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RESEARCH ARTICLE

An Electronic Barrel Bung to Wirelessly Monitor the Biological Aging Process of Fino Sherry Wine

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ABSTRACT Wine aging is a fundamental stage in the creation of special high-quality wines, such as sherries and similar wines. To undergo the process of ''biological aging'', some of these wines are stored in oak casks for long periods. During this process, a thin layer of yeast is spontaneously formed on the surface of the wine. This layer protects the wine from oxidation and contributes to its unique organoleptic characteristics. This work presents the prototype of an instrumented bung capable of monitoring, in real-time, the absorbance evolution of the Fino Sherry wine during its biological aging process. The results of the tests carried out in the laboratory showed that the device can directly measure the absorbance at wavelengths of 420 nm and 520 nm, detecting small changes produced by the wine oxidation processes. This work has significant implications for winery technicians and oenologists as they could analyze the evolution of the wine in real time, detect problems in advance, and avoid work-related accidents. These conclusions solidify the enduring relevance of this research and offer a robust foundation for future developments in the field.

INDEX TERMS Fino sherry wine, biological aging, sensors, IoT.

I. INTRODUCTION

If a generic definition of the Internet of Things (IoT) is given, it could be a system in which physical devices, software, and networks are interconnected and connected to the Internet. These devices can communicate and share information to automatically perform tasks. This tool has become increasingly popular in recent years, owing to the rapid advancement of technology and its great capacity to connect with everything, opening up a wide range of possibilities [1]. Therefore, the first assessment that can be made is that the future of IoT is the transformation of real-world devices into virtual objects that are connected under the same infrastructure, providing not only control but also real-time information about them [2]. Considering the key pillar that IoT is becoming, it is estimated that by 2025, there will be 42 billion IoT devices [3]. According to [4], a brief presentation of the fields where IoT is most used is as follows: (1) manufacturing/industry, (2) transport/mobility, (3) energy, (4) retail, (5) smart cities, (6) healthcare, (7) supply chain, (8) agriculture and (9) buildings.

The implementation of IoT in agriculture has gained exponential interest in recent years [6], [7]. Indeed, the agricultural industry has become increasingly focused on data and data accuracy, becoming smarter than ever before, opening up countless new opportunities [8]. For example, research has been conducted along the lines of crop monitoring to assess crop health, using IoT technologies and artificial intelligence [9]. Another example is described in [10], where a collaborative safety model that aims to minimize safety risks in the agricultural industry is developed. Autonomous farming

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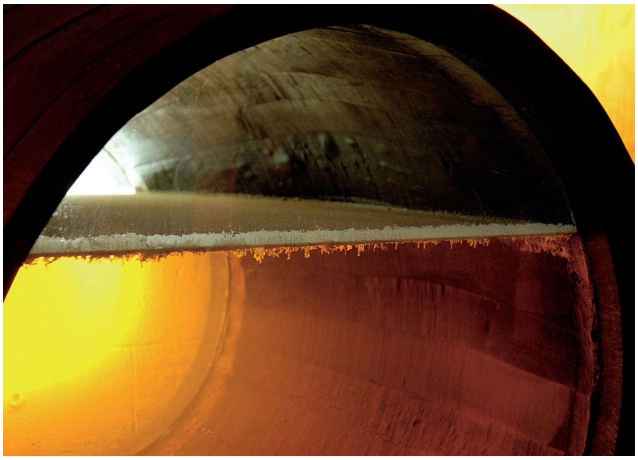


FIGURE 1. **Biological aging of Fino Sherry wine under a veil of flor yeasts [5].**

systems are also very attractive as they present a promising solution to the problem of increasing productivity and labor shortages [11]. In the subfield of agriculture, wine production has increased the adoption of IoT devices, especially in areas such as production and data management [12]. In this context, the advancement of innovative applications and devices grounded in IoT for monitoring and managing wine production systems unquestionably represents a pathway to achieving wines of superior quality while simultaneously minimizing production costs. As stated by the Spanish Wine Federation, the wine industry has a very important role in the economy [13].

Apart from red wines, a special type of white wine is produced in the south of Spain, known as "Fino Sherry wine", whose production process during the aging process is completely different from that of red wines. During the winemaking process, two main phases can be distinguished. In the first phase, the fermentation process occurs, where the sugars of the grape must be transformed into alcohol, glycerol, and carbon dioxide by fermentative yeasts present in the wine. After this phase, the wine with the best organoleptic characteristics undergoes a second phase of aging in the oak barrels. Unlike red wines, the aging process for this type of wine takes place under a layer of yeasts commonly known as "veil of flor" [14]. Figure 1 shows the veil of flor covering the surface of the wine, preventing oxidation. This type of aging process is known as biological aging [15], [16], [17], [18].

The biological aging of wines is a process used in the production of Fino Sherry type wine in five Protected Denomination of Origin (PDOs) in southern Spain, the Vin Jaune from the Jura (France), the Sardinia (Italy), Tokay (Hungary), California, South Africa, Australia and recently in China. Its control has aroused a growing interest worldwide for the special sensory characteristics it brings to wines. According to [19], the biological aging of wines is carried out by the so-called flor yeasts. These are Saccharomyces cerevisiae yeast strains that are present in the wine and when the alcoholic fermentation is finished and the wine has no fermentable sugars, they switch from a fermentative metabolism to an oxidative metabolism and spontaneously form a biofilm called "flor" on the free surface of the wine. Wine under "flor" is subjected to special conditions by the action of these yeasts and the reductive medium established, as they consume the oxygen dissolved in the wine and protect it from the oxidation process. The yeasts that grow under flor facilitate various transformations of its components that lead to the acquisition of the special sensory characteristics of Fino Sherry wines and Sherry-like wines. Fino Sherry is the best known type of biologically aged wine from Spain. It is obtained using the criaderas and solera system, which essentially involves the periodic homogenization of wines of different ages for several years (at least two years and some for seven or ten years). This process is complex and expensive, but it produces wines of consistent quality over time. It also renders the term "vintage" meaningless. The need to store these wines for long periods, their physical, chemical and microbiological analysis, and the maintenance operations involved, jointly with the need to maintain an effective yeast biofilm all add significantly to its price. Hence, there is interest in controlling the effect of yeast metabolism with a simple and inexpensive system, as described in this work.

Color is an important sensory property of any food, and the color of wine in particular is related to the grape variety, the type of wine, and the aging process it has undergone before being marketed. Traditionally, the measurement of absorbance at 280 nm in the ultraviolet range and 420, 520, and 620 nm in the visible range has been used as an index of total polyphenol content, brownish-yellow, reddish-yellow, and blue color compounds, respectively, in wines (OIV-MA-AS2-07B Chromatic characteristics) [20]. Measurements of absorbance at 420 and 520 nm, in the visible region of the light spectrum, have been used as a measure of the degree of browning of white wines. Studies carried out by [21], [22] [23], and [24] on white wines subjected to biological aging, show how the units of absorbance (AU) measured at 420 nm in white wines increase over two years from initial values of 0.138 to final values between 0.164 and 0.144 AU, while the same wines not subjected to this type of aging show 0.330 AU at the end of this period. Absorbance measurements at 520 nm increase from initial values of 0.035 AU to 0.085 AU in white wines not subjected to biological aging and remain constant or decrease to values of 0.020 in wines subjected to this process. In this regard, some researchers, such as [17], use the absorbance at 470 nm as a measure of the evolution of color in wines subjected to biological aging, since this wavelength reflects the yellow-golden-amber tones acquired by wines during aging.

The main objective of this study was to develop a device to wirelessly monitor in real time the changes in the aforementioned absorbances during the biological aging process.

Furthermore, although it is not the aim of this work, the presented device could easily measure chromatic characteristics such as the color intensity (CI) and hue (T) through Equations 1 and 2:

$$I_C = (A_{420} + A_{520})/b \tag{1}$$

where b is length of light path.

$$T = A_{420}/A_{520} \tag{2}$$

This paper presents an accessible and low-impact device that allows for accurate and adequate measurement of the wine aging process. This device is easy to implement as it does not require invasive procedures that may alter the integrity or quality of the final product.

It is important to emphasize that this work makes a significant contribution to the field of precision oenology. It provides the following innovations and improvements in the wine industry:

- It is the first prototype presented capable of monitoring the evolution of biological aging in real-time.
- The prototype helps to minimize the number of samples that need to be removed from the barrel for laboratory analysis. This approach aids in reducing costs and microbial contamination risks.
- The prototype can help to prevent workplace accidents, such as serious falls, especially when handling the bungs on barrels placed in the upper row.
- The prototype can assist in the early detection of anomalous developments of biological aging.
- The work opens up a new field of research in the area of precision oenology.

The following sections of this paper describe the architecture of the system and its feasibility based on a study of a real case. In Section II, the related work is discussed. Section III describes the most relevant hardware components for assembling the system. The design and implementation of the device are presented in Section IV. Section V describes the software platform on which data obtained by the IoT device are uploaded. In Section VI, the results and the evaluation of the system are provided. Section VII discusses the results of this work in relation to those reviewed. Finally, conclusions and future work are presented in Section VIII.

II. RELATED WORK

Recent advances in the Internet of Things [25], [26] have led to its use in various applications such as agriculture, industrialization, and health [27], [28], [29]. In particular, the trend towards monitoring winemaking processes is increasing because it helps to achieve a higher quality product.

As an example, to monitor the evolution of alcoholic fermentation, an IoT system based on carbon dioxide (CO_2) sensors was proposed in [30], which allows real-time access to the measured data wirelessly. Following the same line in [31], winemakers monitor the fermentation process in real time through the data (temperature, alcohol, carbon dioxide, and acidity) that are sent wirelessly to a server. A similar approach was proposed in [32], but the authors used a Bluetooth connection as the transmission method. A novel system architecture and HTTP communication mechanism called Smart Barrel System (Wine-SBS) was presented in [33] to monitor different parameters of the fermentation of the Debina variety of semi-sparkling wine. To monitor wine fermentation during the vinification process, another IoT-based measurement system was proposed in [34]. Inside the tanks where fermentation occurs, a network of sensorized buoys is placed to share the measured data (wine pH, liquid level, and temperature) to a cloud web platform. In [35], the authors presented two algorithms for an electronic nose capable of simultaneously detecting the following properties: (a) wine region, (b) grape variety, (c) vintage, and (d) fermentation process. The results showed high performance in the detection of these four parameters.

Several IoT systems have also been developed to address aging. In [36], the authors proposed a system for monitoring the aging process of tawny port wine. This solution has the disadvantage of using certified sensors with high costs and wired connections. Another wireless monitoring system for the aging process is described in [37], which uses Arduino-based technology and includes a series of sensors integrated into the cask bung to measure wine parameters such as pH and temperature. In [38] a low-cost and low-power wireless sensor that allows simultaneous monitoring of the temperature and ullage of wine was designed. The sensor is embedded in the cask bung and powered by batteries that have a lifetime of 12 months. The software was also designed to allow remote transmission and easy visualization of data and to enable warning signals. Another IoT monitoring system for vineyards and wineries that uses ZigBee and GPRS for wireless communication was described in [39]. The vineyard in question can acquire meteorological data, whereas the sensors acquire data such as temperature, humidity, and soil conditions.

For the particular case of biological aging in [40], an intelligent bung has been developed that enables a real-time monitoring system to evaluate the state of the cask and to control the ullage of wine in casks. An improved proposal of this work is presented in [41] where this advanced prototype achieves significant improvements such as the use of WiFi as a communication technology instead of ZigBee technology, testing under real conditions for a longer period of five months, and a much more efficient energy-saving system that allows it to work autonomously for more than a year, among others.

Additionally, in [42], authors utilize a microphone to determine when a barrel of red wine is not full during the aging process. The audio signals captured by the microphone, which is placed on the surface of the barrel, are processed using the Fourier Transform to analyze the resonance of the barrel when it is tapped. The authors of this work claim to be able to determine whether the wine level in the barrel has decreased by using a non-invasive system.

In another study [43], the chemical composition of three varieties of five-year-aged Fino Sherry wine, fermented with *Saccharomyces cerevisiae raza capensis* yeast was examined. This study also included "oloroso" and "amontillado" wines. Using a Beckman Spectrophotometer, absorbances at 420 and 520 nm were measured. The findings suggest that Fino Sherry wines, which undergo non-oxidative aging, exhibit low light absorption at 420 nm, indicating the influence of flor yeasts on the formation of color-affecting compounds during aging.

Conversely, the study in [44] explored accelerated oxidation in Fino Sherry wine samples to determine the effects of temperature and UV radiation, contingent upon the bottle type. Both transparent and topaz bottles, characterized by low transmittance levels, were used in this experiment. The factors "temperature", "radiation", and "time" demonstrated significant effects on both the absorbance at 420 nm and the concentration of most polyphenolic and volatile compounds. However, the "bottle" factor was only significant in relation to polyphenol content. The Unicam spectrophotometer model PU8730 was employed in their analysis.

Other studies have focused on controlling and monitoring wine color to obtain high-quality wine. For instance, in [45] a novel colorimetric method was developed for monitoring the browning process in sparkling wines. It uses color measurements from digital images obtained using a smartphone camera and diffuse light source as an acquisition device. Experimental tests were conducted during an accelerated browning process of four sparkling Cava wines. The results showed that while the Red and Green channels remained almost constant, the browning process primarily affected the blue channel, demonstrating a linear dependence between blue channel values and time. In [46] a novel colorimeter was developed based on the measurement of the three channels of the RGB color space using bifurcated optical fibers. Experimental tests using several wines were developed and compared with commercial equipment (based on spectrometry techniques), and an excellent correlation between the results of both systems was achieved. The results showed that the colorimeter can be used to obtain color differences between wines of the same type. Another RGBC optical sensor was developed in [47] to measure color intensity. To study the effects of several variables on the sensor response, the sensor was tested in real environments using 91 samples, and the following parameters were recorded: sampling day, grape variety, temperature, degree of alcohol, glass window, pH, color intensity, and shade. The small sensor size and its easy coupling to an industrial glass window (it can be placed in all winemaking stages) make it easy to use and manage, and is cheaper than conventional spectrophotometer-based analysis. The primary distinctions between the last two referenced systems and our proposal are: (1) they use optical RGB sensors that can only detect color, whereas our proposal measures using the same techniques employed in wine laboratories, which is measuring the absorbance of wavelengths sensitive to white wine, and (2) the described proposals are focused on monitoring red wine, while our proposal is centered on monitoring white Fino Sherry wine, where, as mentioned before, a special biological aging process occurs under the veil of flor.

Finally, in [48], an optoelectronic system based on absorbance measurements was designed to monitor the chromatic characteristics of red wines. The developed system also allows monitoring of the gradual maceration of fermented grape musts. Successful results were obtained after comparing the measurements achieved with the developed prototype and those obtained using a spectrophotometer.

Table 1 shows a comparison of the measured parameters and other relevant aspects derived from the reviewed works. In addition, the technical characteristics of each study are also presented in Table 2.

To the best of our knowledge, this work presents the first IoT device capable of analyzing the evolution of wine aging through in situ absorbance measurements at wavelengths of 420 nm and 520 nm. To achieve this, a conventional wooden barrel bung was been replaced with an instrumented IoT bung.

III. MATERIALS: HARDWARE COMPONENTS

All of the most relevant hardware components used to assemble the IoT plug are briefly described in this section.

- **Microcontroller**. ESP32 is a low-cost, low-power microcontroller that combines a dual-core Tensilica Xtensa LX6 processor, Wi-Fi, Bluetooth, and a wide variety of peripherals on a single chip. Its versatility, processing power, and connectivity capabilities make it a popular choice for Internet of Things (IoT) development projects.
- **LEDs**. Two LEDs with wavelengths of 420 (violet) nm and 520 nm (green) were used. The emission angle of the LEDs was 20º. Laser emitters could have been used, but they were much more expensive, and one of the aims of the project was to obtain a low-cost device.
- **LDR**. Two Light-Dependent Resistors (LDRs) were used as light detectors. An LDR is a special type of resistor that can change its value according to the intensity of the light received on its surface. This value can be measured by a microcontroller using a conditioning circuit capable of transforming the resistance level into voltage. Furthermore, compared to other light-sensitive devices, such as photodiodes or phototransistors, LDRs have a much lower cost, which is very important for the device presented in this work.
- **Transistor**. BC547C is a general-purpose NPN transistor widely used in low-power applications. They are commonly used in signal amplification, low-power switching, and control applications.
- **Battery**. The prototype was powered by a pack of two 18650 3.7 V batteries, which were regulated with an LM7805 regulator.

TABLE 1. Summary of the work described based on oenological characteristics.

Ref.	Type of wine	Oenological parameter	Technique	Physical parameter
[31]	Red and white wine	CO_2	Electrochemical	Infrared absorption
[32]	Not Specified	Fermentation process	Electrochemical	Temperature, alcohol, carbon dioxide, and acidity (pH)
[33]	Red wine	Temperature	Optical	Temperature (^{O}C)
[34]	Debina Variety Semi-Sparkling	Fermentation process	Optical and electrochemical	Temperature (^{O}C), pressure, alcohol proportion (ppm), color, transparency and pH (ppm)
[35]	Red wine	Ullage and fermentation	Optical and electrochemical	pH, liquid level (m) and temperature (^{O}C)
[36]	14 kind of wines	Wine region, grape variety, vintage, and fermentation processes	Electrochemical	Electrical conductivity due to volatile molecules
[37]	Tawny Port	Temperature, pH, dissolved oxygen and redox potential	Electrochemical	Temperature (^{O}C), pH, redox potential (mV), oxygen concentration (mg/L)
[38]	Not Specified	Temperature and pH	Electrochemical	Temperature (^{O}C) and pH
[39]	Red wine	Oxygen	Optical	Near infrared absorption
[40]	Not Specified	Fermentation status	Electrochemical	Temperature, humidity and soil conditions
[41]	Fino Sherry wine	Structural health of the barrel	Optical and electrochemical	Ullage (cm), humidity (%), temperature (^{O}C) and light intensity (%)
[42]	Environmental and ullage	Fino and Amontillado wines	Optical and electrochemical	Temperature (^{O}C), humidity (%), atmospheric pressure (hPa) and ullage (mm)
[43]	Red wine	Variations in wine volume inside barrels	Optical	Frequency (Hz)
[44]	Fino, amontillado and oloroso wines	Phenolic compounds and browning	Chromatographic	Color
[45]	Fino Sherry wine	Polyphenolic and volatile content	Chromatographic	Polyphenolic and volatile compounds and 420 nm absorption
[46]	Cava wine	Browning process	Optical and chromatographic	Colourimetric quantification RGB
[47]	Red, rosé and white	Type of wine	Optical	Colorimetric quantification
[48]	Red wine	Color intensity	Optical	Colorimetric quantification
[49]	Red wine	Intensity, brightness and hue	Optical	Absorbance at 420 nm, 520 nm, 620 nm
Proposal	Fino Sherry wine	Aging process evolution of Fino Sherry wine	Optical	Absorbance at 420 nm and 520 nm

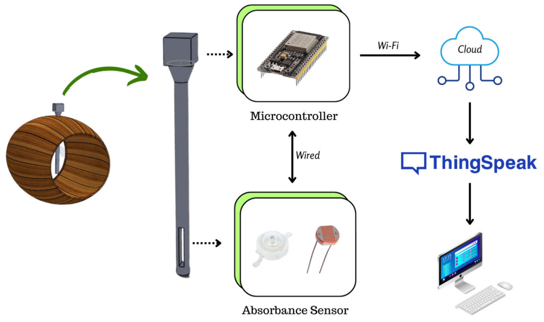


FIGURE 2. System Architecture.

IV. IOT BUNG: DESIGN AND IMPLEMENTATION

In this section, all parts that constitute the entire IoT system and the interconnections between them are presented. As shown in Figure 2, the system consists of an electronic bung whose casing allows the sensors to be introduced inside the wine. Sensors installed at the tip of custom bung will be able to analyze the evolution of wine aging using LEDs and LDRs. Furthermore, the parameters obtained will be sent wirelessly to an IoT software platform (ThingSpeak), which will allow winery technicians to see the evolution of these parameters in real time and from anywhere via computers, tablets, or smartphones.

A. ELECTRONIC BUNG

This section elucidates the comprehensive design of the electronic IoT bung. Figure 3 provides an illustrative depiction of the device architecture, specifically from an electronic perspective. The diagram shows the ESP32 board, which is the primary component of the system. Additionally, a voltage regulator is incorporated to provide the requisite 5 V power supply to certain components. It has a button to assist with the calibration process. Finally, the system integrates two custom absorbance sensors: an LED emitter and LDR.

Subsequently, the IoT bung is explicated through four major parts: (1) housing, (2) sensing system, (3) powering system, and (4) firmware. Each of these constituents is meticulously expounded in the ensuing sections.

B. 3D DESIGN OF THE HOUSING

Structurally, the device was divided into two parts. One part acts as a bung for the wine barrel, and it contains and protects the electronic device (see the upper part of Figure 4a), and the second part consists of a hollow longitudinal tube where the sensors responsible for measuring the evolution of the wine aging color are installed at the end (see Figure 4b). As shown in this figure, at the end of the tube, there is a hole through which the wine passes through the beam of light emitted by the diodes installed on one side. The LDRs used to measure the level of light detected were installed on the front side.

This tube must be sufficiently long for the optoelectronic components (sensors) to be in continuous contact with the wine. As explained above, in biologically aged wines, there is an air chamber between the bung and the wine protected by a velum formed by flor yeasts, which means that in these wines the bung must be large enough to contact the sensors

TABLE 2. **Summary of the work described according to technological characteristics.**

Work	Sensor / Technique	Autonomy	Communication	Data processing
[31]	SEN-0219 CO$_2$ sensor	Not Specified	WiFi (ThingSpeak)	Arduino UNO and ESP8266
[32]	Temperature, wine acidity (pH), alcohol and carbon dioxide released gases sensors	Not Specified	Ethernet and USB	PIC16F877A microcontroller
[33]	LM35DZ temperature sensor	At least two weeks	Bluetooth	MSP430G2553
[34]	Vernier sensor photogate (SEN-12786), alcohol GAS sensor (MQ-3, SEN-08880), temperature sensor (DS18B20), RGB sensor (TCS34725) and Vernier pH sensor (SEN-12872)	Not Specified	HTTP communication	Arduino UNO, Raspberry Pi A and ESP8266
[35]	HI2031 pH-meter, NTC $10k\Omega$ temperature sensor and MB7076 liquid level	At least 16 days	WiFi	Arduino UNO y Raspberry Pi 3
[36]	Electronic nose (six metal oxide semiconductor sensors)	Not Specified	RS485 industrial network	Convolutional Neural Network and MBPNN
[37]	PHEHT and O$_2$ sensors	At least 228 days	RS-485 industrial network and WiFi	Raspberry 2
[38]	DS18B20 temperature sensor and pH sensor	130 days	USB, radio and WiFi	Arduino Mini Pro y Raspberry Pi
[39]	Infrared distance sensor (GP2Y0A41SK0F) and temperature sensor (DS18B20)	one year	Radio and WiFi	Moteino (ATMega328) and FriendlyARM Mini210s
[40]	MCP9700 temperature sensor, HIH-5030 humidity sensor, THERM200 soil temperature sensor probe, EC-5 soil water content, Em50 leaf wetness dielectric sensor, Ecomatik diameter dendrometer DD-S and Vantage Pro2 Plus weather station	At least two months	Radio (ZigBee), M2M communications and WiFi	TSmarT IoT platform
[41]	Ultrasonic distance sensor (SRF08), a humidity, light and temperature sensor (SHT15)	At least 19 days	Radio (ZigBee) and WiFi	Arduino Mega and Raspberry Pi 3
[42]	Ultrasonic sensor (MB1604) and temperature, humidity and pressure sensor (BME280)	Over one year	WiFi (ThingSpeak)	ESP32
[43]	Audio sensor (Iduino)	About five years	LoRa and WiFi	STM32 Nucleo board and Raspberry Pi
[44]	High-Performance Liquid Chromatography (HPLC)	Not Applicable	Manually	Not Applicable
[45]	HPLC and Gas Chromatography (GC)	Not Applicable	Manually	Statgraphics Statistical Computer Package
[46]	Smartphone (Apple iPhone 4S)	Not Applicable	Manually	Shimadzu UV-3600 spectrophotometer and LaChrom WWR-Hitachi liquid chromatograph
[47]	RGB Sensor	Not Applicable	USB and optical fiber	Computer and spectrometer
[48]	TCS3472 RGBC sensor	Not Specified	USB	ATMEL-ATMEGA 32UA and Statgraphics Centurion XVI program
[49]	OPT301 and SFH213 photodiodes	Not Applicable	Manually	NI USB-6211
Proposal	Light Dependent Resistor (LDR)	About 2-3 years	WiFi (ThingSpeak)	ESP32

with the wine. At this stage, it is crucial to emphasize that the progress in technology and the development of 3D printing materials have made it feasible to 3D print the design depicted in Figure 4 using food-safe materials.

C. POWER ENERGY SUBSYSTEM

To power all components of the system, a set of two 18650 3.7 V batteries, connected in series providing 7.4 V, was used. This battery pack was connected to an LM7805 regulator, which provided an output voltage of 5 V and up to 1 A (see Figure 5). This regulated voltage was used to power the LEDs and the ESP32 board through its external power supply pin, labeled as V_{IN} or 5 V.V_{IN} is used to regulate the input voltage from 5 V to 3.3 V via the internal linear regulator AMS1117, which is already on the ESP32 board. This component is fundamental because the microcontroller operates at 3.3 V, which is the voltage supplied to the rest of the pins. In addition, the AMS1117 protects the electronic components of the board against voltage fluctuations, thus avoiding possible overheating.

On the other hand, the 3.3 V pin provided by the ESP32 is used to power the light detector circuit and the high logic level of the push button which is used for the calibration process. The LM7805 regulator was fitted with the components specified in its datasheet.

D. SENSOR SUBSYSTEM

The subsystem responsible for measuring the wine aging evolution is composed of two circuits: (1) a light-emitting circuit and (2) a light receiver circuit. The first circuit emits light at a wavelength sensitive to the wine (wine absorbs part of the light) and the second circuit captures light that the wine has not absorbed. Therefore, the detection system measures the proportion of light passing through the wine sample. This parameter is known as “absorbance” and will vary as the color of the wine evolves.

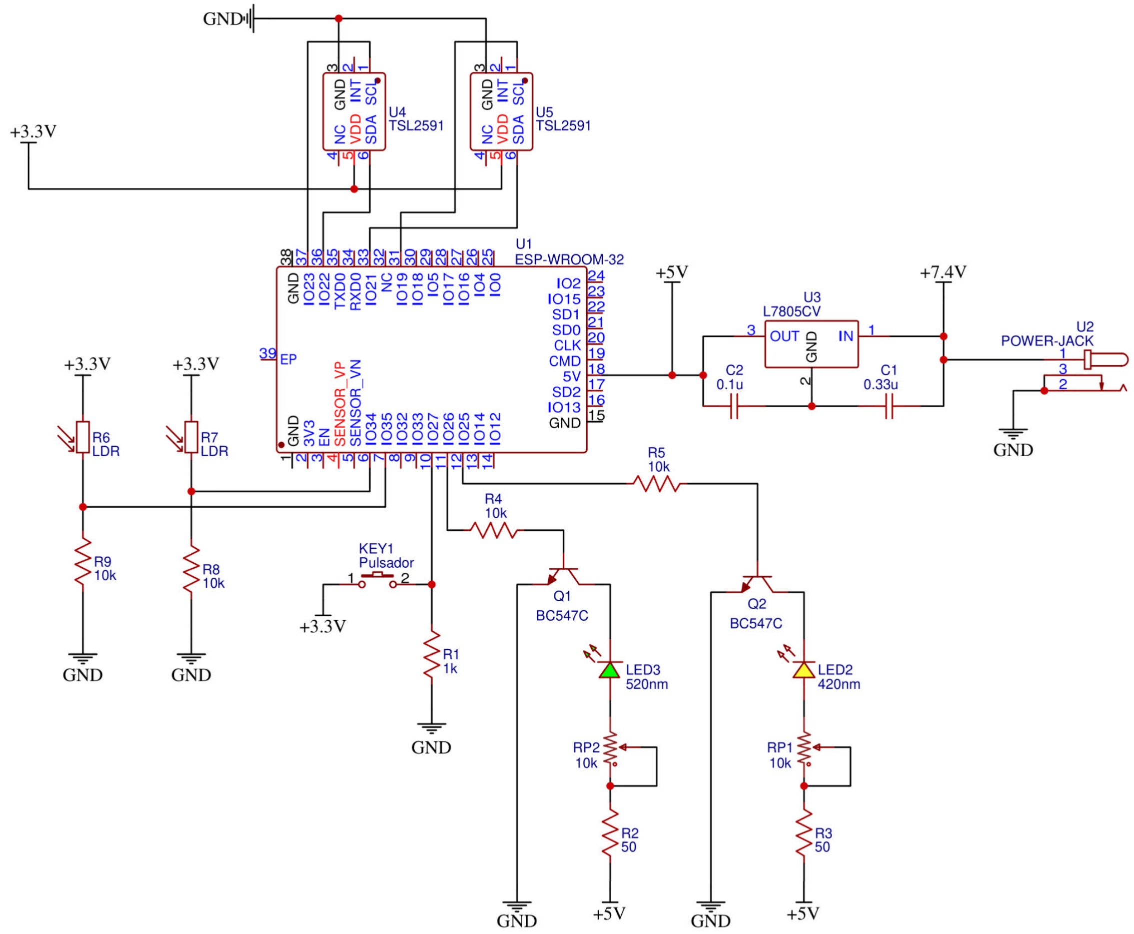


FIGURE 3. Electric Schematic.

Equation 3 shows the formula to calculate the absorbance.

$$A = -\log_{10} \frac{I}{I_o} \tag{3}$$

where A is the absorbance (it is a pure number; there are no units), I is the transmittance of the wine and Io is the transmittance of distilled water (reference value).

Figure 6 shows the tube inserted into the wine. The end contained a rectangular hole with a wall-to-wall distance of 1 cm. The light emitters and receivers are positioned behind each wall such that they face each other.

In the following, the circuits that comprise the absorbance sensor (light emitter and receiver) are explained.

E. LIGHT RECEIVING CIRCUIT

To study the response of the LDR to luminous stimulus, a voltage divider powered by 3.3 V, consisting of a resistor of 10 kΩ and a LDR was used. The voltage divider design causes the output voltage to increase as the light intensity increases, as described in Equation 4.

$$V_{OUT} = \frac{10\,\mathrm{k}\Omega}{10\,\mathrm{k}\Omega + R_{LDR}} \times V_{IN} \tag{4}$$

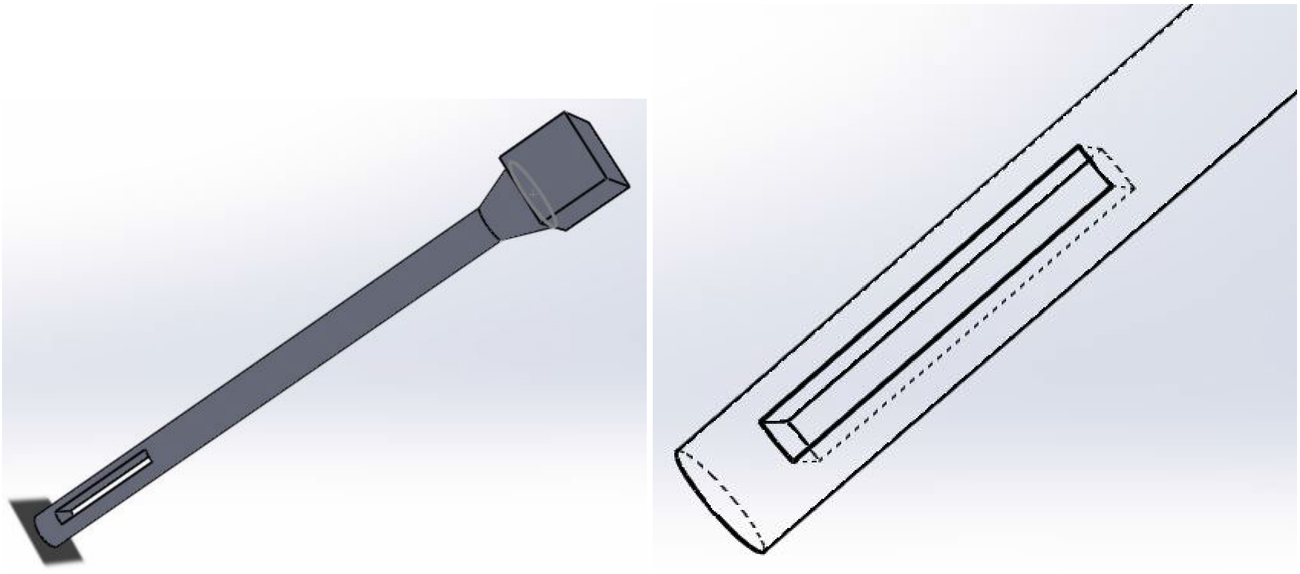
The ESP32 microcontroller acquired these voltages through the GPIO pins (34 and 35). It is important to transform the resistance values of the LDR into voltage values, as these can be read by the microcontroller. The ESP32 is equipped with a 10-bit analog-to-digital converter (ADC), which allows it to represent analog signals with a resolution of 2^{10}, or 1024 discrete levels (from 0 to 4095). Thus, the voltage range from 0 to 3.3 V was mapped into this digital range. With the ADC values obtained, an algorithm transforms these data into voltages ($Vout$) using the established relationship.

R_{LDR} is calculated using Equation 5, which describes the typical relationship between the light intensity, measured in lux, and LDRs. This equation has been widely used in the literature for studies using LDRs, as seen in [49], [50], [51], [52], [53], and [54].

$$R_{LDR} = \frac{500}{\mathrm{Lux}} \tag{5}$$

F. LIGHT EMITTING CIRCUIT

This circuit consists of two LEDs (420 nm and 520 nm) powered by a regulated 5 V supply (see Figure 7). Controlling



(a) (b)

FIGURE 4. Housing details. (a) It shows the entire housing. The top part of the housing protects the electronic device and functions as a bung for the barrel, while the bottom part contains the sensors. This part will be immersed in the wine. (b) It shows the bottom part in more detail.

TABLE 3. Calibration data for optimal energy consumption and lux levels at 420 nm and 520 nm wavelengths.

420 nm					520 nm				
Rc (K)	Vd (V)	Ic (mA)	ADC	Lux (lx)	Rc (K)	Vd (V)	Ic (mA)	ADC	Lux (lx)
0.2	3.08	8.6	3818	686	8.6	2.23	0.30	3808	661
0.4	3.03	4.43	3713	484	8.8	2.22	0.29	3790	619
0.6	3.00	3.00	3623	382	9	2.22	0.29	3765	568
0.8	2.98	2.28	3533	313	9.2	2.22	0.28	3723	499
1.0	2.97	1.83	3447	265	9.4	2.22	0.27	3676	437
1.2	2.96	1.53	3353	225	9.6	2.21	0.27	3674	435

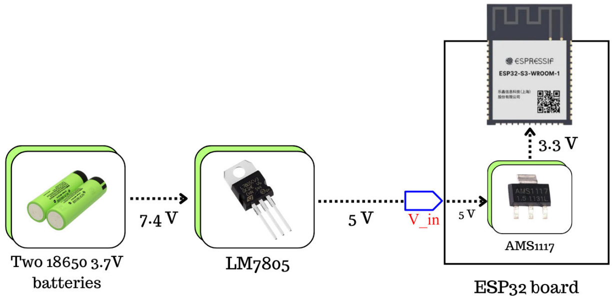


FIGURE 5. Power energy diagram for electronic hardware operation.

FIGURE 6. Housing zone designated for absorbance sensor placement.

the illumination level of each LED is crucial to achieve correct measurements. Excessively high intensity can lead to signal saturation during readings, while a low level of intensity can lead to the detection of the same level of signal regardless of the level of darkness reached by the wine. Therefore, to calibrate the required luminous flux emitted by the LED, an ensuing experimental procedure was conducted. A volumetric specimen of distilled water, confined within a cuvette of standardized width (1 cm), was strategically positioned intermediate to the emitting diode and the LDR. After that, the modulation of different level intensities was orchestrated via the utilization of a potentiometer, denoted as Rc. The aim was to find a trade-off between power

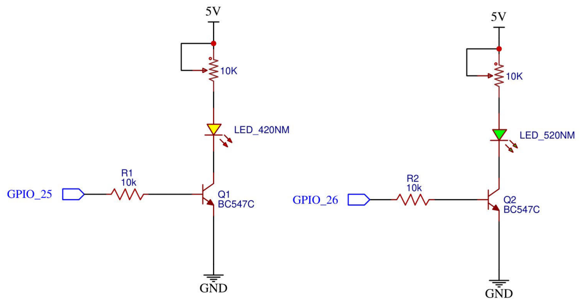


FIGURE 7. **Circuit design for light emission at 420 nm and 520 nm wavelengths.**

consumption required by the emitting LED, and an acceptable level of lux received by the LDR. Table 3 shows the relationship these values for the diodes 420 nm and 520 nm. The values in the first row correspond to the maximum level of lux tolerated by the LDRs, which are associated with 3818 and 3808 ADC values, respectively. From the table, it can be concluded that the appropriate Rc values for the 420 nm and 520 nm light emitters are 200 Ω and 8.6 kΩ. If smaller resistor values were used, the values provided by the ADC would be greater than 4095, and therefore, the signal would saturate. Values lower than 200 Ω and 8.6 kΩ would cause the device to consume less power, but it should be noted that the emitting diodes will not always be on but will only be activated for measurement purposes. Therefore, it is preferable to select resistance values that provide the allowed maximum lux values.

According to the electrical features of the light-emitting LEDs (P = 80 mW, $V_{D(420)}$ = 3 V, $V_{D(520)}$ = 2.2 V), the level of intensities established to turn on them are safe as they are lower than 25 mA.

As mentioned before and indicated in Figure 7, the ON/OFF control of the LEDs is managed via two GPIOs pins (25 and 26) of the microcontroller, which are connected to the base of a bipolar junction transistor (BJT) through an R_B resistor. Therefore, once the appropriate R_C value has been established, it is necessary to calculate the value of R_B to bias the transistor in the saturation or cut-off mode correctly. In other words, the transistor behaves like a switch so that when the pins are set to a low value (0 V) the transistor limits the current flow and the LED turns off. In contrast, when the pin is set to a high value (3.3 V) the transistor will let the current flow (from the collector to the emitter) and the LED turns on.

To obtain the R_B value that allows us to set the transistor in saturation mode, the condition indicated in Equation 6 must be satisfied. Therefore, the R_B value can be obtained by substituting the values I_B and I_C obtained from Equations 7 and 8, respectively, into Equation 6.

$$I_B \times hFE > I_{C(SAT)} \tag{6}$$

$$3.3\,\text{V} = I_B \times R_{B(520\,\text{nm})} + V_{BE}$$

$$I_B = \frac{2.6}{R_{B(420\,\text{nm})}} \tag{7}$$

$$5\,\text{V} = I_C \times R_C + V_D + V_{CE}$$

$$I_C = \frac{5\,\text{V} - V_D - V_{CE}}{R_C} \tag{8}$$

By substituting the values of I_B and I_C into Equation 6, it is obtained that $R_{B(420\,\text{nm})} < 33.25\,\text{k}\Omega$ and $R_{B(520\,\text{nm})} < 953.33\,\text{k}\Omega$. The procedure used to obtain these results can be appreciated in the development of Equations 9 and 10.

$$\begin{aligned} I_{B(420\,\text{nm})} \times hFE &> I_{C(420\,\text{nm})} \\ \frac{2.6}{R_{B(420\,\text{nm})}} \times 110 &> 8.6\,\text{mA} \\ R_{B(420\,\text{nm})} &< \frac{286\,\text{V}}{8.6\,\text{mA}} \\ R_{B(420\,\text{nm})} &< 33.25\,\text{k}\Omega \end{aligned} \tag{9}$$

$$\begin{aligned} I_{B(520\,\text{nm})} \times hFE &> I_{C(520\,\text{nm})} \\ \frac{2.6}{R_{B(520\,\text{nm})}} \times 110 &> 0.3\,\text{mA} \\ R_{B(520\,\text{nm})} &< \frac{286\,\text{V}}{0.3\,\text{mA}} \\ R_{B(520\,\text{nm})} &< 953.33\,\text{k}\Omega \end{aligned} \tag{10}$$

Previous calculations indicate that an R_B of 10 kΩ is enough to bias the transistors that control both LEDs in the saturation zone (switch closed).

G. DEVICE FIRMWARE

At the software level, the control logic is simple and follows the following process:

1) Wake up the system.
2) Perform sensor reading. The system performs seven readings to apply a median filter.
3) Calculate absorbance.
4) Send results to a server (ThingSpeak). This is described in detail in Section V.

The above process can be executed in two ways: manually via a push button and automatically and periodically. Manual execution is designed to calibrate the system, and it is triggered by a button connected to pin 27 of the microcontroller. The calibration process must be performed to obtain the I_o value of Equation 3 using distilled water instead of wine. On the other hand, once the system starts running and detects that it has a recent calibration, it starts to obtain absorbance values at a given frequency. In the test phase, the sampling period was set to 60 seconds; however, in the final deployment, the sampling process could be set to once per day to save energy and, therefore, give the device more autonomy.

H. FINAL PROTOTYPE

Figure 8 shows the final version of the prototype. Figure 8a shows the electronic part that would enter the IoT bung, which would be placed in the wine barrel. On the other hand, Figure 8b shows the bung connected to the tube

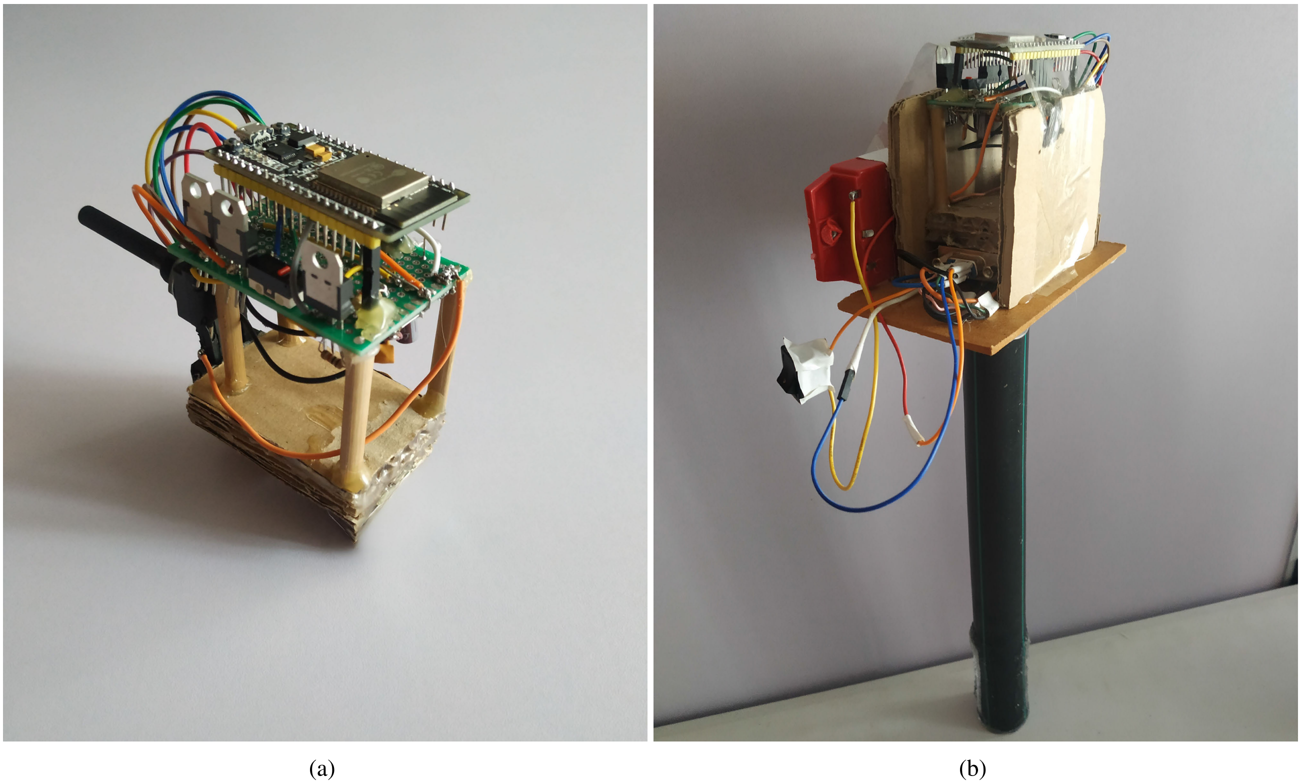

(a) (b)

FIGURE 8. Final prototype.

where the absorbance sensors would be placed. As previously stated, since this tube comes into direct contact with wine, it is essential to consider using stainless steel or a 3D printing material that is food-grade compatible for future development.

V. IOT CLOUD PLATFORM

The objective of this study was to supervise wine aging. To carry out this procedure, hardware design is as important as the acquisition of data and its study. Data obtained from the system must be shown to wine specialists for control and supervision. With the idea of providing more versatility and flexibility to specialists, these data can be saved on a cloud platform. For this study, the ThingSpeak [55] IoT Cloud Platform has been selected based on the following criteria: the API offered by ThingSpeak allows easy integration, enables online and graphical visualization of the sent data, and the free version allows sending data to the cloud every 15 seconds, which is more than sufficient for our device. ThingSpeak defines itself as "an IoT analytic platform service that allows you to aggregate, visualize, and analyze live data streams in the cloud". ThingSpeak provides an API to set up channels to save and share data using HTTP and MQTT communication protocols; therefore, a wide range of devices and software can be used. Moreover, it permits the exportation of data in JSON, CSV, and XML formats to facilitate integration with external services.

To upload the measurements obtained by the IoT bung to the ThingSpeak platform, four channels were created: "channel1" for absorbance at 420 nm wavelength, "channel2" for absorbance at 520 nm wavelength, " channel3" for ADC values obtained from LDR_{420} and "channel4" for ADC values obtained from LDR_{520}. Through the ThingSpeak platform, specialists can consult information uploaded to these channels online and from anywhere.

VI. EVALUATION AND RESULTS

A. TESTING METHODOLOGY

To test the correct functioning and viability of the device, a test protocol was designed based on the oxygenation of the wine. As wine is oxygenated, the browning of wine occurs. In other words, its color evolves towards darker shades (see Figure 9); therefore, the absorbance obtained by the device should increase.

The test methodology consisted of two phases. In the first phase, the device was placed in a container with distilled water to obtain the reference value or calibration value against which future measurements would be compared. In the second phase, the tests were performed using two different types of wine. The tests consisted of filling a container with the wine to be tested and gradually oxygenating it with 5% hydrogen peroxide using a pipette to simulate its oxidation (aging process).

To avoid contamination from ambient light, all the tests were conducted in a completely dark environment.

FIGURE 9. Unoxidized wine (left) vs. Oxidized wine (right).

B. ADDRESSED TESTS

The tests carried out with two types of wine are described below: (1) a commercial Montilla-Moriles wine and (2) a wine of the year (non-aged wine) from the Montilla-Moriles wine-growing area. The two wavelengths described in the previous sections were analyzed for both wines.

In this phase, all the tests consisted of: (1) filling the container with the wine to be tested, (2) measuring the absorbance for each wavelength (420 and 520), (3) adding five drops of hydrogen peroxide, and (4) waiting for ten minutes and returning to point 2.

1) TEST 1: COMMERCIAL “FINO” WINE FROM THE MONTILLA-MORILES AREA

In the first test, as expected, no browning occurred despite the addition of hydrogen peroxide. This is because commercial wines are treated with activated carbon and other additives to eliminate substances that are susceptible to oxidation.

2) TEST 2: WINE OF THE YEAR (NON-AGED WINE) FROM THE MONTILLA-MORILES WINE-GROWING AREA

Figure 10 shows the evolution of the absorbance of wine, detected by the developed device, at different wavelengths: 420 nm (see Figure 10a) and 520 nm (see Figure 10b). These absorbance values are obtained by using Equation 3. At the beginning of the test, five drops of hydrogen peroxide were added to the container. As can be seen in both graphs, there was an abrupt variation in the absorbance that coincided with the moment when the drop was added until it stabilized after 10 min. At this point, the values are stabilized but are higher than the first two readings. This indicates that the device detected the oxidation of wine. At the 15th minute, another five drops of hydrogen peroxide are added. In this case, the initial change detected was less abrupt. However, once the values stabilized, the mean absorbance value increased again compared with the previous values. Finally, at 21 min, another five drops of hydrogen peroxide were added. This time, at wavelength 420 nm, there is a small change, and then the values stabilize, although the difference from the average of the previous values is quite small. On the other hand, for 520 nm, no major changes were observed.

VII. DISCUSSION

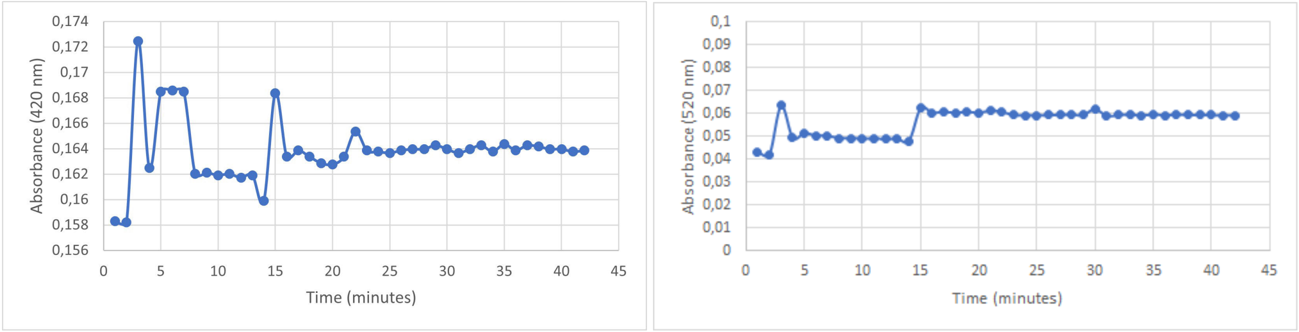
In the domain of precision oenology, a marked expansion is observed, as reflected in the specialized literature. An examination of 19 studies in this area reveals innovations in the measurement of oenological parameters, with an emphasis on the wine fermentation and aging processes. The unique characteristics and technical comparisons of the devices under scrutiny are elaborately delineated in Tables 1 and 2.

The methods of data transmission in these studies exhibit variation: some employ wired connections [31], [35], [46], [47] while others integrate wired with WiFi [36]. Alternatively, some studies depend on Bluetooth [32], or a combination of radio and WiFi modules [37], [38], [39], [40]. The device proposed in this work uses exclusively WiFi technology, as in [33] and [34]. However, it differs by incorporating a different microcontroller, which facilitates the direct transmission of data to the cloud.

Going into detail, the studies [33] and [34] utilized a combination of Arduino UNO with ESP8266, and Arduino UNO with Raspberry Pi 3, respectively, for data collection and transmission. In contrast to these approaches, our proposal adopts the ESP32 board, distinguishing itself from Arduino-based solutions. This selection is strategic, as the ESP32 board inherently combines WiFi and Bluetooth functionalities within a singular module. This integration not only simplifies the overall system design but also provides a more robust and efficient platform for wireless communication and connectivity. Furthermore, the fact that it is a non-invasive proposal in the form of a bung is a clear advantage when it comes to monitoring the aging of wines, especially Fino. Compared to other non-invasive proposals, [56] specifically highlights this advantage over alternative solutions in precision oenology.

The literature review, as detailed in Table 1, reveals that previous studies have not utilized the optical technique to measure the aging evolution of Fino Sherry wines. The only exception for Fino Sherry wine is the study presented in [40]. However, this approach is designed to monitor environmental parameters such as temperature, humidity, and light.

Our proposal has proved to be a simple solution for measuring the aging process of Fino Sherry wines. It employs a pair of LDRs and LEDs for monitoring absorbance values. The measured data are wirelessly and in real-time transmitted to the cloud. Specifically to the ThingSpeak platform. This allows for the data to be accessed from anywhere and everywhere. This approach effectively avoids the disadvantages associated with manual methods, notably



(a) (b)

FIGURE 10. Experimental results showing the evolution of absorbance at 420 nm and 520 nm wavelengths.

the time consumption and the risk of oxidation stemming from frequent opening of the wine barrels.

The results of our work show the gradual progression of wine oxidation and confirm that the device is effectively detecting these changes. The absorbance values recorded by this new device align with the ranges previously reported by other researchers. This consistency is observed in studies focusing on wines undergoing biological aging, encompassing both cellar and laboratory environments [21], [22], [23], [24], [43], [44].

Finally, there is the work presented in [48]. In terms of its operational principle, this device bears the closest resemblance to the one proposed in this work, as both employ spectrophotometric techniques for wine color analysis. However, our proposed system diverges significantly in two key aspects: Firstly, it is specifically tailored to measure characteristic wavelengths pertinent to Fino Sherry wine. This specialization contrasts with the other device, which is designed for red wine analysis. The ability to target wavelengths unique to Fino Sherry is crucial due to the distinct properties and quality indicators of this wine variety. Secondly, our system stands out in its design approach. Unlike the other device, which requires manual sample provision and thus limits continuous monitoring, our device is innovatively crafted for direct integration into the wine barrel. This integration enables ongoing, real-time monitoring throughout the aging process of Fino Sherry wine. This capability marks a significant advancement over traditional methods, offering enhanced insights into the wine's development and allowing for more precise quality control during its production.

In a real environment, oxidation would occur very gradually; therefore, the peaks (abrupt changes) mentioned in Subsection VI-B would not be produced. Furthermore, it is important to highlight that in a real-world setting, the device should have a protective casing to shield it from aggressive or deterioration processes occurring during the aging process. It should also include a power system that enables the device to operate autonomously for 2-3 years, given the slow and prolonged nature of the aging process. This autonomy, as in [42], aims to surpass the capabilities of other devices discussed in this paper, including those detailed in [32], [34], and [37].

VIII. CONCLUSION AND FUTURE WORK

This work presents an IoT bung capable of measuring the evolution of Fino Sherry wine by simulating its aging in barrels. The results demonstrate that the device is capable of measuring the evolution of absorbance at the characteristic wavelengths of these wines, specifically at 420 nm and 520 nm. Although the prototype has been presented and tested only at the laboratory level, the results show that it is feasible to develop an instrumented bung that can be fully integrated into the barrels where aging takes place, and thus be able to follow the evolution of the wines over long periods.

In conclusion, our study has successfully introduced a groundbreaking instrumentalized bung designed for real-time oenological measurements, specifically tailored for the nuanced process of analyzing the biological aging of Fino Sherry wine. The emphasis of this work was on technological innovation and practical application rather than generating traditional numerical results. The instrumentalized bung serves as a pivotal tool for advancing the understanding of the dynamic processes within the wine barrel, opening avenues for further exploration and refinement in the field of oenology. While our approach may differ from conventional research, the significance of our contribution lies in the creation of a unique and valuable tool for the wine industry.

Future works aim to solve the observed drawbacks and develop a more advance prototype capable of autonomously monitoring the Fino Sherry wine aging over an extended period (at least one year). Additionally, developing algorithms to analyze data from spectrophotometry sensors would be beneficial for the early detection of potential anomalies. Moreover, it will be crucial to investigate the impact of suspended particle deposition in the wine on sensor performance.

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