ANALYSIS OF CLIMATE CONTROL IN A CROP ROTATION GREENHOUSE

ANÁLISIS DEL CONTROL CLIMÁTICO EN UN INVERNADERO DE ROTACIÓN DE CULTIVOS

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DOI: https://dx.doi.org/10.6036

1. INTRODUCTION

In Extremadura, the importance of the agricultural sector and its associated industries is substantially higher than the national average. Most of the agricultural production in Extremadura is carried out by means of traditional cultivation, however, due to the high winter insolation and moderate temperatures, cultivation in greenhouses is feasible. Greenhouse cultivation is one of the most effective and widely used methods which provide a suitable environment for plants growth, integrating passive technologies and renewable energies, such as local biomass, like the olive pips, which will be used as fuel in the hot air generator for heating the greenhouse instead of using fossil fuels, such as traditional agricultural diesel, can significantly contribute to reducing the energy consumption [1].

The study carried out in this work try to contribute to energy savings through proper greenhouse management, identifying the cost of this, using greenhouses to cultivate in land that is not naturally suitable for crops (SUPPLEMENTARY MATERIAL). Thanks to greater efficiency, unit costs have been lowered, but at the same time market prices have fallen and the profit obtained per hectare cultivated is lower, making it necessary to manage a larger surface area to obtain the same income. Consequently Extremadura has lost 8,5 % of cultivated area between 2013 and 2018. The main contribution of this work is to provide a method for calculating the energy consumption of a greenhouse that maintains optimal conditions for crop development, based on the climatic characterization of the area and the crop in question, providing as a reference the consumption per unit area obtained from a practical case in Extremadura.

Greenhouses are an alternative to the line of research aimed at the use of these less productive or "marginal" lands for energy crops [2], because the hydroponic greenhouse cultivation system can be applied in most areas, (SUPPLEMENTARY MATERIAL) in this type of greenhouses, heating systems are used to be able to grow crops during the coldest months; the use of combustion generators leads to high CO2 emissions that are intended to be reduced through an evaluation of the energy needs and the use of olive pits as fuel. Another problem lies in the lack of control of the interior parameters, which negatively affects the crop, therefore, the use of equipment to record the interior climatic parameters is proposed, achieving productivity improvement by crop rotation (SUPPLEMENTARY MATERIAL), seeking to increase it and adapt it to demand, through climate control, as many producers use cover crops as a means to increase soil health and agricultural productivity, but the benefits of this practice vary depending on environmental and management conditions [3], achieving such controlled climates through the use of renewable energies [1], the modern agriculture systems are characterized by an intensive use of land and energy to maximize the productions so the greenhouses are one of the best ways to assist small farmers in obtaining competitive products [4].

2. MATERIALS AND METHODS

The intervening factors are the external climatic conditions, which depend on the location of the greenhouse and the interior requirements for cultivation, depending from the cultivated specie in the greenhouse because there is crop rotation throughout the year.

The tools to achieve the aforementioned objectives are the covering greenhouse and the auxiliary energy supply, as well as the choice of suitable crop. For the economic analysis, we chose to collect tabulated costs from specialized bibliography, selecting the costs corresponding to the equipment available in the greenhouse studied and the costs associated with the activities that take place there (labor, phytosanitary products, plant costs, etc.). The same process is carried out considering the equipment and activities carried out for a parral type greenhouse and traditional cultivation for comparison. Regarding income from product sales, an average harvest yield per unit area is taken according to the type of greenhouse and these yields are compared considering the same average price of the product, which is confronted with the investment cost per unit area and annual operating cost of each type of greenhouse.

A technical and economic study on the achievement of these objectives is prepared, as well as a practical case study in Extremadura (SUPLEMENTARY MATERIAL).

So the first step consists of identifying the theoretical outdoor climate throughout the year in Extremadura. For the temperature, the average temperature of the average temperature for last 15 years has been use for each month (SUPLEMENTARY MATERIAL).

The second step consist of identifying the indoor climate suitable for cultivation, maximum and minimum temperature and relative humidity, among the commons species to be grown in greenhouses in Spain. The indoor climate suitable conditions for cultivation are shown in Table 1.

Crop	Minimum lethal temperature (°C)	Minimum biological temperature (°C)	Optimum temperature (°C) Day	Optimum temperature (°C) Night	Maximum biological temperature (°C)	Minimum germination temperature (°C)	Optimum germination temperature (°C)	Relative humidity (%)	Optimum pH	Optimun luminosity (klx)
Tomato	-2 - 0	8 - 10	22 - 26	13 - 16	26 - 30	9 - 10	20 - 30	60 - 80	5,8 – 7,2	1-4
Cucumber	0	10 - 13	24 - 28	18 - 20	28 - 32	14 - 16	20 - 30	65 - 80	5,7 – 7,2	1-2
Melon	0	12 - 14	24 - 30	18 - 21	30 - 34	14 - 16	20 - 30	65 - 80	5,7 – 7,2	1-2
Bean	0	10 - 14	21 - 28	16 - 18	28 - 35	12 - 14	20 - 30	65 - 70	5,8 – 6,8	2-3
Pepper	-2 - 0	10 - 12	22 - 28	16 - 18	28 - 32	12 - 15	20 - 30	70 - 75	6,3 – 7,8	1-3
Aubergine	-2 - 0	9 - 10	22 - 26	15 - 18	30 - 32	12 - 15	20 - 30	50 - 65	5,4 – 6,0	2-5
Zucchini	0	4 - 8	20 - 25	10 - 12	28 - 35	14 - 16	20 - 25	65-80	5,6 – 6,8	1-2
Lilium	0	10 - 12	20 - 25	12 - 16	25 - 30	12	14	80 - 85	5,5 - 6,5	2-3

Table 1. Indoor required conditions for different crops.

The crop rotation sequence selected in this study consists of a zucchini (curcubitacea) crop from December through February, followed in March by a tomato (solanacea) crop through May, from June through August a melon (curcubitacea) crop and concluding with a bell pepper (solanacea) crop from September through November (SUPLEMENTARY MATERIAL).

The natural crop rotation for traditional cultivations methods consist in one crop of cucurbitaceae (like zucchini, cucumber or melon) , followed by a crop of brassicaceae (like cauliflower or broccoli), then a crop of solanaceae (like tomatoes, peppers, tobacco, potatoes or aubergine and ending the cicle with a crop of fabaceae crop (legumes) [5] - [7], this sequential cropping has a usual duration of two years, if the climate conditions are favorable and growth accelerates can be added to the sequence winter cereal crop [6]. Mostly of this crops in traditional cultivations systems start in spring, with a solanaceaea crop and end at summer, usually in winter there is a crop of brassicaceae crop, the next spring start a crop of legumes and when this crop end, start a curcubitacea crop [6] and [7].

Based on the above, in this study, it has been decided to divide the crop year-rotation based on the climatic needs of the crops, according to their suitability to the external climate, in order to optimize the energy demand, also taking into account the investment in equipment, productivity suitability and cost-effectiveness by amount. The greenhouse design is a multi-factorial optimization problem (SUPPLEMENTARY MATERIAL).

About investment cost, a multi-tunnel structure has an investment cost of 18 €/m^2, triplast polyethylene cover cost 1,36 €/m^2, an indirect heating system (0,5 MW) cost 40.000 € and drip irrigation system cost 1,4 €/m^2 [8]. For a type 4 greenhouse dedicated to tomato cultivation, which despite having lower ridge height and under-gutter height dimensions than the greenhouse study in the practical case, has similar equipment regarding the covering materials, the lateral and zenith ventilation system with anti-insect nets and the substrate, also the presence of a heating system has total costs, without considering the opportunity cost of 105,230 €/ha compared to the cost of 71,750 €/ha for a type 1 greenhouse, metallic structure greenhouse, covered with mesh, with cultivation on the ground and without heating and compared to a cost of 15,400 €/ha for traditional cultivation (in the open air),estimated from the cost ratio of [8]-[10].

Crop development requires abundant irrigation, however the soil isn't suitable for crops, so a complex fertilizer N-P-K-Ca-Mg, 4-1,8-5-5-5-0,7, whose electrical conductance is 1,9 mS and pH 6,2 is applied together with the irrigation water, over a coconut fiber substrate with pH between 5,5, assuming an input of 0,29 l/m2·day, with a drained volume of 20 %, and foliar treatment using complex fertilizer N-P-K, 1-7-3.

To estimate the energy demand the energy balance in the greenhouse used is shown in Fig. 1.

eISSN :1989-1490 ISSN-L: 0012-7361 | DYNA Ingeniería e Industria, March-April, vol. 98, no. 2, p. xxx. DOI: https://doi.org/10.6036/10180

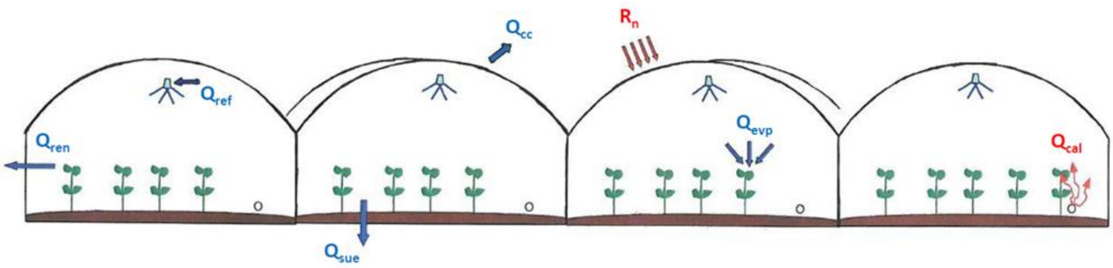

Fig. 1. Energy balance in a greenhouse (SUPPLEMENTARY MATERIAL).

The theoretical results from energy demand will be contrasted by means of experiments, in which the inside temperature of the greenhouse will be recorded over different days and, according to the outside temperature recorded on the same days, the demand will be estimated. Also, the measurement of indoor climatic conditions serves to identify those values that favour plant development and to detect possible anomalies in the roof, based on readings such as an adverse thermal gradient, inadequate luminosity or high humidity fluctuations, among others.

The possible limitation of this methodology lies in the climate change with more extreme temperature values recorded that may limit the suitability of the climatic conditions taken as reference, Fig. 2, in this case it would be necessary to modify the climatic values of the exterior, as well as to modify the sequence of crops in search of a better suitability.

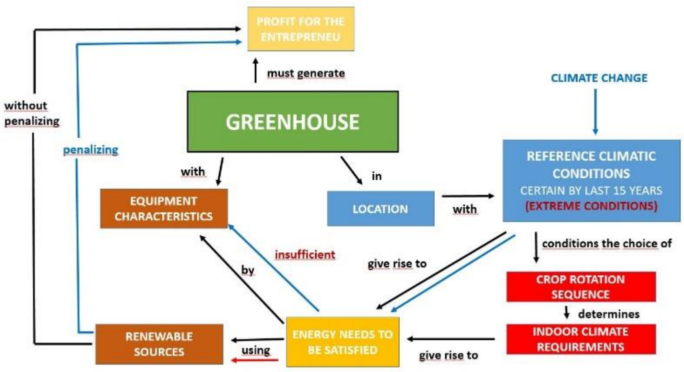

Fig. 2. Operation flowchart with the referred constraint.

The explanation of Fig. 2 is as follows: we start from a greenhouse, with equipment and characteristics in a location, which has reference climatic conditions that together with the price of the products determine the sequence of cultivation and therefore the indoor climatic requirements, the difference between the indoor climatic conditions and the location reference climatic conditions determines the energy needs of the greenhouse, which when covered by renewable sources (solar thermal and ventilation mainly) do not involve a cost that threatens the profit for the entrepreneur.

Climate change would make these location reference climatic conditions more adverse, which would increase the energy needs of the greenhouse, and it could be the case that the ventilation system or the greenhouse roof could not provide or extract the energy demanded. This would lead the entrepreneur to have to invest in more equipment or increase the energy input, spending on fuel for heating or electricity for cooling, which puts his profit at risk.

3. RESULTS

The external climatic conditions in Extremadura, temperature, relative humidity and solar insolation for each month are shown in SUPLEMENTARY MATERIAL, also the natural season of crop [5] and [6], and the crop year-rotation based on the climatic needs (sequential cropping established as optimal for Extremadura).The established sequential cropping takes into account the ability to modify the length of the growing cycle and the vegetables demanded by the market, and crops with similar suitable conditions which avoids changes in the greenhouse equipment.

eISSN :1989-1490 ISSN-L: 0012-7361 | DYNA Ingeniería e Industria, March-April, vol. 98, no. 2, p. xxx. DOI: https://doi.org/10.6036/10180

The measurements obtained of indoor climate conditions are shown in Table 2.

Crop	Range of temperature (°C) Day	Range of temperature (°C) Night	Range of relative humidity (%)	pH	Range of luminosity (klx)
Tomato	28 - 48	21 - 29	45 - 79	6,2	2,0-2,5
Melon	18 - 31	11 - 25	61 - 85	6,1	1,2-1,8
Pepper	20 - 38	16 - 28	55 - 78	6,5	2,5-2,8
Zucchini	10 - 27	8 - 15	45-84	6,1	1,0-1,5

Table 2. Indoor conditions measurements.

The energy demand estimated (GJ/m²) for the sequential cropping and the percentage of this demand covered by each source is in Table 3.

Heating (GJ/m²) (%)	Solar radiation (GJ/m²) (%)	Ventilation (GJ/m²) (%)	Refrigeration (GJ/m²) (%)	Total (GJ/m²) (%)
0,21 2	5,51 62	2,87 33	0,26 3	8,85 100

Table 3. Estimated energy demand through the year with this sequential crop.

In Table 4 the energy consumption before and after analysing the greenhouse is shown.

Season	Heating (GJ) (%)	Refrigeration (GJ)
Before study (2018-2019)	720	690
Before study (2019-2020)	750	720
After stuty	529,2	655,2

Table 4. Estimated energy demand through the year with this sequential crop.

An example of the results of temperature variation is in SUPLEMENTARY MATERIAL.

The simulated economic crop yield increased considerably with increasing technology from 9,77 €/m²·year for the parral type to 18,47 €/m²·year for the multi-tunnel equipped with all climate modification techniques. The economic analysis of the different greenhouses estimate an average crop yield of 27,71 kg/m² and 23,65 €/m² for a whitewash greenhouse with air heating with total investments cost of 35,89 €/m², fixed cost of 5,26 €/ m²·year, variable cost of 9,31 €/m²·year [8].

As far as the production is concerned, it goes from 50 grams per plant and day to obtain 80-100 grams per plant and day due to the heating contribution.

4.- DISCUSSION

The theoretical outdoor climate throughout the year is representative of the average year in Extremadura [11] and [12], more detailed and accurate zoning than those previously existing (SUPLEMENTARY MATERIAL).

Comparing the values in tables 1 and 2 (SUPLEMENTARY MATERIAL) , for melon and pepper crops have been measured values that include a range greater than optimal [13] and [14], both for temperature and humidity, for the tomato crop [15], the temperature range is higher than optimal for both day and night, and the humidity range is lower, this is due to the influence of the summer climate in the months that this crop is grown, for the zucchini crop the temperature range measured is lower than the optimum, which is due to the influence of the winter climate with cold temperatures, however the humidity range is lower because the air from the heating system is very low in humidity [16].

eISSN :1989-1490 ISSN-L: 0012-7361 | DYNA Ingeniería e Industria, March-April, vol. 98, no. 2, p. xxx. DOI: https://doi.org/10.6036/10180

Thanks to the practical case, it is possible to notice other parameters that must be controlled, although they do not intervene directly in the energy balance: flow rate and frequency of irrigation (which influences the humidity, since it must be abundant), in turn requires an optimum pH for the substrate, is also necessary a high level of luminosity (Table 1 and 2), being necessary to resort to a pruning to avoid the shade of the own leaves of the plant of the crop, a more uniform distribution of temperature and no more suffering from oidium was achieved, improving very significantly [11] and [17].

The selected crop sequence is adapted to the outdoor climate, since, as can be seen from the evaluation of the energy demand, it is satisfied mainly by ventilation and solar radiation, with less heating and biomass.

About the energy demand throughout the year, an observe from theoretical results, is that in some moths: November, March, April, June and December it necessary to use ventilation during the daytime when the temperatures has to be lowed, while using heating at night when the temperature has to be raised, it agrees with the greenhouse study in"Improving automatic climate control with decision support techniques to minimize disease effects in greenhouse tomatoes" (SUPLEMENTARY MATERIAL).

Regarding the results of temperatures, the temperature rise significantly in the central hours of the day which is due to the higher insolation in those hours, being the solar radiation the cause of this temperature increase, according to what was expected. In comparison to other studies, the tendency is similar (SUPLEMENTARY MATERIAL).

The productivity adequacy is achieved through climate control, the selected crop sequence and the energy inputs of heating (olive pit) or cooling (ventilation), the climate control makes it possible to bring forward or delay the development phases of the crop (growth, pollination, flower formation and fruiting) so as to obtain fruit at the time of demand in market and the selected crop-sequence allows obtaining the most attractive product for the market at that time. While a great improvement in crop health, based on the appearance of the crop, (SUPLEMENTARY MATERIAL), leafiness and quality of the harvested fruit.

About equation crop yield (SUPLEMENTARY MATERIAL), there are alternatives for different types of greenhouses, the climate conditions and the possible improvements in crop yield choose the best election for each greenhouse. To diminish the risk to fluctuating price trajectories one should operate a low-tech greenhouse with low investments, a high tech greenhouse would cover better the weather risk, which should in turn allow for a higher price, a high tech greenhouse would be more beneficial at high prices (because production is maintained in times of low supply) but suffer more at low price levels with vegetables with more competitive prices from traditional cultivation [8].

From this study it can be deduced that adequate equipment of the greenhouse in terms of ventilation system leads to minimize the cooling energy input and the choice of crop must be made on the basis of the outdoor climate and the market price, so that the energy demand to be met by heating or cooling is as low as possible but the price of the product is sufficient to cover the costs, in the future, it would be interesting to control the temperature gradient inside the greenhouse used in the case study in order to avoid thermal stress for the plants.

CONCLUSIONS

Hydroponic greenhouse cultivation system can be applied in most areas, achieving productivity improvement by crop rotation and climate control through renewable energies.

Thanks to greenhouse cultivation with fertigation systems, it is possible to grow in unsuitable soils, improving productivity through crop rotation (SUPLEMENTARY MATERIAL). This production system allows higher income from the sale of the product, which offsets the high cost of a greenhouse of this type.

Analysing of energy demand makes possible to discriminate between the covering materials that will lead minimized energy consumption, also by selecting the crop that requires climatic conditions that have less disparity with the outside climate at the same price.

Energy demand is met by renewable sources: solar radiation, ventilation and heating by olive seeds, due to its abundance, its PCI and its low chlorine and sulphur content.

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eISSN :1989-1490 ISSN-L: 0012-7361 | DYNA Ingeniería e Industria, March-April, vol. 98, no. 2, p. xxx. DOI: https://doi.org/10.6036/10180

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ACKNOWLEDGEMENTS

Prof. Ruiz-Celma was funded by the Government of Extremadura and the European Regional Development Fund, through IB18008. Government of Extremadura and the European Regional Development Fund (FEDER), through the research group GR18137.