m	Semi-axis a
b	1,5 m	Semi-axis b
α	180°	Sector Corner

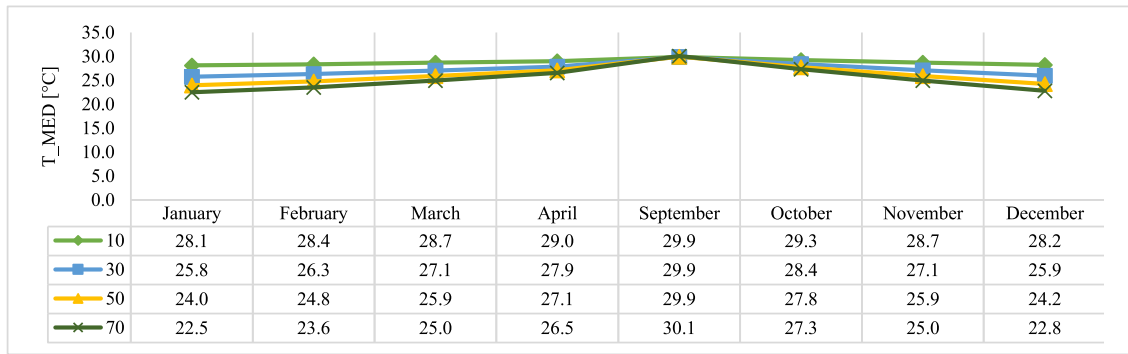
**Fig. 2.** Implemented geometry configurations for the curved roof solar greenhouse: (a) n. 20 underground pipelines available; (b) n. 11 underground pipelines available; (c) n. 4 × 7 vertical pipelines available; (d) n. 3 × 7 vertical pipelines available.

3. Results and discussion

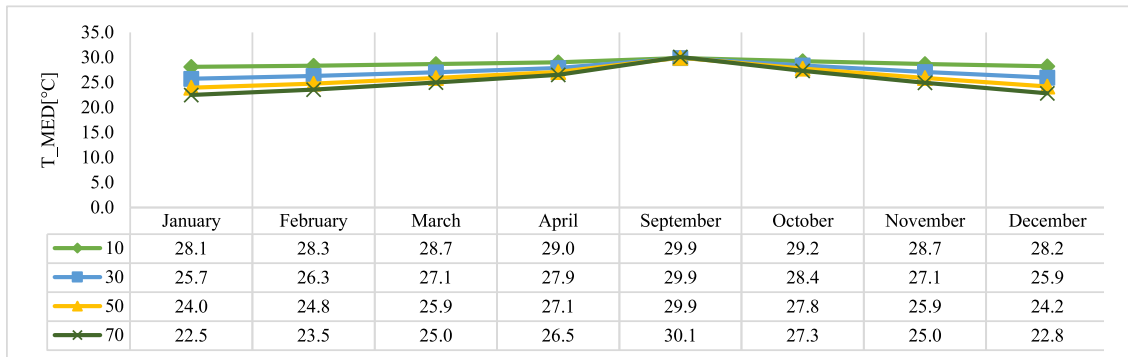
3.1. Results from the pitched roof greenhouse numerical scenario

Results from the pitched roof structure simulation scenario, which computes the horizontal distribution of temperature within the middle cross section plane, are shown in Fig. 3.

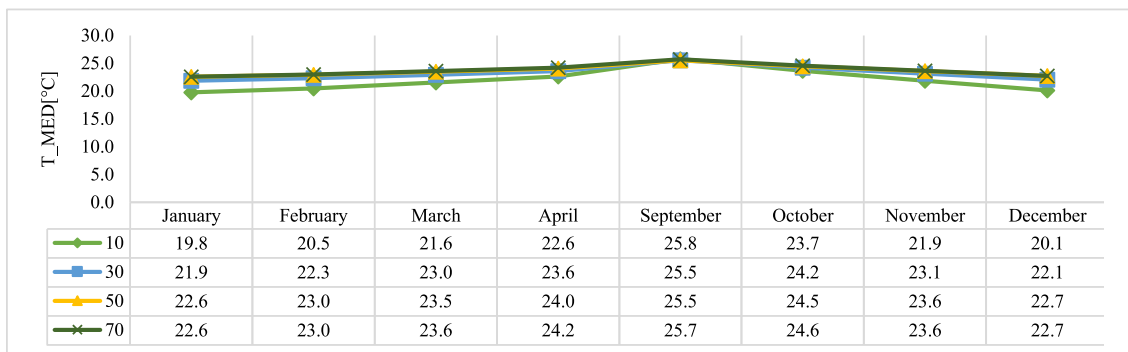
From the graphs concerning the underground pipes, it should be noticed that the temperature trend along the height of the plant is not constant and the greatest difference is found for January and December, as it starts from 28 °C at the base and reaches 22 °C at the top of the analyzed domain. This shows that the two configurations with



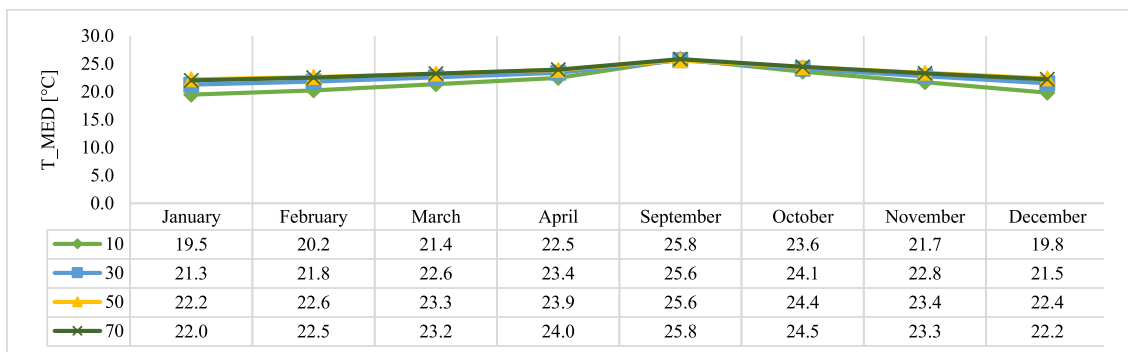
(a)



(b)

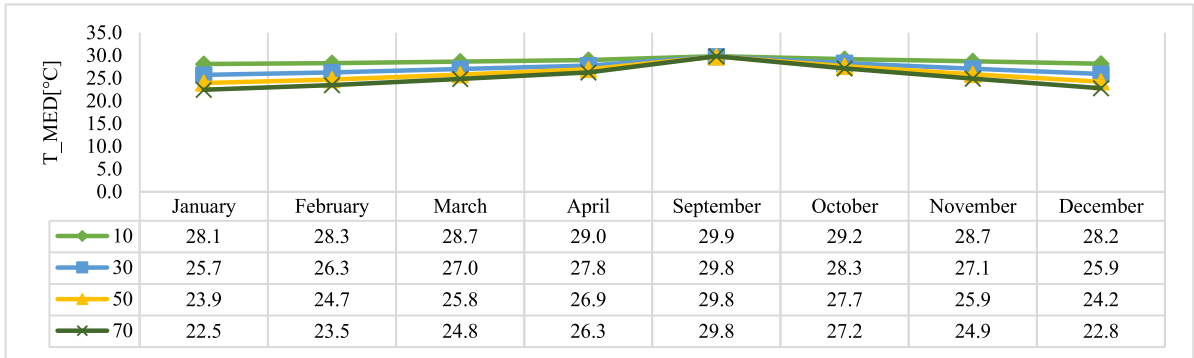


(c)

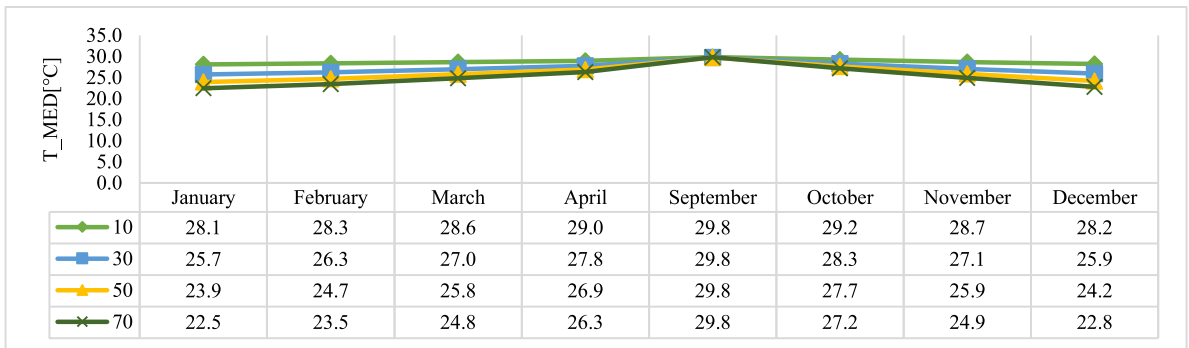


(d)

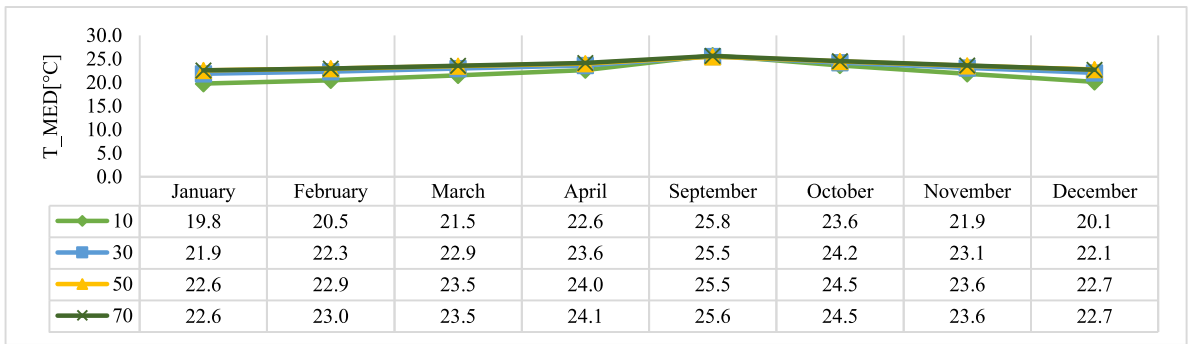
Fig. 3. Temperature distribution along the horizontal direction of the analyzed cross section plane of the pitched roof greenhouse, at different height from the ground level: (a) n. 20 in-ground pipes configuration; (b) n. 11 in-ground pipes configuration; (c) n. 4 × 7 vertical pipelines configuration; (d) n. 3 × 7 vertical pipelines configuration.



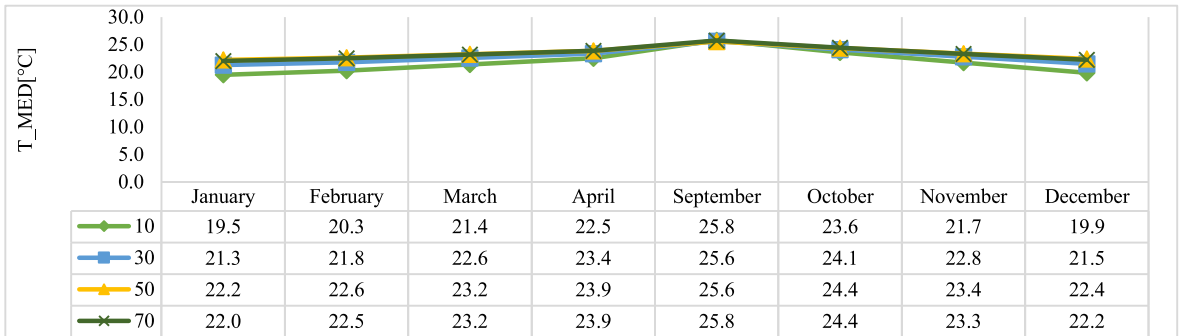
(a)



(b)



(c)



(d)

Fig. 4. Temperature distribution along the horizontal direction of the analyzed cross section plane of the curved roof greenhouse, at different height from the ground level: (a) n. 20 in-ground pipes configuration; (b) n. 11 in-ground pipes configuration; (c) n. 4 × 7 vertical pipelines configuration; (d) n. 3 × 7 vertical pipelines configuration.

the underground pipes do not allow the proper development of the plant. After analyzing both configurations it is clear that the one with the vertical tubes, unlike the one with the underground pipes, manages to keep the average temperature along the height of the plant almost constant and below the limits imposed (for all year months where the heating is enabled). It is therefore much more efficient to configure with vertical tubes for two reasons, the first because the temperature of the underground pipes must necessarily be higher than the vertical ones, since in addition to the thermal exchange for convection is also present the thermal exchange for conduction, the second reason is that the vertical pipes allow to have a temperature difference between the base and apex of the plant of up to 3 °C and the underground pipes instead reach up to 6 °C, this temperature difference between apex and base is too high for plant development [6].

3.2. Results from the curved roof greenhouse numerical scenario

Results from the pitched roof structure simulation scenario, which computes the horizontal distribution of temperature within the middle cross section plane, are shown in Fig. 4. Even in the case of a greenhouse with a curved roof provided with underground pipes, temperatures exceed the limits allowed for the survival of plants. The same is true for temperature differences between apex and base that are too high.

Temperatures obtained with vertical tube configurations are within the expected ranges for the development of the plant, and even if the study was carried out for the flowering crops, it also gave excellent results for the horticultural species.

4. Conclusions

The simulation campaign, which aimed to determine the temperature [23] range inside a greenhouse, has identified the best heating system solution for the proper development of flowering crops, once grounded and vertical pipelines for heating are implemented. From the scenarios, regarding the configuration with underground pipes, the position of the flowering crops will have to be modified to allow the survival of the same crops. From the analysis carried out, the setup that uses vertical pipes turns out to be the most effective. In fact, in the scenarios with underground pipes the values of the average temperature computed along the horizontal direction at different distances from the ground level (measured with the parametric sweep of radiation and ambient temperature to simulate every monthly condition) reach 30 °C and over, not allowing the proper conditions for the growth of the flowering crops. Therefore, the analysis of all the simulated scenarios demonstrates that vertical pipes are a suitable solution to allow the use of the heating system for most of the year, except during summer period, when the heating is turned off. In fact, the temperature range detected with this configuration allows the maximum development of the cultivation and makes it possible not to have to change the configuration of the heating system every month. Although in the other operating conditions temperature values detected are beyond the ideal threshold, there are other techniques that can be used to manage heat transfer within the analyzed configuration, such as cooling the greenhouse through special devices or using pallets in order to raise plants to a height that could guarantee a proper development. The configuration with vertical pipelines allows the most efficient use of thermal energy, since the transmission of heat takes place only by convection and not by conduction through the soil like for underground pipelines configuration. This study laid the groundwork for the development of a standalone greenhouse design application, which allows to carry out multi-parameter analyses, varying the secondary parameters that are not considered in this study thus obtaining more accurate results.

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