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ENERGY PERFORMANCE OF A GEOTHERMAL HEAT PUMP SYSTEM COUPLED TO A GREENHOUSE

Desempeño energético de un sistema de bomba de calor geotérmico acoplado a un invernadero

Desempenho Energético de um Sistema de Bomba de Calor Geotérmico Acoplado a um Estufa

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ABSTRACT

INTRODUCTION. The research focuses on designing and implementing a geothermal heat pump adapted to a 470 m^2 greenhouse in the Andean region. **OBJECTIVE**. The goal is to maintain a temperature of 15 °C at night and 30 °C during the day, replacing conventional energy sources such as LPG and contributing to the sustainability and efficiency of food production in challenging climatic conditions. **METHOD.** We estimated the energy potential of solar and geothermal sources through precise measurements, which were compared to theoretical models. Subsequently, we calculated the appropriate size for the geothermal heat pump using the vapor compression cycle from the greenhouse's energy balance. Finally, we considered critical variables such as temperature and relative humidity to assess the energy efficiency of a geothermal heat pump. Prediction intervals were determined for the relevant variables to investigate values outside statistical control, and the construction of a heat map revealed heat transfer and thermal behavior in the greenhouse. **RESULTS.** The results demonstrated the impact of climatic conditions on the performance of the geothermal heat pump. Out of the 3169 analyzed data points, 7% fell outside the prediction intervals. **CONCLUSIONS**. This analysis underscores the critical influence of the environment on the energy efficiency of greenhouse cooling systems in the Andean region, suggesting the need for more efficient energy management strategies based on environmental conditions.

Keywords: Energy performance, Greenhouse, Geothermal heat pump, Environmental conditions, Energy efficiency.

RESUMEN

INTRODUCCIÓN. La investigación se centra en el diseño e implementación de una bomba de calor geotérmica adaptada a un invernadero de 470 m^2 en la región andina. **OBJETIVO**. El objetivo es mantener una temperatura de 15 °C por la noche y 30 °C durante el día, sustituyendo fuentes de energía convencionales como el GLP y contribuyendo a la sostenibilidad y eficiencia de la producción de alimentos en condiciones climáticas difíciles. **MÉTODO**. Estimamos el potencial energético de las fuentes solares y geotérmicas mediante mediciones precisas, las cuales fueron comparadas con modelos teóricos. Posteriormente, calculamos el tamaño apropiado para la bomba de calor geotérmica utilizando el ciclo de compresión de vapor del balance energético del invernadero. Finalmente, consideramos variables críticas como la temperatura y la humedad relativa para evaluar la eficiencia energética de una bomba de calor geotérmica. Se determinaron intervalos de predicción para las variables relevantes para investigar qué valores estaban fuera de control estadístico, y la construcción del mapa de calor reveló la transferencia de calor y el comportamiento térmico en el invernadero. **RESULTADOS**. Los resultados mostraron el efecto de las condiciones climáticas en el rendimiento de la bomba de calor geotérmica. De los 3169 puntos de datos analizados, el 7% queda fuera de los rangos de predicción. **CONCLUSIONES**. Este análisis destaca la influencia crítica del medio ambiente en la eficiencia energética de los sistemas de enfriamiento de invernaderos en la región andina, lo que sugiere la necesidad de estrategias de gestión energética más eficientes basadas en las condiciones ambientales.

Palabras claves: Desempeño energético, Invernadero, Bomba de calor geotérmica, Condiciones ambientales, Eficiencia energética.

RESUMO

INTRODUÇÃO. A pesquisa concentra-se no design e implementação de uma bomba de calor geotérmica adaptada a uma estufa de 470 m^2 na região dos Andes. **OBJETIVO**. O objetivo é manter uma temperatura de 15 °C à noite e 30 °C durante o dia, substituindo fontes de energia convencionais, como o GLP, e contribuindo para a sustentabilidade e eficiência da produção de alimentos em condições climáticas desafiadoras. **MÉTODO.** Estimamos o potencial energético das fontes solares e geotérmicas por meio de medições precisas, as quais foram comparadas com modelos teóricos. Posteriormente, calculamos o tamanho apropriado para a bomba de calor geotérmica utilizando o ciclo de compressão de vapor do balanço energético da estufa. Finalmente, consideramos variáveis críticas como temperatura e umidade relativa para avaliar a eficiência energética de uma bomba de calor geotérmica. Foram determinados intervalos de previsão para as variáveis relevantes, a fim de investigar quais valores estavam fora do controle estatístico, e a construção do mapa térmico revelou a transferência de calor e o comportamento térmico na estufa. **RESULTADOS**. Os resultados mostraram o efeito das condições climáticas no desempenho da bomba de calor geotérmica. Dos 3169 pontos de dados analisados, 7% ficaram fora dos intervalos de previsão. **CONCLUSÕES**. Essa análise destaca a influência crítica do meio ambiente na eficiência energética dos sistemas de resfriamento de estufas na região dos Andes, sugerindo a necessidade de estratégias mais eficientes de gestão de energia com base nas condições ambientais.

Palavras-chave: Desempenho energético, Estufa, Bomba de calor geotérmica, Condições ambientais, Eficiência energética.

INTRODUCTION

Global vegetable production surpassed 1,148 million tons in 2021, with approximately 500,000 hectares dedicated to greenhouse cultivation [1]. This increase in production was influenced by the restrictions imposed due to the COVID-19 pandemic, as people displayed a heightened interest in consuming vegetables for their health benefitst [2].

Using geothermal heat pumps in the greenhouse enhances heating or cooling, accelerating plant growth [3] because extreme temperature and moisture conditions attenuate. Also, geothermal improves energy usage; for instance, Chiriboga et al. [1] conducted a study based on temperature profiles (the system depends not only on input or output energy but also on transfer capacity driven by temperature differentials), showing that the gradual increase or decrease of temperature to reach goal conditions, can significantly reduce the energy consumption.

A challenge that faces greenhouses is the meteorological complexity that shows the Ecuadorian Andean with high solar radiation during the day and freezing temperatures at night. Therefore, trustful observations are essential for evaluating the relevant environmental variables through dry and rainy seasons [4]. This study evaluates the performance of a geothermal conditioning system by means of simultaneous measures of temperature and relative humidity inside the functioning greenhouse.

The greenhouse is the first system of its kind that operates in Ecuador. It is in Tumbaco-La Morita, Pichincha province, 25 km from Quito (coordinates: 0°13'41.8"S 78°22'18.5"W, Altitude: 2,357 meters above sea level), covering an area of 470 m^2. The annual average temperature is 14.3 ± 5 °C, and precipitation amounts to 2,877 ± 315 mm. **Figure *1*** indicates the greenhouse's location. It belongs to the Central University of Ecuador and was designed and built for research applications. The system functions as a conventional heat pump with the particularity of an underground circuit with automatic control and the system operates like a conventional heat pump (evaporator, condenser, compressor, and expansion) with the particularity of an underground circuit with automatic control and a unique system with a reversing valve that allows switching the system between heating and cooling modes.

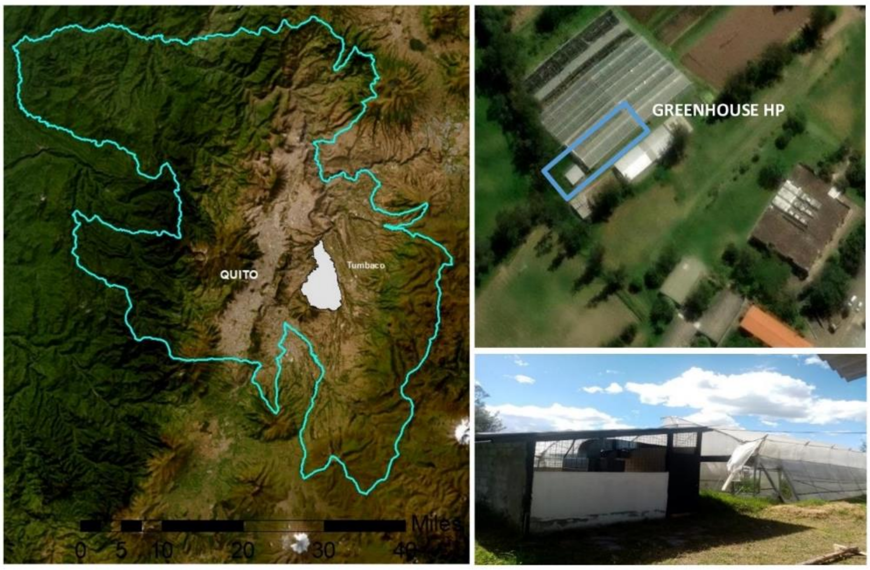

Figure 1. Project georeferencing imagery**.**

Specific operational conditions were established to outline the thermodynamic cycle, incorporating a 6 °C superheat in the evaporator, a compressor efficiency of 90%, and a 5 °C subcooling in the condenser [5]. The Maximum Coefficient of Performance (COP) was determined in relation to the minimum work required for heating or cooling operations, opting for refrigerant R290. The choice of high-density polyethylene piping was based on guidelines established by [6] . The selection of central units was supported by specific information about the fluid and thermodynamic properties.

The project splits into four phases:

The operation of the system leverages the thermal stability of the soil to provide a constant heat supply in winter [7]. Through a reversing valve, it can offer cooling during the summer by transferring excess heat from the greenhouse back into the soil [1]

To verify the performance of the equipment using independent temperature and relative humidity indicators, the grid method is applied [8]. This method allows the examination of variable behavior at a specific distance and height. Measurements were taken in May and June, considering critical heating and cooling intervals.

For model evaluation, regression analysis will enable the observation of the relationship between temperature and relative humidity variables over time. The use of prediction intervals will inform about the estimated effects in the study. Preventive actions applied to process variability (Ishikawa diagram) will examine the interrelation between uncontrolled parameters (cause) and the resulting effect [9] The heat map will analyze the temperature behavior in the greenhouse [10]

The document presents the evaluation of the feasibility of implementing low-enthalpy geothermal energy in agricultural greenhouses. It provides a valuation of the results regarding the effectiveness and sustainability of using geothermal energy compared to conventional sources such as electric energy and fossil fuels.

METHOD

Units of Measurement / Samples

The diagram illustrates the methodology employed in the case study, which comprises two key processes: prediction intervals and heat map. Each box in the diagram represents these processes and includes their inputs and outputs. Specific methods and materials are elaborated upon in the respective sections of the study, as depicted in ***Figure 2***

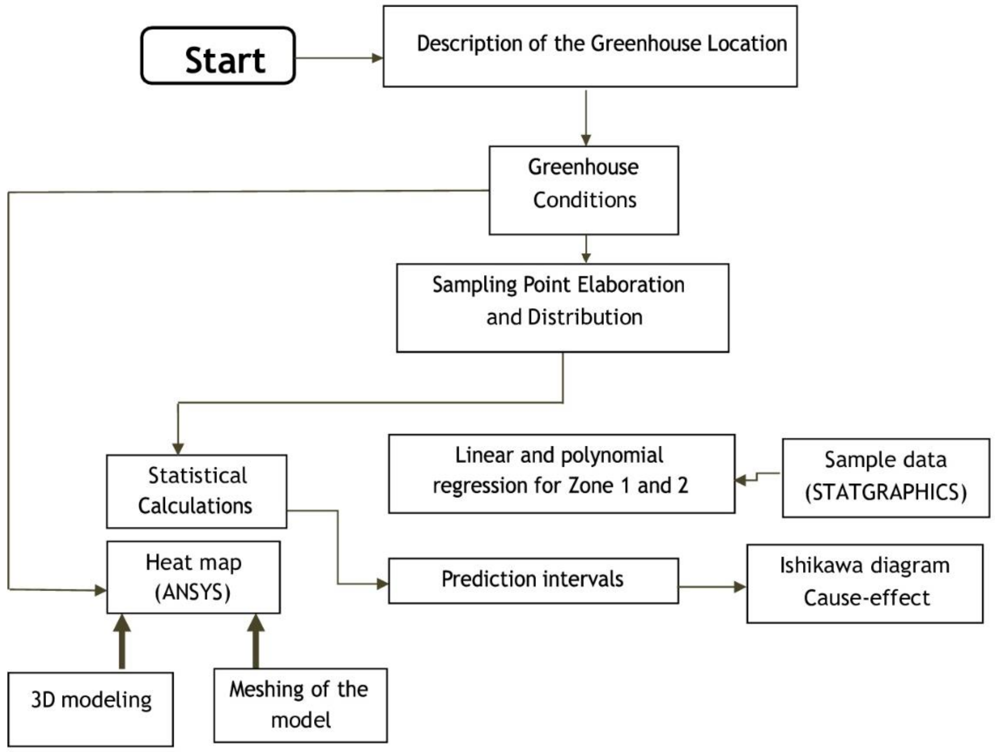

Figure 2. Process flow diagram.

To check the performance of the team with independent temperature and relative humidity indicators and assess the impact of implementing a Quality Assurance/Quality Control (QA/QC) System on the process [11]

Ethical research standards

The analysis of the energy and exergy produced by the pump is essential to determine optimal values and maintain the necessary conditions in the greenhouse. This involves understanding key concepts such as available energy, energy consumption, reversibility, and lost work (Luis, 2013). Available energy refers to the amount of energy that can be converted into useful work. Energy consumption refers to the amount of energy the pump requires to operate. Reversibility relates to the efficiency of the pump, i.e., how much energy is converted into useful work compared to the total energy consumed. Lost work is the energy that is not converted into useful work and is dissipated in the form of heat or other unwanted forms of energy[1]

Data Colection Technicques

The experiment's design aims to establish parameters that allow understanding the operation of the heat pump and acquiring prior knowledge about geothermal energy, as well as evaluating its advantages and disadvantages in its application. The LSI weather station - LASTEM ELO 105 data logger with 3DOM® software collected data during the months of May and June. For measurements at each point, the random method was applied, with the help of Microsoft Excel®, using statistical tools such as regression analysis to observe the model fit and interpretation of data. A high coefficient of determination (R-squared) considers significance as a predictive model. It is necessary to make decisions (Ishikawa diagram), which will help correct the process's operation to finally create a heat map that will accurately identify patterns and changes over time. The system will be modeled using ANSYS FLUENT®, with a focus on analyzing temperature as the variable of interest. ANSYS Fluent enables fluid dynamics (CFD) simulations, allowing for an in-depth analysis and simulation of heat transfer phenomena. This procedure was carried out ethically and transparently, ensuring that participants fully understood the nature of the research. The study strictly adhered to ethical standards, thereby ensuring the integrity and validity of the study on the energy performance of the system in question [13].

Data análisis Techniques

In the evaluation of simulation models, the statistical method commonly used is regression analysis due to its simplicity of application. The coefficient of determination (R^2) and the linear regression coefficient are used to assess the fit of the regression model. This allows representing the behavior of an observed variable as a function of a fixed set of values (X) for each condition studied and a functional relationship, using a random sample (Y) [14]In addition, prediction intervals provide information about the estimation of effects in the study, which can offer a more consistent and accurate estimation of the results. Computational Fluid Dynamics (CFD) will be used to analyze the thermal behavior of a greenhouse with dimensions of 470 m² of surface area and 3.5 m in height. The greenhouse is made of polyvinyl chloride with a thickness of 7 µm. The system will operate for 4 weeks in May and June, with temporal assessments every 24 hours. The temperature inside the greenhouse varies depending on solar radiation since there is no internal air flow when the pump is not in operation, allowing the simulation of appropriate thermal conditions [15]

Procedure

The properties of the materials and the sizing of the greenhouse are represented in **Table *1***. They contribute to the creation of the grid for sampling.

Table 1. Greenhouse conditions

Parameter	Value
Materia	Polyninyl choride
Wall thickness [µm]	7,0
Lenght [m]	23,5
Width [m]	20
Height [m]	3,5

The specifications of the greenhouse are shown in the **Figure *3***

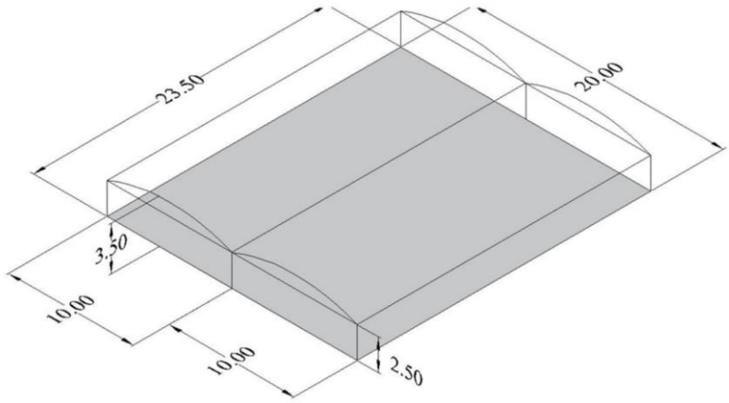

Figure 3. Greenhouse sizing.

The modeling method used is the grid method, which involves the arrangement of geopositioned points Each point provides a sample composed of multiple subsamples in a specific region, allowing for detailed analysis of a particular sector.

The sampling followed the method of the Unified Text of Environmental Legislation of Ecuador (TULSMA). A grid of 147 x 143 cm was established, resulting in a total of 448 squares, divided into 224 squares in the lower part and 224 squares in the upper part. The distance from the ground was set at 57 cm to avoid influencing the soil temperature, and 1.71 cm to accommodate the height at which crops grow, as indicated the **Figure *4***.

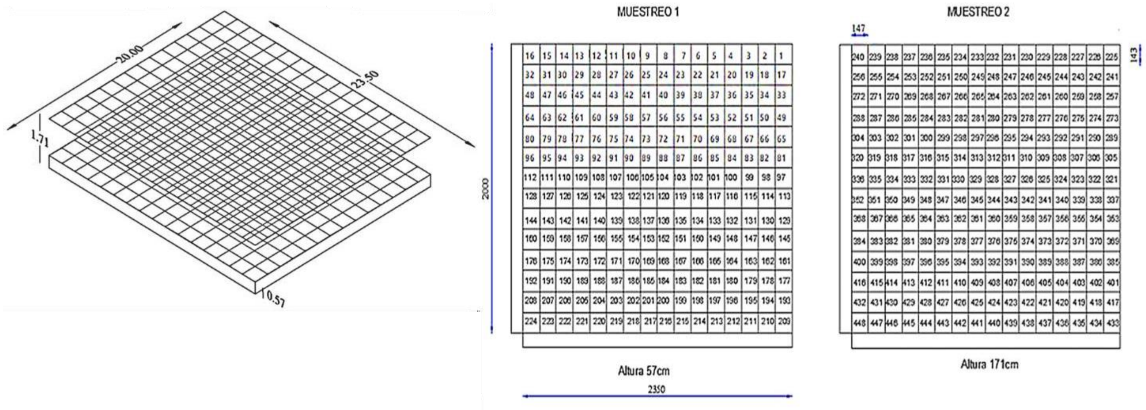

Figure 4. Representative Samples (Meshing Method).

The **Figure *5*** represent Temperature (T) and relative humidity (RH) data were collected in a total of 3169 samples from May to June, with a data collection schedule every 10 minutes. The temperature samples were divided into two zones: Zone 1 with 1475 samples and Zone 2 with 1738 samples. As for relative humidity, Zone 1 had 1378 samples, while Zone 2 had 1826 samples.

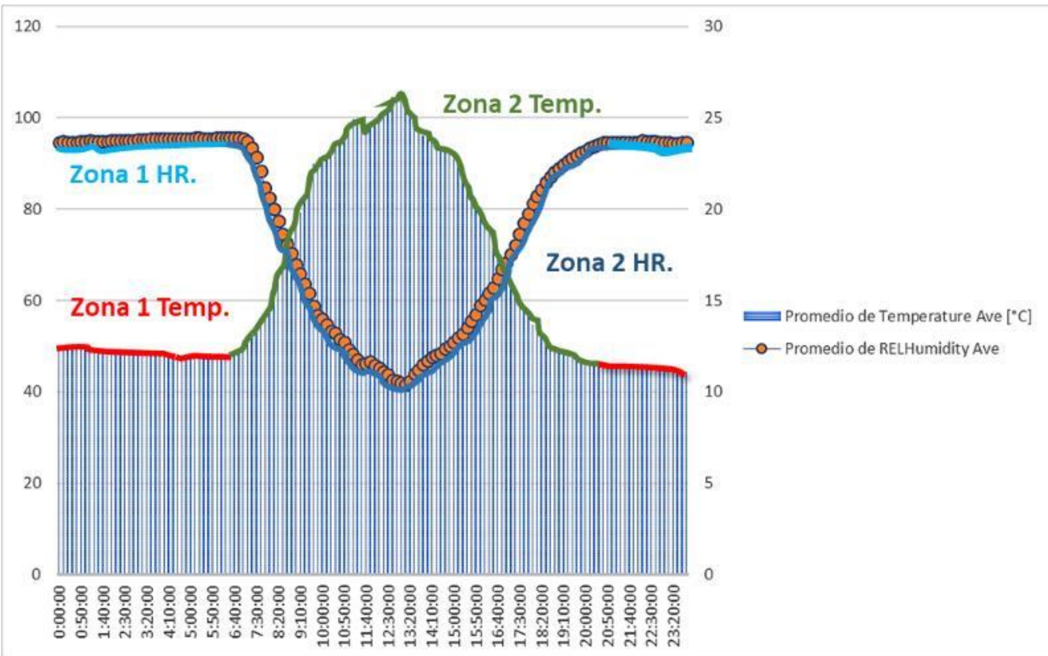

Figure 5. Established zones for Temperature and Relative humidity.

The variable to be analyzed is temperature, which will be divided into two zones: Zone 1, which covers the time period from 20:00:00 to 7:00:00, and Zone 2, which is established from 7:00:00 to 20:00:00. This will be modeled in ANSYS FLUENT.

RESULTS

The equipment controller is configured in such a way that when the pump is operating, the system aims to maintain the temperature within a specific range. During the day, the desired maximum temperature is 30°C, and during the night, it is targeted to be kept at 15°C, with a margin of error of ±2°C in both conditions. The most critical periods are the heating period from 24:00 to 08:00 and the cooling period from 10:00 to 15:00. The system automatically shuts off at 8 a.m. and 3 p.m., as at those times, solar radiation and heat losses manage to reach the desired set point.

Figure *6* details the following:

The temperature in Zone 1, a simple linear regression is applied from 20:00 to 7:00, as there is a linear relationship between the average temperature and time during that period. In Zone 2, from 7:00 to 20:00, a fourth-order polynomial regression is used, as there is a good fit between the curve and data points. From 20:00 onwards, the greenhouse takes advantage of the solar radiation stored during the day.

The relative humidity in Zone 1 is modeled with a simple linear regression from 20:40 to 7:00, as there is a linear relationship between the average relative humidity and time during that period. In Zone 2, from 7:40 to 20:00, a third-order polynomial regression is used, as there is a good fit between the curve and data points.

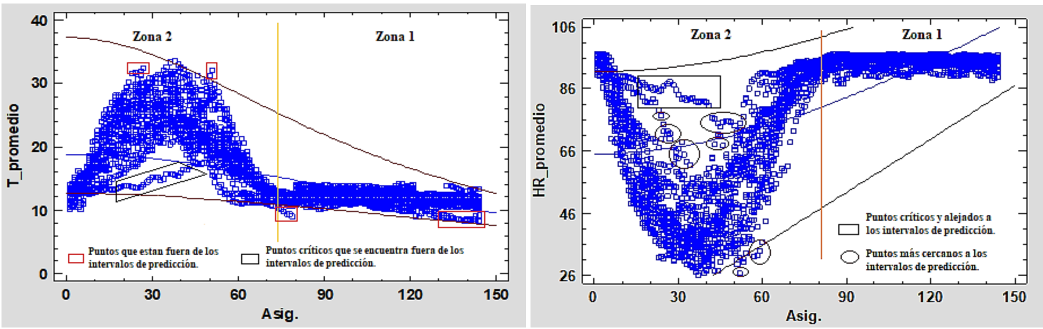

Figure 6. Prediction limits for zone 1 and 2 (average temperature and average relative humidity).

A 3D modeling is carried out over a period of 4 weeks, considering temperature variations in the subsurface throughout the day and weather conditions. To expedite the process, an evaluation is conducted every 24 hours [13]. Mesh refinement is applied to the entire greenhouse body, including walls, floor, and roof, as these areas are more exposed to temperature variations from the external environment and the ground. The initial temperature inside the greenhouse is maintained at a uniform 25°C.

In **Figure *7***, Zone 1 from 20:00 to 7:00 is described. The heating system allows the control of temperatures. At 0.57 cm above the ground, the temperature is 11°C and decreases as the height increases, reaching a minimum of 9°C. In the greenhouse's extremities, where there is more contact with the ambient temperature, colder areas are reached. Additionally, it is observed that during the night and early morning, temperature conditions decrease significantly. The heating system manages to maintain a homogeneous system around 12°C inside the greenhouse, which is ideal for cultivation.

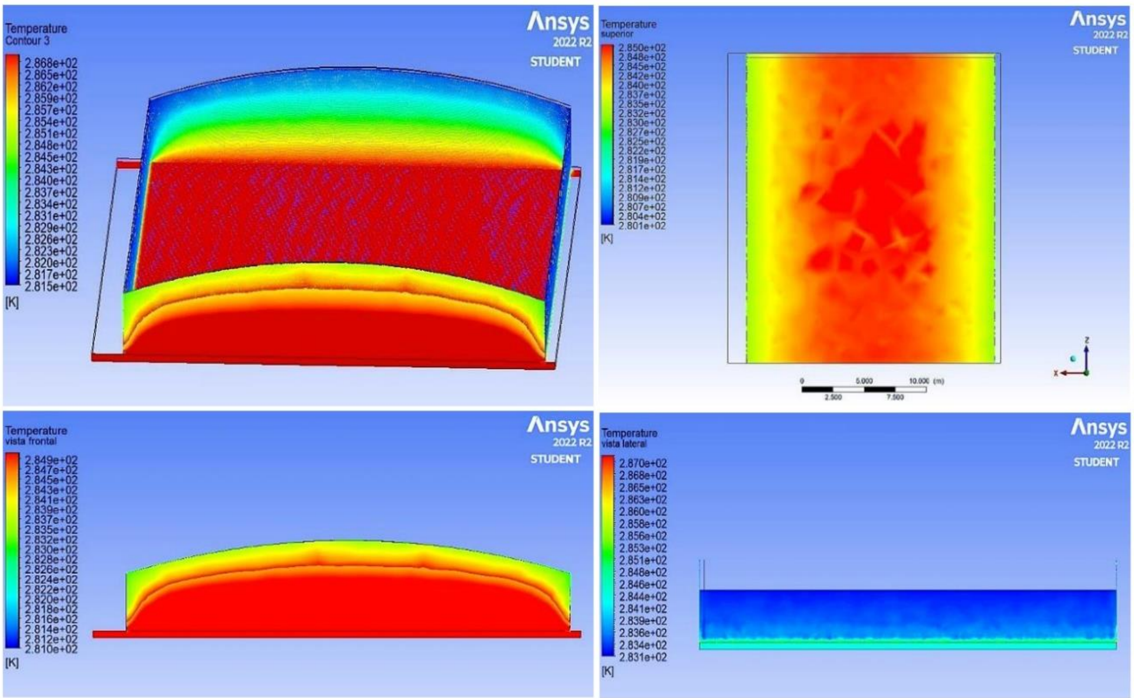

Figure 7. Zone 1, 20:00-7:00.

In **Figure *8***, Zone 2 from 7:00 to 20:00 is described. The cooling system enables the system to cool rapidly, and the temperature at 1.71 cm above the ground is maintained at 30°C, making it feasible for plant growth. Along the sides of the greenhouse where the walls are in contact with the environment, the temperature ranges between 18 and 20°C, allowing for thermal dissociation and the creation of cooler zones.

It is observed that the system successfully maintains a homogeneous temperature around 28°C, which is ideal for cultivation. However, the airflow inside the greenhouse is erratic with low intensity, resulting in dispersed temperatures. Some areas in the greenhouse are warmer, while others are cooler.

At the top of the greenhouse (2.5m), temperatures range from 15 to 22°C, effectively meeting the intended cooling objective. This allows for optimal crop growth, in contrast to a heating system that takes longer to warm up the greenhouse.

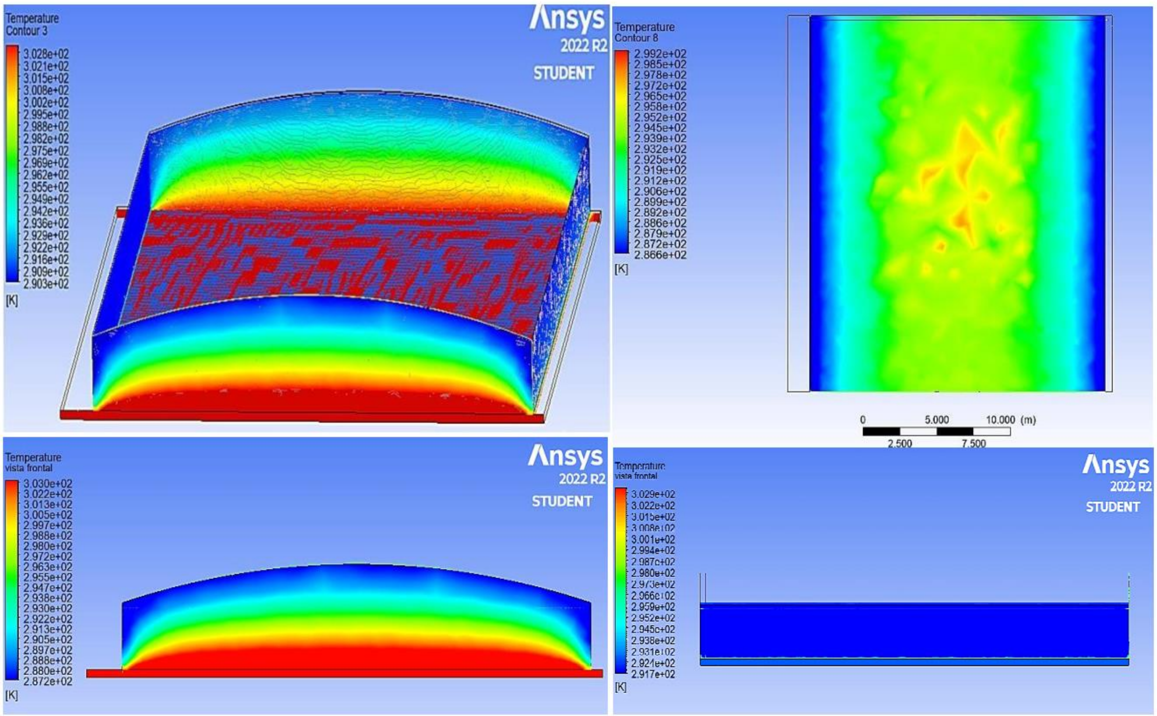

Figure 8. Zona 2, 7:00-20:00.

The factors that affect the variability of a process can be either random or common, as well as assignable or specific. When a data point in the variables exceeds control limits, it is considered problematic, but it does not reveal the underlying cause of the issue. In the presence of such anomalies, an investigation is conducted to identify the responsible causes of instability, followed by preventive actions to prevent their recurrence [16]. The use of the Ishikawa diagram as a tool allows for the examination of the interrelationship between uncontrolled parameters (cause) and the effect they produce. As seen in a **Figure *9***.

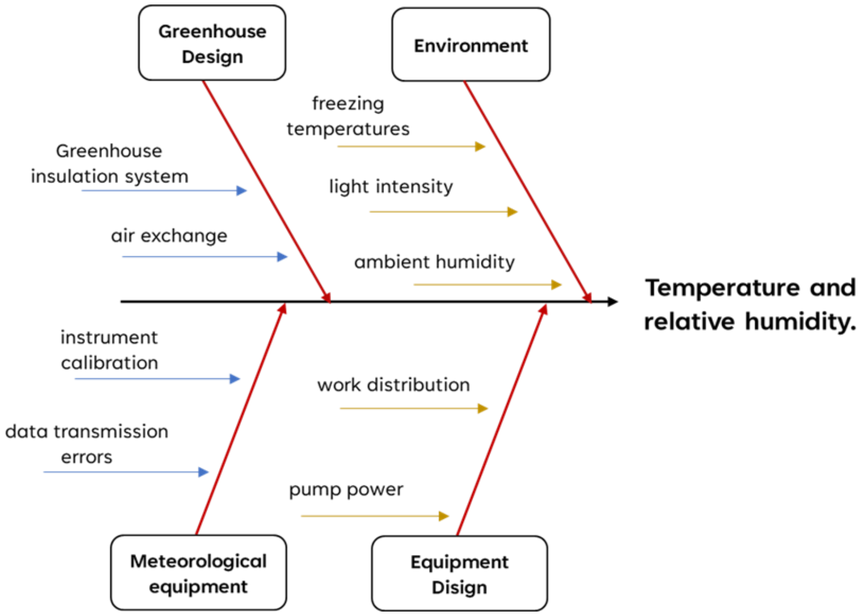

Figure 9. Ishikawa diagram, preventive solutions.

DISCUSSION

Perspective of use of geothermal energy in agroindustry

In Ecuador, studies have been conducted to quantify the energy demand of crops, particularly focusing on biofuels [1]. It is necessary to perform a detailed analysis that breaks down the type of energy consumed by each fruit and vegetable crop[17]. This will allow for a precise evaluation of energy diversification in this agricultural sector.

The scenarios clearly demonstrate that the cost-effectiveness of coupling a geothermal heat pump to a greenhouse to achieve high yields also aligns with sustainable practices by harnessing renewable energy from the Earth's natural heat [18]. The crops considered demand optimal growth temperatures, either day or night, as indicated in **Table *2***. The greenhouse under study has crops such as tomatoes and capsicum, since they have similar growth temperatures. Which guarantees optimal conditions for growth but also contributes to diversifying crops in the Andean basin. The data is available in the Agricultural Public Information System of Ecuador (SIPA)

Table 2. Suitable temperatures for horticultural crops

Species	Germination temperature		Optimal Temperature	
	Mínimum	Óptimal	Night	Day
Strawbarry	9-10	20-30	15-20	22-26
Tomate	13-17	17-20	13-20	24-28
Capsicum	12-15	23-29	18-21	21-26
White onion	7-15	20-24	15-21	20-25
Citrus	10-13	25-30	13-16	24-32
Lettuce	3-5	18-20	5-8	14-18

Figure *10* shows the most common products in the country that could be grown in greenhouses, their yield. The data is available in the Agricultural Public Information System of Ecuador (SIPA). The vegetables that are most produced in the greenhouse are white onion, Capsicum and tomato. However, fruits are a sector 11 times larger than vegetables [1], so it is necessary to generate more information, just like flowers, it is important to apply feasibility studies to non-food markets[19].

Therefore, the study addresses the changes in energy consumption in agriculture, showing that renewable energies allow spaces to be conditioned, that is, heat-type energy, in addition to being adaptable in other sectors such as residential, commercial and industrial.

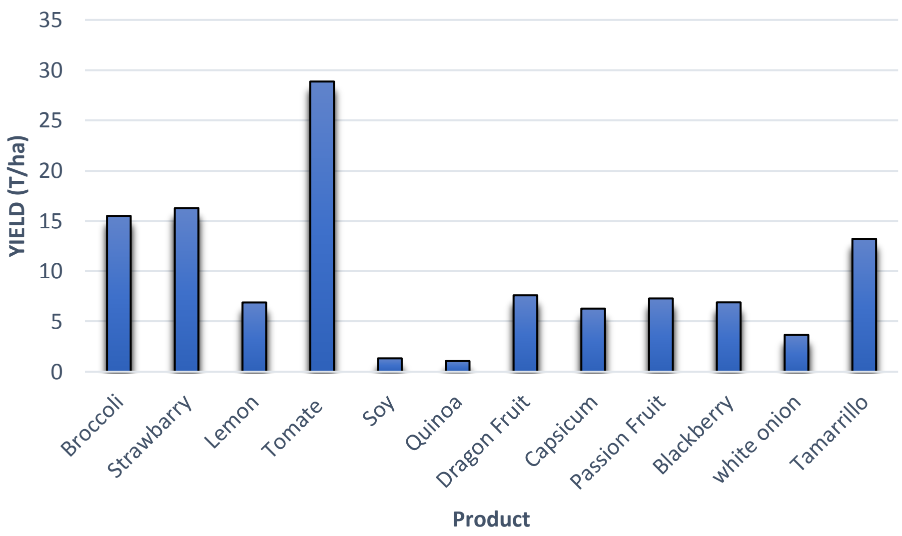

Figure 10. Yield of greenhouse´s cultivable crops.

System performance

In Zone 1, econometric models show that the average temperature has an insignificant relationship with a coefficient of determination (R^2) of 15.25%. Heating is turned on from 00:00 to 8:00 at 12.18°C and from 20:00 to 00:00 at 11.39°C. **Figure *6***, on June 6th from 23:00 to 00:00, 0.41% of the points are outside the prediction intervals, indicating the need to schedule heating from 22:00 to 8:00. From 22:00 to 23:50 on May 26th, 27th, and 29th, 2.51% of the points are outside the prediction intervals.

The average relative humidity in Zone 1 has a coefficient of determination (R^2) of 0.67%, indicating a moderate but insignificant relationship. Heating is turned on from 00:00 to 8:00, with an average relative humidity of 95.21%, and decreases to 94.65% from 20:40 to 00:00. In **Figure *6***, 2.03% of the points on June 4th, 14th, 16th, and 17th are outside the prediction limits, with June 14th being the farthest at 0.29%.

In Zone 2, both average temperature and average relative humidity are fitted with fourth-order and third-order polynomial regressions, respectively, with coefficients of determination (R^2) of 70.76% and 74.08%, indicating a significant relationship due to data variability. The cooling system is activated from 10:00 to 15:00 at 28.32°C, while from 7:00 to 10:00, the average temperature is 17.21°C, and from 15:00 to 20:00, it is 15.96°C. In **Figure *6***, 1.27% of the points on June 4th, 5th, and 12th are outside the prediction intervals, with June 3rd being the farthest at 1.61%.

The average relative humidity in Zone 2 shows fluctuations due to the continuous exchange of energy between the internal and external environments of the greenhouse. In **Figure *6***, it can be observed that from 7:00 to 10:00, the average relative humidity is 75.27%, from 10:00 to 15:00, it is 47.42%, and from 15:00 to 20:40, it is 76.06%. In total, 1.70% of the points are outside the prediction interval on June 3rd, while the aggregated average of 1% is closely distributed on several dates.

Greenhouse Desing

Greenhouse design is crucial for its performance, as it allows better climate control and facilitates pest monitoring. Placing it in the equatorial zone has advantages due to high solar radiation, which eliminates the need to track solar movement. However, there are limitations since two digital meters at the ends provide data for a single area, assuming that the entire zone has the same temperature and humidity, which is not true. The plastic covering the greenhouse does not do so uniformly, and being close to other greenhouses causes thermal interaction, resulting in abrupt energy fluctuations, as illustrated in **Figure *7***.

In Zone 1, heating is important in the greenhouse, while the cooling system is only used in conditions of high solar radiation. Maximum temperatures remain acceptable for crops, and cooling is achieved through natural ventilation or evapotranspiration [20].

The temperature in the greenhouse is affected by air leaks and soil influence, creating a thermal gradient. More heating is needed during cold days, generating higher consumption points when transitioning from night today. **Figure *8*** shows options for proper operation even though there are no windows; air renewal from the outside improves temperature and crop growth [1]. The current crop distribution may not be optimal or adaptable to temperature changes. Improving the distribution would allow better space utilization.

CONCLUSIONS

Regression Models in Different Zones

Figure *6* represent the linear regression model in Zone1, the coefficient of determination (R2) is 15.25% for average temperature and 0.67% for average relative humidity. This indicates that the temperature values are dispersed during most of the night (20:00 to 0:00) and are grouped in the early morning (00:10 to 7:00) when the system turns on automatically and begins heating. During the night period the system acts efficiently.

In Zone 2, fourth- and third-order polynomial regression models fit the data best. The coefficient of determination (R2) is 70.76% for the average temperature and 74.08% for the average relative humidity, which indicates a significant correlation, that is, the values are grouped because the process is in balance, starting at 10:00 the solar radiation influences the thermal load. At 15:00, the system is turned off and the radiation no longer significantly affects the temperature.

The models used in our study are based on large samples and meet established parameters, demonstrating strong predictive ability. Although some critical points fall outside the prediction intervals, they represent a small percentage of the data and can be discarded. These outliers can be due to a variety of factors, and a cause-and-effect diagram will guide decisions about greenhouse operation and process redesign, if necessary.

5.8% and 5.02% of points, representing average temperature and average relative humidity respectively with reference to 3169 total data are outside these prediction intervals. Preventive actions to obtain better system performance require that the maximum temperature during the day be 32°C and 17°C at night, with a variation of ±2°C. In addition, the heating time will be extended from 19:00 to 07:00 and the cooling time from 09:00 to 17:00. The system will turn off automatically at 7 am and 5 pm, taking into account that in the Andean region there are abrupt weather conditions; However, additional studies are needed.

Performance of the Heat Pump

The performance of the heat pump depends on the temperature difference between the heat source and energy absorption. The soil acts as a primary energy source since its stored temperature offsets heat loss during the night. **Figure *7*** and **Figure *8*** show that the environment is the main factor reducing energy in the system [21]. During the day, the cooling system requires more work because the greenhouse temperature is higher than outside. However, during the night, temperatures balance out as there is no solar radiation. Furthermore, the electrical demand of the pump is offset by the addition of carbon dioxide [22].

The location of the greenhouse in the Andean region

Results in frequent shifts between the heat pump and cooling due to climate fluctuations. In areas with more stable climates, the system would be more efficient. Improving the greenhouse insulation, such as adding a second horticultural glass wall, can reduce heat losses and electrical consumption [23]. However, there are limitations as losses also occur due to evaporation and air renewal, which are essential for maintaining the appropriate conditions for cultivation.

Air renewal within the greenhouse is not considered, as the heat pump controls the carbon dioxide (CO2) concentration during cooling [24]. Furthermore, the lack of airflow does not affect the system modeling.

Relevance of the study:

The importance of the study lies in its ability to provide an effective method for greenhouse climate control using geothermal heat pumps [25]. Additionally, this technology could be extended to areas with extreme climates to condition indoor spaces. The computational modules developed in this research also hold substantial value as they can serve as references in other studies involving geothermal utilization.

It is crucial to emphasize the importance of government involvement in promoting and developing this technology. Governments at the federal, state, and municipal levels should implement public policies and offer incentives to support the adoption of renewable energies like geothermal energy. This not only benefits the greenhouse agriculture industry but also contributes to the progress towards a more sustainable and environmentally friendly energy matrix.

The study demonstrates that the implementation of the geothermal heat pump in a greenhouse is technically viable and feasible. It is evident that optimal cultivation requires maintaining average temperatures above 25°C and, at the same time, ensuring that they do not exceed 33°C during the day, which is acceptable for the development of the plantation. On the other hand, it is observed that average temperatures close to 12 °C at night are also favorable for cultivation.

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It was not financed by any institution.

CONFLICTS OF INTEREST STATEMENT

The authors declare no conflicts of interest.

CONTRIBUTION OF THE ARTICLE IN THE LINE OF RESEARCH

It lies in its ability to provide an efficient method of greenhouse air conditioning through the use of geothermal heat pumps. In addition, this technology could be extended to areas with extreme climates for indoor space conditioning. The computational modules developed in this research also have significant value, as they can serve as a reference in other studies involving the use of geothermal energy.

STATEMENT OF EACH AUTHOR'S CONTRIBUTION

Jonathan Cepeda: Conceived and designed the experiments.

Gonzalo Chiriboga and Ghem Carvajal: Analyzed and interpreted the data.

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