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Automated Irrigation System Guided By Evapotranspiration Compensation

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Abstract:

Background*: The accelerated growth of the world's population drives an increasing demand for food, highlighting Malthus's prediction about the unsustainability of population growth in the face of food production. Given the projection of almost nine billion people by 2050, optimizing agricultural production becomes crucial, with irrigation emerging as a key method to increase crop efficiency. The proposal to develop an automated irrigation system, based on evapotranspiration compensation, aims to face this challenge, promoting the sustainable use of water and improving agricultural productivity, aligning with the needs of a more sustainable and efficient agriculture.*

Materials and Methods*: This study presents the development of an automated irrigation system based on evapotranspiration compensation using the Penman-Monteith method (FAO) and applied to a curly lettuce cultivation. The core of this system is a control module equipped with an ESP32 microcontroller, responsible for the precise calculation of evapotranspiration. This microcontroller is linked to sensors that provide atmospheric data in real time, and to actuators, responsible for executing irrigation according to the decisions of the developed algorithm. The system was designed following the Cascade Methodology that ranges from requirements gathering to implementation. The arrangement of the pots was planned to avoid competition for light and the experiment tested two techniques, irrigation by compensating evapotranspiration and irrigation using the accumulation of radiation. Six lettuce seedlings, under controlled conditions, using a completely randomized design were used in the experiment. The system integrates electronic components and sensors for real-time data collection and irrigation management, with interfaces developed to ensure simplicity and intuitiveness in monitoring cultivation.*

Results*: During a 15-day study in October 2023, the expectation of high temperatures in Central and North Brazil was confirmed, with most days exceeding 38°C and reaching a maximum of 41.69°C. The analysis of climatic conditions showed significant variations in solar radiation and relative humidity, correlating with Reference Evapotranspiration (ETO). The comparison between the two irrigation methodologies indicated a slight advantage in water consumption efficiency for the technique using evapotranspiration as a parameter, but statistical analyzes did not find significant differences between them, suggesting that both are comparable in terms of effectiveness in water use.*

Conclusion: *The study proved that an automated irrigation system, adjusted by evapotranspiration, is an effective and sustainable solution to face the challenges of climate change and improve water use in agriculture.*

Key Word*: Automated irrigation, Evapotranspiration, Agricultural sustainability, Climate change*

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I. Introduction

The rapid increase in the world's population has resulted in an unprecedented demand for food. British economist Thomas Robert Malthus proposed that population growth rates were unsustainable, arguing that while population increased in a geometric progression, food production grew only in an arithmetic progression [1]. Based on these premises, Malthus concluded that population growth would outpace the increase in food production, making sustainable food security one of the biggest global challenges. This challenge is amplified by population growth projections, which estimate that the world population will reach close to nine billion people by 2050 [2,3].

The expanding need for food has encouraged producers around the world, both large and small, to reconsider their farming methods. In this context, it was identified that the main challenge lies in optimizing agricultural production, aiming to increase the efficiency of crops in the same area of land. A potential solution to this problem is the improvement of irrigation systems, which can be fundamental to increasing crop productivity. This practice, if properly managed, can result in significantly greater production compared to non-irrigated areas.

Irrigation is considered the most effective strategy to guarantee the necessary water supply during all phases of crop development, representing the greatest demand for this finite resource. However, irrigation is often criticized for its extensive water use. Many irrigated areas lack efficient water management, raising questions about the sustainability of this essential resource. This challenge has been a recurring theme in discussions about the future of food production, including in forums of the Food and Agriculture Organization of the United Nations (FAO), which highlight the importance of the sustainable use of irrigated agriculture.

Thus, the problem arises of how to increase food production to reduce the disparity between population growth and agricultural production capacity, promoting efficient farming practices and sustainable water use. Resolving this dilemma will not only ensure that billions are fed, but also preserve natural resources crucial to environmental sustainability and quality of life on the planet.

The agricultural sector, responsible for the largest water consumption in Brazil, using 70% of the country's water resources, also leads in terms of waste. Inefficiency in irrigation and inadequate control over the volume of water used in crops contribute to almost half of this water being wasted [4,5]. However, the importance of irrigation goes beyond increasing agricultural production, also encompassing global food and nutritional security. The need to adopt innovative practices for the efficient use of water and to increase agricultural productivity is evident [6].

In this scenario, evapotranspiration in terrestrial ecosystems is a good indicator for evaluating water resources and determining the water needs of crops. It is therefore proposed to develop an automated irrigation system that manages water through computational technologies, based on Evapotranspiration Compensation. This system focuses on improving the rational use of water and optimizing cultural management related to irrigation [7].

Considering the above, this research proposes the development of an automated irrigation control system based on evapotranspiration compensation, aiming to optimize water use in agriculture. The general objective is to create a technological solution that adjusts irrigation to the specific water needs of crops, considering water losses through evaporation and transpiration. This system aims to promote more efficient and precise irrigation, contributing to agricultural sustainability through water savings and improving plantation productivity.

To achieve this objective, the project focuses on several specific goals. Firstly, the necessary requirements for the development of the controller will be identified, including the analysis of environmental variables. This is followed by the specification of hardware components, such as sensors and actuators, and the implementation of the firmware that will govern the system logic. Subsequently, the prototype will be tested to demonstrate its effectiveness in controlling irrigation. Finally, the automated system will be compared with a traditional irrigation method, aiming to highlight its superiority in efficient water management.

Furthermore, it is crucial to consider integrating this automated system with other emerging agricultural technologies, such as precision agriculture and the use of drones for crop monitoring. These synergies can maximize the benefits of evapotranspiration-controlled irrigation, offering a real-time, holistic view of crop conditions [9].

Another fundamental aspect to be addressed is the accessibility and scalability of this technology. It is essential that the developed system is accessible to farmers of different scales and regions, taking into account socioeconomic and technological disparities [12]. Additionally, the system's ability to expand and adapt to different types of crops and agricultural environments is crucial for its widespread adoption and long-term sustainable impact.

To ensure the effectiveness and acceptance of the system by farmers, it is necessary to invest in training and education programs. Farmers need to understand the benefits of evapotranspiration-controlled irrigation and receive adequate training to operate and maintain the system efficiently [10]. Partnerships with research institutions, government organizations, and private sector companies can facilitate the implementation of these programs and promote cultural change regarding irrigation practices [11].

Furthermore, it is crucial to consider the economic and financial aspects associated with adopting this technology. While the initial investment may be challenging for some farmers, the long-term benefits such as water savings, increased productivity and reduced operating costs can outweigh the initial costs. Financing strategies and government incentives can be explored to make the system more accessible and attractive to farmers [15].

Finally, it is important to highlight that the successful development and implementation of this automated irrigation control system will not only contribute to global food security and environmental sustainability, but can also serve as an inspiring model for innovative solutions in other agricultural sectors. and environmental [14]. By addressing the challenge of water scarcity and food production in a rapidly expanding world, we are not only responding to immediate concerns, but also shaping a more resilient and sustainable future for future generations [13].

II. Material and method

In this chapter, the materials and methods used to automate the irrigation process are detailed, ranging from the selection of the controller board, assembly of the hardware prototype and the development of the firmware that manages the system's operation. Initially, the ideal controller board for the project was identified and specified, considering its processing capacity, compatibility with the sensors and actuators involved, and support for the development and execution of the necessary firmware.

Study Design: Experimental study.
Study Location: The experiment was carried out at the address: Street 24, num.:12, Manaus – AM – Brazil Latitude: 3°06'49.9"S
Study Duration: The study took place over a period of 15 days, between 10/01/2023 and 10/15/2023.
Sample size: In this experiment, 6 heads of curly lettuce of the *Amanda species were used*, in stage 3 of development, already transplanted into 8.5L pots.
Sample size calculation: The number of plants was chosen due to the possibility of observing them all during the study period, in a way that reproduced growing conditions close to those found in the field. The pots were placed at a distance of 50 cm from each other, ensuring that, throughout growth, the plants did not compete for light.
Subjects & selection method: Curly lettuces, Amanda variety, were used in stage 3 of development, already transplanted into 8.5-liter pots. The irrigation system was built using 1/2-inch pipes and rubberized hoses to connect the pipes to the pumps and water reservoir.

An automated irrigation control module was developed with the ESP32 microcontroller, selected for its Wi-Fi connection capability, prototyping platform, and compatibility with the Arduino IDE. A notebook with internet access was used as a server to communicate with the ESP32. For the development of the controller hardware, EasyEDA software was used, a web-based suite of tools that facilitates the construction and discussion of schematics, simulations and printed circuit boards. The platform allows you to create and edit schematic diagrams, perform SPICE simulations of analog and digital circuits and develop printed circuit board layouts, with the option of manufacturing. Working in a browser, the tool integrates several applications. The cascade methodology was adopted for the development of the firmware and management system, covering the stages of requirements gathering, analysis, design and implementation.

The experiment used a Completely Randomized Design (CRD), with the plants exposed to the same environmental conditions (location, climate and substrate) throughout the experiment, only varying the irrigation method. Six Amanda curly lettuce seedlings were tested in a protected environment, with eight days since planting and three leaves (phenological stage 3). The seedlings were numbered from 01 to 06 and randomly divided into two groups, A and B, each with three seedlings, subjected to irrigation techniques A and B.

Details of the irrigation techniques in the design: Pots with nomenclature A received automatic irrigation using the evapotranspiration compensation technique. Pots with nomenclature B were automatically irrigated using the radiation accumulation technique, as shown in Figure 1.

Inclusion criteria:
1. Curly lettuce seedlings of the Amanda variety.
2. Plants in stage 3 of phenological development, with a number of leaves equal to 3.
3. Seedlings that were transplanted into 8.5-liter pots before the start of the experiment.
4. Seedlings that are being grown in a protected/covered environment.
5. Seedlings subjected to irrigation tests 8 days after planting the seed.
6. Plants that can be continuously monitored by automated irrigation systems controlled via Wi-Fi.
7. Seedlings that will be subjected to the same environmental conditions (location, climate, substrate) throughout the experiment.

Exclusion criteria:
1. Seedlings of other lettuce varieties or of other stages of development than stage 3.
2. Seedlings that were not transplanted into 8.5-liter pots before the start of the experiment.
3. Plants grown outdoors or not protected.
4. Seedlings that are not in the 3rd phenological stage or that do not have exactly 3 leaves at the beginning of the experiment.
5. Plants that cannot be monitored by automated irrigation systems or that are not compatible with Wi-Fi control.
6. Seedlings subjected to environmental conditions that vary or differ from those stipulated for the study group.
7. Plants that already show signs of disease, pests or water stress before the experiment begins.

Figure 1: Experimental Design

Source: the author (2023)

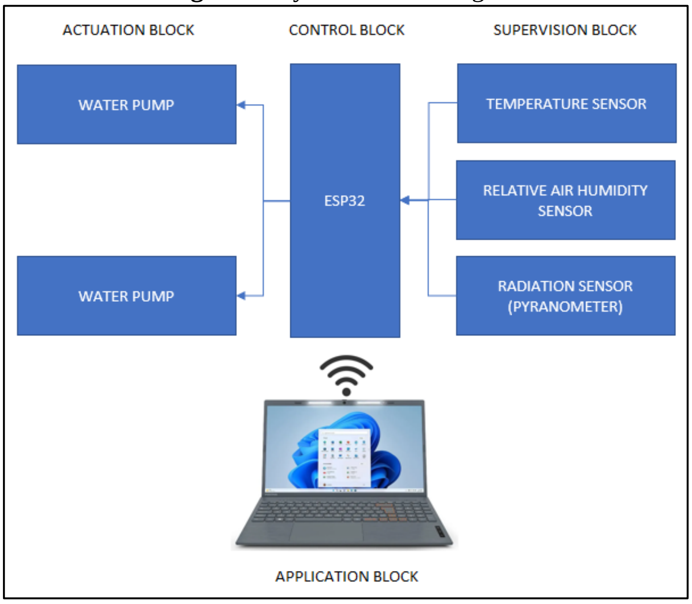
The experimental design adopted, which was entirely randomized, with the plants exposed to the same environmental conditions (location, climate and substrate) throughout the experiment, only varying the irrigation method. The pots were numbered from 01 to 06 and randomly divided into two groups, A and B, each with three seedlings, subjected to irrigation techniques A and B. Pots with nomenclature A received automatic irrigation using the compensation technique by evapotranspiration. Pots with nomenclature B were automatically irrigated using the radiation accumulation technique.

Procedure methodology

For the development of the hardware, the construction was based on the following main components: ESP32 controller module, Arduino Nano V3 ATMEGA238, Relay Shield module with 4 5V relays, a 12V and 5A power supply (converting from alternating current to direct current), three motor pumps for aquarium, air humidity and temperature sensors, radiation sensor (pyranometer), a 20x4 display coupled to an L2C Module, and a specific current regulator module for the pyranometer. All these components were assembled inside a waterproof electrical panel measuring 30x25x15 cm, protecting the system from possible interference from the external environment.

The automated irrigation system combines hardware elements, such as microcontrollers, sensors and actuators, with software and database, communicating through the MQTT protocol. This architecture was carefully planned to collect data accurately and efficiently in real time, aiming to improve irrigation management. Additionally, a conceptual model for the database was developed, with the objective of mapping the data entities and their interrelationships, providing an organized structure for managing the system's information. Figure 2 illustrates the system block diagram showing the relationship between these elements.

Figure 2: System Block Diagram



Source: the author (2023)

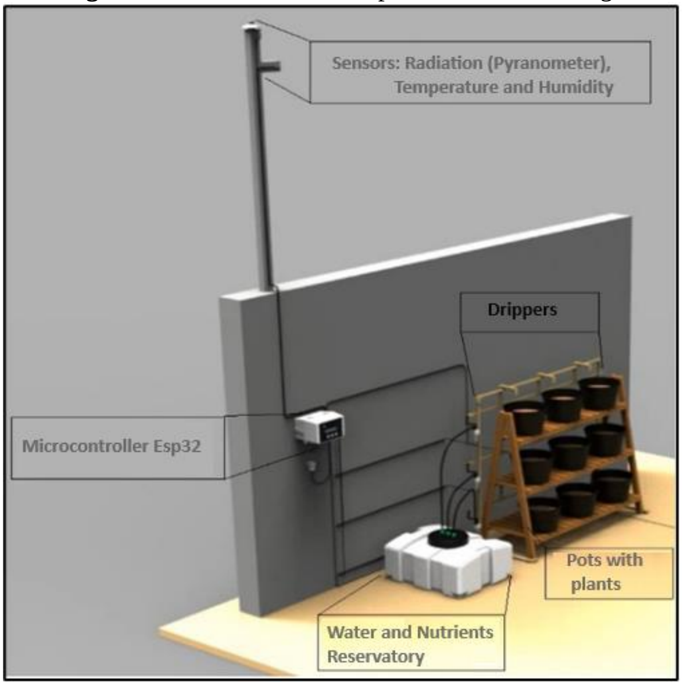
The system block diagram provides a representation of the essential components that constitute the proposed system. These components have been systematically organized into distinct blocks, namely: supervision, control, actuation, and application server.

In the supervision block, sensors responsible for reading the environment are located. These include Temperature, Relative Humidity of the air and Radiation sensors. These sensors collect environmental data according to predefined settings in the system, with a flexible reading interval that can be adjusted by the user. The control block is the processing center equipped with the ESP32 microcontroller, a crucial component. It receives data from sensors, processes calculations of evapotranspiration, using the Penman-Monteith method (FAO) [16], Crop Evapotranspiration (ETC) [17], irrigation pulse based on evapotranspiration and irrigation pulse based on accumulated radiation.

With the calculated evapotranspiration and irrigation pulse data, the ESP32 controller send instructions to actuators to irrigate plants. Simultaneously, the MQTT protocol is used to establish communication between Esp32 controller and the application server block, facilitating continuous updating of the application database with meteorological information and the latest irrigation data. In the actuation block are devices directly involved in the irrigation process. These devices receive the irrigation pulse duration in seconds from the ESP32 controller and execute the irrigation process as needed. The application server block plays a central role in user interaction and database management. To optimize the user experience, a set of interfaces has been developed, each playing a fundamental role in user interaction with the system. This ranges from the initial login process to the careful insertion of essential data related to irrigation methods, crop coefficients (Kc), and plantation management.

An experiment was designed to validate the functionality and effectiveness of the system. Figure 3 provides a detailed view of the experiment, illustrating the connection of various system components in a real-world scenario. The system design ensures continuous communication and coordination among various hardware, software, and user components. This holistic design approach, covering hardware, software, and user experience, aims to provide a robust and user-friendly solution for efficient crop and irrigation management. The integration of advanced sensing, calculation, and actuation components highlights the system's ability to enhance agricultural practices through intelligent, data-driven irrigation management.

Figure 3: Overview of the experiment and seedlings



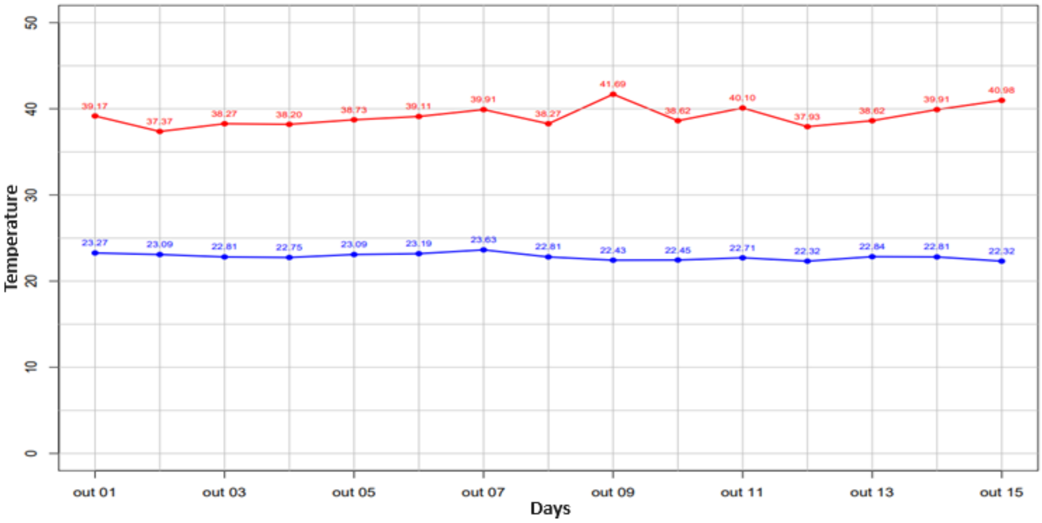
Source: the author (2023)

Figure 03 shows the arrangement of all parts of the system: Sensors, actuators, controller, Cultivation system with pots, irrigation pumps, drippers and tank for water and nutrients.

III. Result

The experiment was carried out over a period of 15 days, starting on October 1st and concluding on October 15th, 2023. It was anticipated that this month would present high temperatures, particularly in Central Brazil and the Northern Regions, according to forecasts of meteorological services [8]. These expectations were corroborated by the data captured by the experiment's sensors. The graph in Figure 4 shows the temperature data for the period.

Figure 4: Maximum and Minimum Temperatures for the period

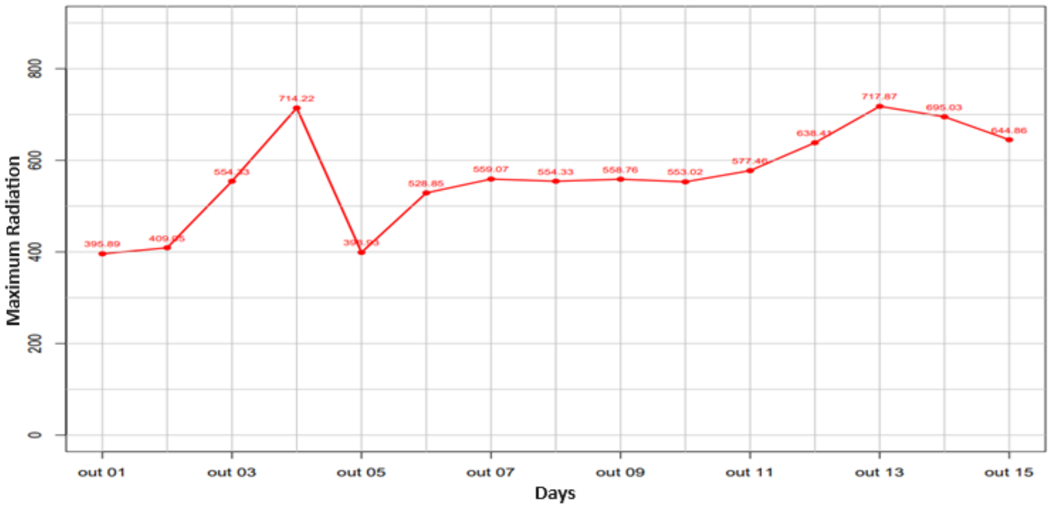


Source: the author (2023)

During the analysis interval, from October 1st to 15th, temperatures remained relatively stable, with 86% of days recording temperatures above 38°C. The maximum temperature recorded was 41.69 °C on October 9th, while the lowest minimum temperatures were observed on October 12th and 15th, recording 22.43°C on both days. These data reflect a significant thermal variation within the short period studied, highlighting the volatility and complexity of climatic conditions. The observed thermal amplitude, ranging from 22.43°C to 41.69°C, was 19.26°C).

On October 9th, when the maximum temperature was recorded, solar radiation also reached a considerably high value, as shown in the graph in Figure 5, with 558.76 Wh/m².

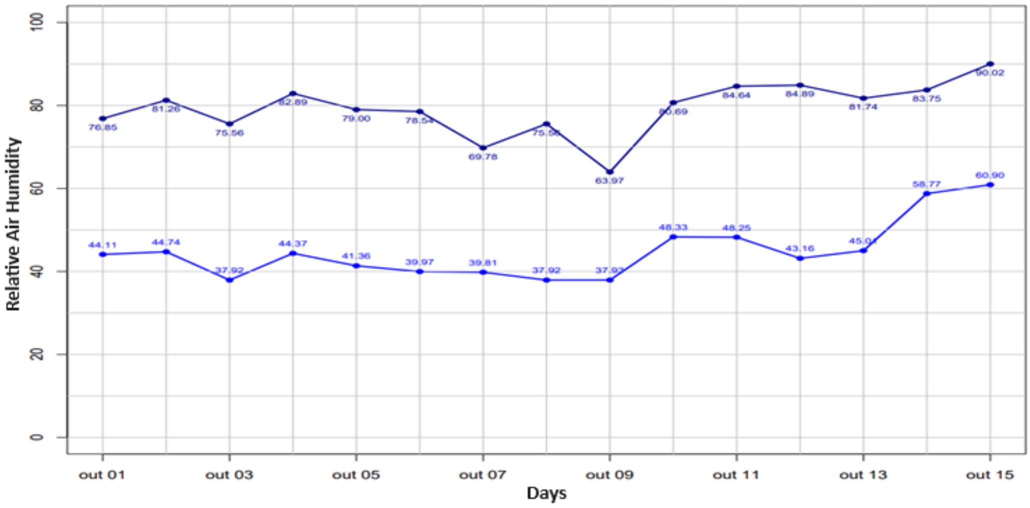
Figure 5: Radiation history for the period



Source: the author (2023)

The graph in Figure 5 provides a visual representation of the radiation flux over the analysis interval. This visualization is essential to understand the amount of solar energy received during the studied period and its distribution over the observed days and allows a detailed analysis of the lighting conditions during the period, contributing to a more complete understanding of the climatic context. The graph in Figure 6 shows how the Relative Air Humidity behaved during the experiment period.

Figure 6: Maximum and minimum relative humidity of the period



Source: the author (2023)

During the analyzed period, a significant variation in relative air humidity was observed, with peaks and valleys over the 15 days. Maximum humidity reached its highest point on the 15th, reaching 90.02 %, indicating wetter conditions in that specific period. Furthermore, an inverse correlation was noted between maximum and minimum temperatures and relative humidity, with hotter days being associated with lower humidity levels. Particular events, such as the 9th with a minimum humidity of 37.93%, suggest relatively dry conditions. The analysis can also be expanded by considering the influence of radiation, which is related to the evaporation of moisture.

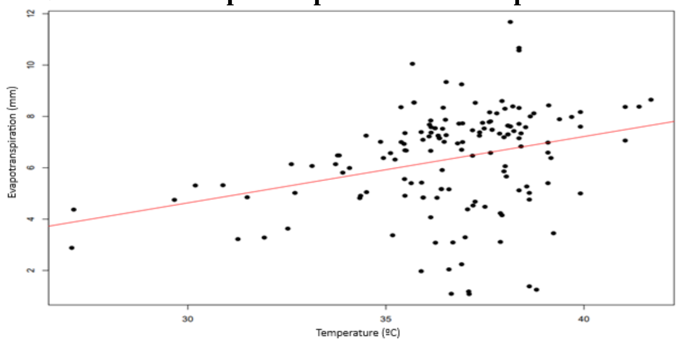
To demonstrate the prototype's ability to control irrigation, the proposed experiment was carried out comparing two irrigation methods. The experiment setup, including the components and physical layout, is illustrated in Figure 7. This arrangement provided a basis for testing and comparing the efficiency of the prototype in managing irrigation, without making value judgments about the methods.

Figure 7: Experiment physical layout

Source: the author (2023)

A dispersion analysis was carried out to identify significant relationships between climatic variables, such as Temperature, Radiation and Relative Air Humidity, and Evapotranspiration. Examining these graphs, it is identified patterns and trends that can guide decisions in water resources management and climate modeling. This analysis is crucial to understand the behavior of Evapotranspiration and its relationship with climate. The graph in Figure 8 illustrates the relationship between Evapotranspiration, Y axis, and Temperature, X axis.

Figure 8: Reference Evapotranspiration and Temperature scatterplot

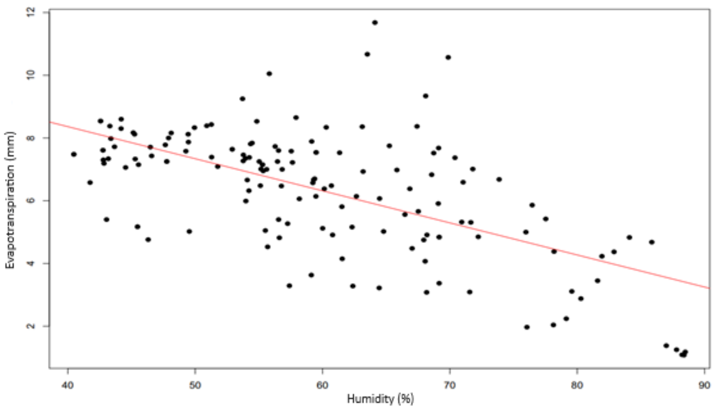


Source: the author (2023)

The graph reveals a proportional increase between the two variables. The rising trend line indicates a positive correlation, suggesting that as the temperature rises, evapotranspiration also tends to increase. The calculated correlation coefficient of 0.3034615 points to a positive, although weak, relationship between the variables. This implies that, although both variables tend to increase together, this relationship is not particularly strong, as the value is close to zero.

The graph in Figure 9 highlights the relationship between Evapotranspiration, Y axis and Relative Air Humidity, X axis, showing a decreasing trend.

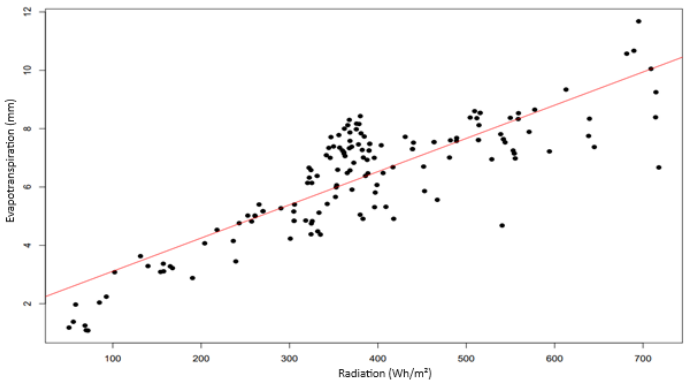
Figure 9: Scatterplot Reference Evapotranspiration Humidity and Relative Air Humidity



Source: the author (2023)

In the graph in Figure 9, the descending trend line indicates a negative correlation, that is, as relative air humidity increases, evapotranspiration tends to decrease. The correlation coefficient found, of -0.6183553, denotes a moderate negative relationship between the variables. This means that, on average, an increase in one variable leads to a moderate decrease in the other. Finally, the graph in Figure 10 demonstrates the relationship between evapotranspiration, Y axis, and Radiation, X axis, with a simultaneous increase in both variables.

Figure 10: Reference Evapotranspiration and Radiation scatterplot



Source: the author (2023)

The ascending trend line reflects a strong positive correlation, evidenced by the correlation coefficient of 0.845743, this indicates a linear and almost perfect relationship between the variables, suggesting a strong association between them. In summary, when one variable increases, the other tends to increase considerably, indicating a substantial connection between Radiation and Evapotranspiration.

The collected data were analyzed using the Shapiro-Wilk normality test and the Student's t-test, with a confidence level of 95%, using the RStudio software, version 2023.09.1+494, using the R package in version 4.3. 1. The Shapiro-Wilk test was applied to verify the normality of the data, while the Student's t-test was used to compare the means between two groups, assuming a normal distribution of the data. These statistical procedures were chosen to evaluate significant differences in the data collected during the study.

Table 1 presents water consumption data during the experiment for methodologies A (Irrigation based on the Evapotranspiration Compensation) and B (Irrigation based on Radiation Accumulation).

Table 1: List of items, quantity and values of materials used in the irrigation and cultivation system

Date	Methodology A	Methodology B
01/10/2023	791.03	966.62
10/02/2023	754.41	949.50
03/10/2023	893.82	1279.80
04/10/2023	790.55	1037.54
05/10/2023	848.29	1062.10
06/10/2023	916.35	1138.57
10/07/2023	923.87	1216.18
10/08/2023	893.82	1279.80
10/09/2023	1376.17	1166.76
10/10/2023	1076.93	929.79
10/11/2023	1225.01	1043.86
10/12/2023	1196.14	1056.12
10/13/2023	1240.75	1171.39
10/14/2023	1352.70	1268.61
10/15/2023	699.95	593.24
Total	14979.79	16159.88

Source: the author (2023)

From Table 1, it can be seen that methodologies A and B used a total of 14.96L and 16.15L of water for irrigation, respectively. Analysis of the results indicates that methodology A was more efficient than methodology B, with a smaller difference in consumption of 1.18L, representing approximately 7.87%.

The difference in the result, although it seems small, motivated the performance of the unpaired and two-sided t- student statistical test, with a significance level of 0.05, to determine whether there are significant differences in water consumption between the two methodologies. Two hypotheses were established for the test: H0: There is no significant difference between the average water consumption of methodologies A and B, that is, they are statistically equivalent; H1: There is a significant difference between the average water consumption of methodologies A and B, indicating that they are statistically different.

The test resulted in a p-value of 0.91, which is greater than the established significance level (α =0.05), leading to the acceptance of the H0 hypothesis. This p-value suggests that there is not enough evidence to consider the water consumption averages between methodologies A and B to be statistically different. Additionally, the 95% confidence interval for the difference in means covers the value zero, ranging from -2623.545 to 2345.738, which indicates that the true difference between the means may be insignificant. Therefore, it is concluded that there is no statistically significant difference in water consumption between the tested methodologies, implying that both can be considered equivalent in terms of the amount of water used, according to the data in this study.

IV. Discussion

The identification of the requirements for the development of the automated irrigation controller made it possible to analyze the variables of the agricultural environment, including the calculation of reference evapotranspiration, considering everything from soil characteristics to the complexities of the local climate. This allowed us to understand the plants' water needs and other relevant factors, resulting in the definition of comprehensive technical and operational requirements. Preparing this solid foundation ensured that the controller was well aligned with the particularities of the environment, maximizing the efficiency of the irrigation system.

For automation, a careful selection of simple and low-cost hardware components was carried out, resulting in a robust, stable and economical system. This choice not only met practical needs, but also ensured the economic viability of the project.

The development of the firmware was essential for the operational functionality of the controller, taking into account the interaction between hardware, software and database, and adapting to different environmental conditions. The creation of intuitive visual interfaces, such as dashboards and operation screens, focused on providing a friendly user experience, aiming for functionality and ease of use.

The effectiveness of the prototype was tested in an experiment with lettuce, comparing irrigation based on evapotranspiration with that which considered the accumulation of solar radiation. The stability and performance of the system confirmed the robustness and efficiency of the developed controller.

The irrigation methods tested showed comparable water efficiency, but the use of evapotranspiration as a reference proved to be 7% more efficient, validating the effectiveness of the controller and highlighting the importance of this parameter for optimizing water use in agriculture. These results not only reinforce the practical applicability of the system, but also promote more sustainable irrigation practices.

This study achieved its main objective of developing an automated irrigation controller based on evapotranspiration compensation, offering a vital solution in the face of severe climate adversities, such as the worst drought ever recorded in Amazonas. The work stands out as an important contribution to combating climate change and promoting sustainable practices in the use of water resources, marking a significant advance towards smarter and more responsible agriculture, aligned with the sustainable development of the region.

V. Conclusion

This study demonstrated the effectiveness of an automated irrigation controller, developed based on evapotranspiration compensation, as an innovative solution to the challenges posed by climate change and the need for sustainable agricultural practices. Through the meticulous selection of cost-effective hardware components, combined with the development of integrated firmware and intuitive user interfaces, the project achieved a balance between operational efficiency, economic viability and ease of use. Validation of the system, through practical tests with lettuce crops, not only confirmed its robustness and efficiency in water management, but also highlighted the superiority of using evapotranspiration as a criterion for irrigation. The results highlight the importance of advanced technological approaches in improving the use of water resources in agriculture, significantly contributing to sustainable development and mitigating environmental impacts.

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