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Chain of Trust: Integrating IoT and Blockchain to Certify Wild Mushroom Growth Quality

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***Abstract*—This paper presents the preliminary results of the study developed within the scope of the "*Safe2Taste*" project presenting the main concept of hardware and software architectures. The project aims to build a monitoring system supported by IoT technologies and covered by a security layer through interaction with a blockchain network to be applied in an edible mushroom production system. The hardware and software components were validated in the laboratory and taken to domestic production for the concept phase. the impacts caused by the inconsistent production management are in the analysis phase as the data collection is not finalized. At this stage, the implementation of low-cost IoT nodes is intended for collecting and monitoring parameters, these parameters are sent via the MQTT protocol to the cloud, starting the blockchain mining process and storing the mining result in an immutable database. The information from monitoring, as well as the keys generated in blockchain mining, will be presented in an intuitive way through a user interface built using the NODE-red framework.**

***Index Terms*—IoT, Mushroom production, Blockchain, wireless network.**

I. Introduction

With the popularization of vegetarian diets, the consumption of mushrooms became even more popular in an attempt to replace protein needed for a healty diet. Several studies show the nutritional capabilities of mushrooms as well as new and diverse strategies for marketing and increasing added value [1] [2] [3]. Mushroom cultivation has been carried out in different ways over the years due to its great potential in the composition of high-value products in addition to its proportional great benefit to health given the nutritional density found in the most varied edible species [4]. Sara et al. [5] have emphasized the significance of mushroom-derived eco-friendly industrial products. Lu et al. [2] have investigated mushroom cultivation, bioactivity, and application.

With the increase global demand, the need for innovative development in the production, transport and marketing of mushrooms emerges in the search for more sustainable and efficient forms of cultivation [6]. As new forms of production are developed, new biological analysis processes advance at the same pace, enabling the discovery of still unexplored benefits, both economic and nutritional, related to the treatment of diseases and human health in general.

The fungus cultivation process involves several techniques that can be used individually or together, among which we can mention control of environmental variables, mixing of substrates and improving the mycelia. Techniques applied to filamentous fungi, models and methods of synthetic biology and improvement of culture media formulations are presented by Rama and Quandt [7]. Lee et al. [8] presents the quantification of miscellar growth while Landingin [9] studies the impact on growth dynamics through the effects of culture media, PH levels and physical factors. This research, among others, techniques that optimize the cultivation of fungi in real applications, ranging from new natural products to food fermentation and the creation of new materials.

The relevance of productive innovations aimed at cultivating fungi is not new today. From an industrial point of view,

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technological evolution implies the possibility of cultivating new edible species with different nutritional capabilities. The discovery of new natural products highlighted by [7] exemplifies the impact of optimization in culture media formulations. In another aspect, Luo [10] shows the applicability of fungi in the construction of microlandscapes based on innovative design methodology. The cultivation of non-conventional edible species in a controlled environment is another aspect covered by current cultivation models, guaranteeing a greater range of opportunities for the market.

Although much progress has been made regarding the innovative cultivation of fungi in the industrial context, many challenges encountered in the traditional model continue to be influenced by manual practices and techniques applied by farmers. Cultivation outside the conditions considered ideal can cause a major impact on productivity as well as a drastic reduction in the quality of mushrooms,as well as proportional proliferation of diseases and pests. However, providing monitoring of parameters such as solar exposure, humidity and temperature, in addition to irrigation control, is a complex task in conventional cropping models [11].

Overcome the problems faced by conventional models of mushroom cultivation, monitoring technologies have emerged that can be applied in different conditions. In this aspect, the applicability of Internet of Things (IoT) technologies helps in the management and control of information considered mandatory in the cultivation process. A closed system composed of sensors and actuators, attached to a data analysis system, allows farmers to monitor and control in real time, ensuring that the production environment respects conditions favorable to mushrooms. The applicability of cultivation process monitoring systems may occur in large-scale productions such as on farms Kassim et al. [12] and domestic crops as presented by Chong et al. [13]. In Aggarwal and Singh [14] a comparative study was carried out between crops with a monitoring system and crops in the classical model. Systems based on IoT provide control of environmental variables in real time in addition to the possibility of remote control and visualization of parameters associated with cultivation. Furthermore, the Internet of Things (IoT) has gained significant ground and shown its potential to assist and provide technological innovations in agriculture, revolutionising it.

In controlled environment production systems, another aspect to consider is the sources of energy integrated into the mushroom cultivation process since necessity to create an artificial environment with characteristics that align with the needs of mushrooms. In the article [15], renewable energy sources based on IoT systems are presented, contrasting with the use of energy from fossil or non-renewable sources. The innovation of energy sources, compared to conventional ones, ensures ecologically sustainable and economically viable production in the long term.

Regarding the reliability of data related to the cultivation process, significant advances have been made. Failures in the actuator or monitoring system, even for short periods, can alter the nutritional or sensory characteristics of mushrooms, leading to their loss of value for consumption. Data storage models such as MySQL and MongoDB are commonly used and ensure that information is not lost in case of failures in external communication to the system [16]. However, conventional databases alone do not guarantee the immutability of data after storage.

The motivation of this work addresses the need for integration between the phases of the mushroom cultivation process, such as IoT-based monitoring and control technologies, combined with a layer that ensures the reliability of data from the IoT system, using Blockchain to guarantee their immutability, covering the entire chain from cultivation to commercialisation. A system will be developed that collects and analyses production parameters, providing the producer with all the necessary information for a successful mushroom production. The Blockchain layer will be developed for data security, as well as the user interface for data visualisation.

The activities carried out in this work are part of the Safe2Taste project, a project funded by the Foundation for Science and Technology, where it is expected to obtain a system that improves production efficiency safely and sustainably through the development of cyber-physical systems.

II. Related work and cultivation models

Currently, several models of mushroom cultivation can be used whether for commercial or domestic cultivation, the most common being production in straw bales or wooden logs which requires a series of steps that must be followed from inoculation of the mycelia to harvesting.

For production in wooden trunks, it is necessary to ensure high internal humidity in the trunks as well as performing a mechanical shock after the inoculated mycelia. Conventionally, they are inoculated through holes made with specific spacings that guarantee that the inocula do not overlap. Once the inoculation has been carried out, the holes are covered with wooden dowels or beeswax as shown in Figure 1.

Fig. 1. Inoculation in Wood.

With regard to production in straw bales, inoculation is carried out directly into the bales without the need to cover the holes. However, it is extremely important that the bale is previously sterilized, thus ensuring that there will be no proliferation of unwanted fungi that could inhibit the growth of mushrooms. The cleaning and sterilization process commonly used is boiling where the straw is immersed in boiling water. After this stage, the bale is tied and can move on to the mycelium inoculation phase. Figure 2 shows straw bales for edible mushroom cultivation.

Fig. 2. Inoculation in Straw Bales.

These cultivation models are constantly subject to the actions of environmental variables even if carried out in a controlled conditions. Furthermore, it must be ensured that potentially competing species are not produced simultaneously since spores can be contaminating agents and are constantly dispersed in the air.

In the current days, it is possible to find systems that monitor temperature and humidity, in addition to controlling water spraying, regulating ambient humidity and changing the opacity of windows to adjust the entry of sunlight. Many of these systems are individually compatible with mobile applications or computers with closed protocols without allowing any type of change in the system's control variables. Therefore, it is difficult to parameterize new values based on each species to be produced. It should be noted that sometimes the integration between monitoring and actuators is done through adjacent modules that do not belong to the native system, causing incompatibility between protocols and being susceptible to failures.

The quality standards imposed by entities that use mushrooms, whether culinary, medicinal, among others, must be fullfiled. The guarantee of this quality comes from the safety of the cultivation system, thus creating the need to insert this layer of validation of data from the processes.

III. System Architecture

This section is intended to present the system architecture, listing the functionalities, necessary technologies and an overview of the entire traceability system. One of the concerns of this project is its scalability and ability to adapt to both low volume growers and high production turnover activities.

A. System Functional and Technological Requirements

The general concept of the project architecture is to build a monitoring network for parameters associated with the mushroom production process in a controlled system and generate a quality certificate called "Safe2Taste". The real-time flow of data collected by the IoT system, will be presented in a summarized and direct way in an user interface.

The system must have an interface with more technical characteristics across the entire chain. This inference will present the transaction indicators carried out by the blockchain upon each reception of data from each of the production batches as well as a recent history of each of the variables.

The main functionalities of the system are presented below:

1) **System Connection:** MQTT over Wi-Fi.
2) **Storage:** local: internal memory and cloud: MySQL table.
3) **System monitoring elements:** Temperature, Humidity, solar radiation, battery voltage, System connection quality.

B. Overall System Architecture

Figure 3 presents an overview of the system architecture illustrating all the components involved. The monitoring nodes (NODE) must be equipped with IoT technologies supporting wireless communication and capable of managing the acquisition of information from the array of sensors. These nodes are responsible for sending all information collected to an MQTT broker via WiFi connection, which in turn, is connected to a database. In the cloud, this data is processed, analyzed and encrypted by the block chain. In parallel to data processing, the user interface, presents the data received from each node as well as the quality indicator discussed previously.

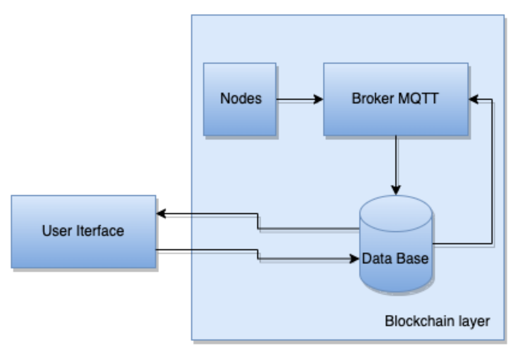


Fig. 3. System Architecture.

IV. Implementation and Preliminary Results

Having defined the system's functionalities, the implementation phase consists of choosing the sensors and microcontroller that will be embedded in the hardware of the monitoring nodes. The sensors must be compatible with the conditions they will be subjected to. Furthermore, the microcontroller to be used must be capable of supporting the connections required by the sensors as well as the desired communication protocols.

The chosen microcontroller was the WROOM-ESP32-S2 (ESP32 DATASHEET), which has built-in Wi-Fi connectivity, high-resolution A/D converter (Analog/Digital) as well as the possibility of Low-Power Mode configuration. The sensors used to monitor the parameters were SHT22 (SHT20 DATASHEET), low-cost sensor for monitoring ambient temperature and humidity that provides values on a 12-bit scale for humidity with a range of 0 to 100% and 14 bits for temperature with a range of -40 to 125ºC, considering a tolerance of 3% in readings, and the TLS2561 (TSL20 DATASHEET) to capture the light intensity of the visible spectrum, an easy-to-integrate sensor with 16-bit resolution, configurable and low power consumption.

A factor considered when choosing hardware components concerns, not only compliance with technical specifications but also the cost of the solution developed. The search for low-cost hardware allows the solution to have greater adoption since the cost associated with the service is relatively low when considered with competing solutions on the market. In this way, the system discussed and developed in this article is intended not only for small producers but also allows scalability and adaptation for commercial and large-scale productions since the cost associated with acquiring the components is considerably low, thus breaking the commercial barrier.

Figure 4 shows the structure of the developed hardware.

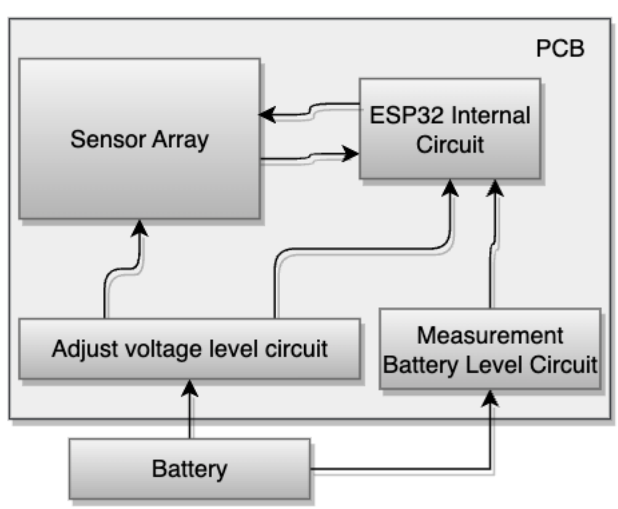


Fig. 4. Hardware Architecture.

Figure 5 shows the components that make up the data analysis, storage and block-chain layer as well as the connection to the user interface.

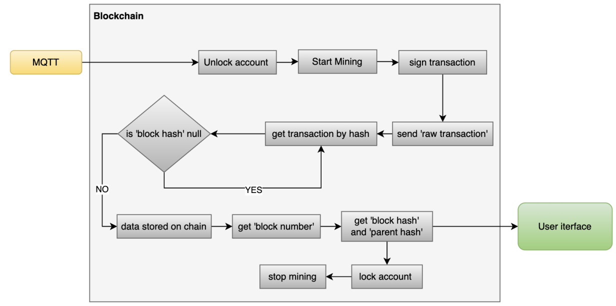


Fig. 5. Cloud Architecture.

A. Preliminary Results

Continuing with the implementation phase, the module-by-module development typology was adopted. This subsection is dedicated to describing the development process of modules and connection networks.

The development process ranges from the choice of components to be used, implementation of the user interface in accordance with ergonomic standards, conditions of use, to the mechanical characteristics and materials to be used in making the knots considering the production conditions to which the nodes will be subjected.

Figure 6 shows, on the left, the PCB layout project and on the right, the 3D view of the finished project. KiCAD software was used to develop the project. This process is crucial to check if all the hardware components can be connected and will be in the exact place as expected anticipating any schematic problems that may have occurred during the project's processing and in order to optimize the development of connections between components, mitigating electromagnetic incompatibilities and ensuring signal stability.

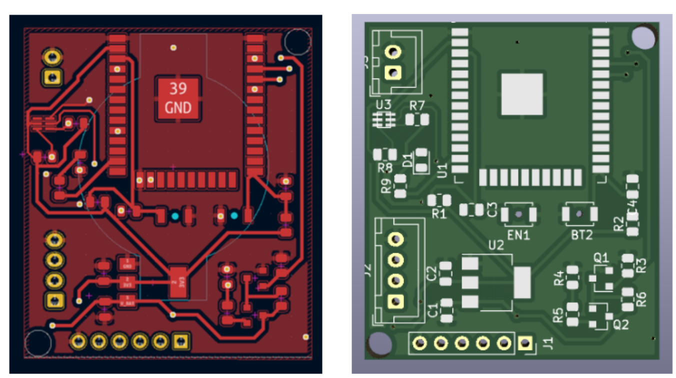


Fig. 6. PCB project design.

The project was prototyped in the laboratory and after checking all functionalities, a final version was produced and can be validated in a real cultivation system, applying the PCB to production conditions considered ideal for the productive processor of mushroom species such as shown in Figure 7.

With the Hardware validation completed, a box was designed using 3D modeling software to protect the PCB. This

Fig. 7. PCB final version.

protective box was built using a PLA 3D printer. The entire surface of the board was protected, with only the connectors for the SHT22 sensor and the battery connections showing. The final visual of the data collection nodes can be seen in Figure 8.

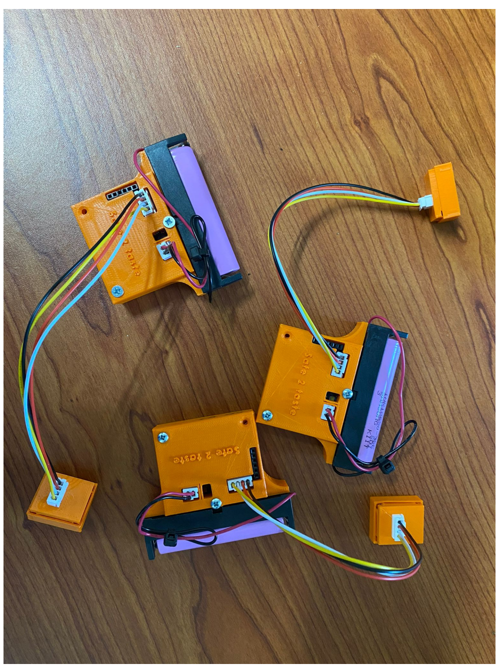


Fig. 8. Monitoring Node.

In parallel with the development of the hardware, the dashboard was implemented using the node-RED framework to visualize the data measured by the sensors. The interface provides the user with all the desired information in a connected and coherent way. The user interface is shown in Figure 9.

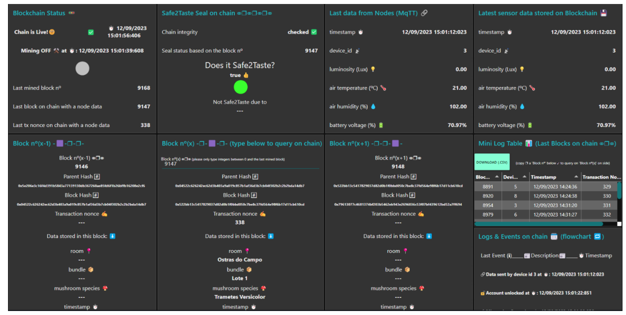


Fig. 9. User Interface.

The user interface represents the visualization of all variables involved in the process of collecting and processing information, this option makes it difficult to interpret the parameters. However, a dashboard has been developed where the user previously defines the parameters they wish to see and analyze, thus facilitating interpretation.

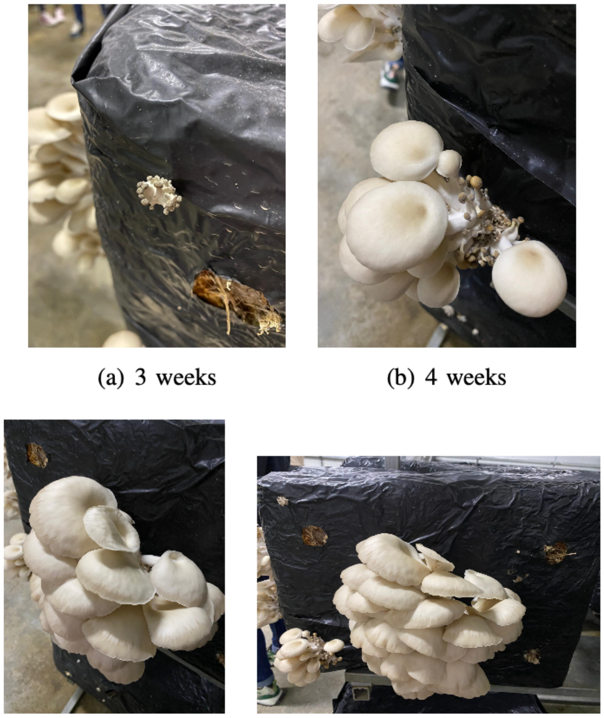
Once all laboratory tests were completed and validated, the process of system monitoring in a real environment began. The chosen location was the company *Ostras do Campo* located in the North of Portugal. This company produces several edible species of mushrooms using the methods presented in section II. In order to validate the functioning of the system and increase the flow of information collected, production was divided into small batches where each batch received a set of sensors as shown in Figure 8.

The batches inoculated on wooden logs intended for the case study are shown in the figure below. After inoculation, the trunks are wrapped in plastic to avoid contamination by other spores.

Fig. 10. Use case validation.

In addition, mycelia were also inoculated into straw bales, however, for these, the nodes were attached to the metal structure that holds the bales. With this, the wooden trunks with plastic a new controlled atmosphere was created.

After a period of data collection and analysis, it was possible to verify the evolutionary phases of the mushrooms as well as some interferences arising from the variation of the parameters involved during the vegetative growth process. The results obtained through inoculation in straw bales are presented in Figure 11 shown by months of cultivation.



(a) 3 weeks (b) 4 weeks

(c) 5 weeks (d) 6 weeks

Fig. 11. Mushroom growth.

V. Conclusions and Further Work

This paper presents the preliminary results obtained from the implementation of a monitoring system based on IoT technologies for the production of edible mushrooms. Two forms of inoculation were carried out for the same case study with the intention of establishing comparative parameters. However, only inoculation in straw bales demonstrated progress in fungal growth, with inoculation in wooden trunks not having the same success. However, it was possible to conclude about some interferences arising from failed monitoring or poor management of production parameters. By creating a private atmosphere by surrounding the wood with plastic, it was not possible to adjust the humidity levels in the lots, which ended up inhibiting the growth of fungi, unlike what happened with the straw bales that were exposed to control actions. It was also possible to validate the first layers of interaction with the blockchain in a superficial way.

As future work, it is necessary to test the immutability of data through database invasions with the intention of the blockchain alerting about attempts. It is also suggested to improve the choice of hardware and optimize the firmware in order to optimize the battery's useful life and establish a relationship between vegetative growth and data acquisition periods.

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