IoT-based Solution to Reduce Waste and Promote a Sustainable Farming Industry

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***Abstract*—Waste and the necessity to increase sustainability in the farming industry are some of the challenges addressed in the agri-food chain. With the potential of digital technologies, e.g., the Internet of Things (IoT) and Artificial Intelligence, to revolutionize agriculture by enabling more efficient and intelligent monitoring, system architecture and IoT nodes were developed to support relevant parameters for composing a Sustainability Index for the Bio-economy (siBIO). These nodes are scalable, modular, capable of meeting on-demand production needs, and provide a cost-effective alternative to commercial solutions or manual data collection methods. The collected data is transmitted to middleware and then stored, analyzed, and displayed on a user-friendly dashboard, providing data to siBIO and consequently contributing to a more sustainable farming industry and reducing waste of resources and food. The results include the implementation of IoT nodes in a case study involving a vineyard and an apple orchard. The nodes are successfully collecting data on environmental, operational, and energy parameters such as temperature, air humidity, soil moisture, precipitation, and water and electricity consumption for irrigation. The tests of data transmission and collection, functionality and robustness of the proposed solution were promising, offering a way to quantify the sustainability index and facilitate the exchange of agricultural information in a reliable and standardized way.**

***Index Terms*—Internet of Things, Agriculture 4.0, Sustainable Production.**

I. INTRODUCTION

The Internet of Things (IoT) refers to the interconnected network of physical devices, vehicles, buildings, and other objects using the Internet. These objects are equipped with sensors, software, and connection, allowing them to gather and exchange data. The field of IoT has been expanding rapidly, mainly as they take advantage of improvements in computing power, electronic miniaturization and network connectivity to offer new capabilities [1], which can revolutionize a wide range of sectors, including manufacturing, healthcare, transportation and agriculture, allowing for more efficient and intelligent decision-making [2].

Agriculture 4.0 involves the use of technologies to digitize agricultural production systems, value chains, and overall food systems [3], with IoT acting as a backbone to collect different data, e.g. location, weather, consumption, energy usage, prices, and economic information, from sensors, machines, drones, and satellites. The collected data can be analyzed by using Artificial Intelligence (AI) algorithms to perform more accurate and timely monitoring, prediction, and optimization.

According to [4], around 14% of the world's food is still lost after being produced and before reaching stores. At the same time, the world's population is projected to reach nearly 10 billion by 2050 [5], and food production will need to increase to meet this demand. Reducing food waste and increasing food production sustainability is crucial to address these issues. Sustainability in food production means that food is produced in a way that is economically, socially and environmentally sound. Additionally, reducing food waste can also help to reduce the pressure on natural resources, which are already stretched due to population growth and climate change.

One of the issues addressed in the agri-food chain is the lack of standardization of methodologies for assessing the sustainability of companies and how they can achieve higher levels of sustainability, as well as the respective impacts at environmental, economic and social levels. The BIOMA project proposed a Sustainability Index for Bio-economy (siBIO) [6] that aims to provide an answer to these questions, enabling the assessment of sustainability through the definition of requirements and standards, and also providing a road map to raise the sustainability levels of companies. In this context, the calculation of the siBIO index requires the automatic acquisition of data from different and heterogeneous sensors, by using IoT technologies, to be used as indicators for the assessment of sustainability in the agri-food value chain.

The use of emerging technologies, mainly IoT to achieve Agriculture 4.0, can bring many benefits to the agri-food value chain, which faces some challenges and presents some issues, such as food waste and the search for sustainable production. Food waste is a significant problem that not only affects the environment but also has economic and social impacts [7], contributing to food insecurity and economic losses.

Having this in mind, this paper describes an approach to support the aggregation of IoT solutions that are made up of modular, scalable, open-source, low-cost, secure and reconfigurable IoT devices, contributing to a more sustainable production system, and reducing waste. The IoT nodes consider the use of different types of sensors to measure different parameters, i.e. environmental, operational and energy parameters, and adopt different communication technologies, selected according to the place where the physical devices need to be installed. The proposed IoT devices are set to be incorporated with a suitable and secure middleware that enables effortless connectivity, facilitating the gathering of data from diverse sources throughout the entire process from farm to fork. The ultimate goal is to seamlessly visualize and analyze the collected data in an unified manner and make them available to be aggregated in an innovative way of calculating a sustainability index, which takes into account quantitative and qualitative aspects [6]. The proposed approach was applied in a case study, specifically in a vineyard and an apple orchard, where essential parameters will be collected to quantify the sustainability index of the production.

The remainder of this paper is organized as follows: Section II describes the related work of using IoT technology for the digitization of agricultural production systems to increase their sustainability and reduce food waste. Section III presents the system architecture and the development of the proposed IoT devices to support sustainable production. Section IV presents the preliminary implementation for a case study and discusses the achieved results. Finally, Section V rounds up the paper with the conclusions and points out future work.

II. RELATED WORK

The farming industry is experiencing an industrial revolution, known as Agriculture 4.0, which incorporates the use of emergent ICT technologies, e.g. IoT, Cloud Computing, Big Data, Artificial Intelligence, Remote Sensing, image processing and Unmanned Aerial Vehicles (UAV), allowing better management of agricultural inputs, i.e. fertilizers, seeds, herbicides and irrigation, increasing the farm profitability and the crop productivity [8].

Agriculture 4.0 is the most recent advancement in precision agriculture and it is centred on the idea of sustainable agriculture [9]. As part of the BIOMA project [10], in line with the “Farm to Fork” strategy in the context of the European Green Deal [11] that aims to create a more robust, safe and sustainable food system, the inclusion of IoT technologies plays a crucial role in promoting the real-time monitoring and the information exchange along the farm to fork value chain. The IoT is one of the key technologies to develop sustainable agriculture, adopting sensor-actuator solutions to measure or act on parameters that are relevant within this perspective [12].

Several studies have been developed regarding the application of IoT elements in the agriculture domain, most of them focusing on irrigation optimization and remote sensing. For example, a low-cost wireless sensor network (WSN) for measuring the soil moisture levels to aid farmers in optimizing irrigation processes in precision agriculture is presented by [13], where the network is comprised of sensor nodes, each one containing four soil moisture sensors capable of measuring moisture levels at varying depths that enable to make decisions and improves irrigation efficiency. Also, [14] proposes a sustainable automatic irrigation system using distributed WSN with different sensors and micro-controllers, covering the different regions of a farm to collect soil moisture, temperature, and fertility data, and the application of machine learning algorithms to predict irrigation patterns according to crops and weather scenarios.

In terms of communication technologies and protocols for the transmission of the collected data, there is no specific combination to be used in the agriculture monitoring context [15]. The most used communication technologies are Wi-Fi, LoRa, Bluetooth and 3G/4G/5G, and for the IoT protocols, the Hypertext Transfer Protocol (HTTP), Message Queue Telemetry Transport (MQTT) and LoRaWAN can be selected. The best communication technologies and protocols to be used depend on the specifications of the system being created and deployed, taking into consideration, e.g., the transmission range, the energy consumption, and the cost to develop and maintain the device [9]. A review of wireless communication technologies and protocols is provided by [16], which points out the use of LoRa and ZigBee as the more convenient technologies for agricultural applications due to their low power consumption and communication range.

According to [17], the key drivers of technology in agriculture are automation, climate effects, resource optimization (including land, water and chemicals) and higher yields (food crops and cash crops). When it comes to using a sustainability index to measure specific factors and categorize production indices, there is still a sizable gap including challenges related to connectivity, power management, data processing and analysis, sensor accuracy and reliability, data security and privacy, and cost-effectiveness. Given the growing concerns about climate change and the increasing demand for resources, it is critical to establish sustainable methods across various industries. Farmers could gather information on numerous aspects, e.g., soil moisture, temperature, and humidity, by adopting IoT-based monitoring devices. With this information, a sustainability index might be created to determine the environmental impact of their farming operations. The sustainability index could take into account factors such as water usage and energy consumption and would provide farmers with a score that reflects their overall sustainability.

Commercial solutions and low-cost projects have been developed to utilize IoT technology for data collection in agriculture, aiming to assist in decision-making processes and optimize production as well as the calculation of sustainability indexes. Commercial solutions often encompass comprehensive but closed systems, and come with high costs, along with monthly usage fees. Conversely, low-cost projects leverage open-source technologies, resulting in total costs ranging from 20 USD to 160 USD [18], [19].

However, as identified during the BIOMA project, there is a recognized gap in existing solutions for capturing quantitative data with a specific focus on sustainability in agricultural practices. While current solutions primarily target decision-making and optimization, there is a clear need for adaptable and scalable solutions that can collect and analyze diverse data points relevant to the sustainability index of each specific production context.

III. Development of IoT Nodes for Sustainability Calculation

As part of the BIOMA project, and given the need to assess the sustainability of agri-food companies, the siBIO is constructed by examining a set of indicators covering economic, social and environmental aspects, as these elements together form the basis for achieving sustainability. Using a web-based platform, the calculation of the score for each indicator is primarily based on the application of best practices in land management and the resulting impact on farmers. This includes considerations such as the time and financial resources invested in implementation and the effect on crop yields, as well as on-farm monitoring where feasible, particularly in relation to biodiversity (e.g. soil and nutrient monitoring), energy and water consumption. This approach will ensure the widespread applicability of siBIO to farms across the country. The optimal scenario involves consistently high scores across all indicators, effectively integrating the technology used in all farming systems. This integration is seen as the key to moving agriculture towards sustainability.

A. System Architecture

The agri-food value chain comprises three main stages: production, transport, and consumption. This work focuses on developing IoT nodes to collect data from the production stage, although the nodes' versatility allows easy interchangeability throughout the entire chain by changing parameters to be acquired. Fig. 1 presents the system architecture for calculating the sustainability index.

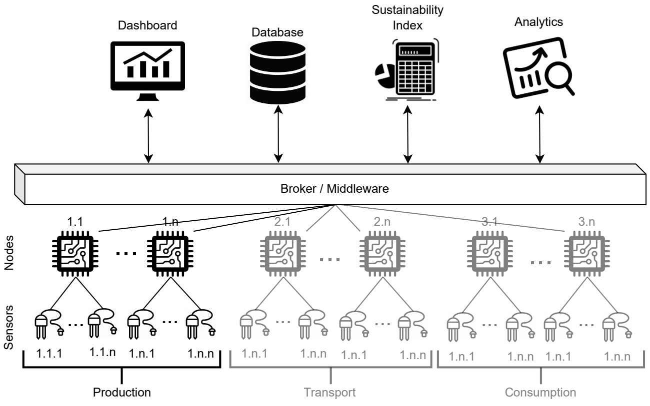

Fig. 1. System architecture for calculating the sustainability index.

The data acquisition is performed using different and heterogeneous sensors, which must be selected according to each relevant parameter for each stage of the agri-food chain. The architecture of a generic IoT node is illustrated in Fig. 2 and comprises a power supply, a microcontroller, a communication infrastructure and several analogue and/or digital sensors, that are reconfigurable to support this sensor diversity. Additionally, the nodes are scalable and modular, capable of meeting on-demand data collection needs, e.g., production operations can incorporate multiple nodes to collect data from various sensors at different locations and receive it in a unified dashboard. The system's versatility is further enhanced by combining nodes to collect data throughout the entire production process (e.g., from planting to storage to manufacturing).

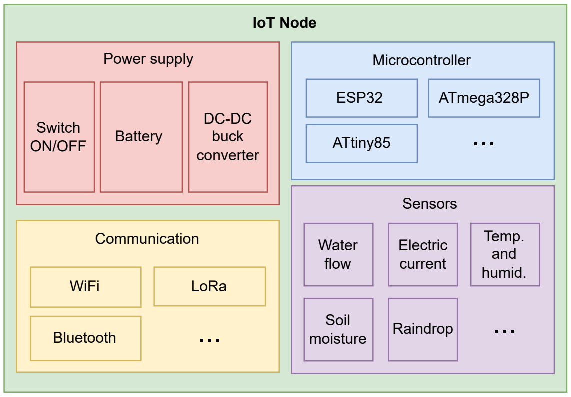

Fig. 2. Architecture of a generic IoT node.

The data obtained by each node is sent to a middleware responsible for aggregating, authenticating, and encrypting them. They are then saved in a database, displayed in real-time on an easy-to-view dashboard to provide resources for calculating the sustainability index and analyzing the results.

In the context of sustainable agri-food production, water and energy consumption are major factors, given their direct reliance on natural resources. Nonetheless, the sustainability index can encompass further qualitative factors that are linked to local temperature and humidity. Through the utilization of the developed reconfigurable device, the system can be expanded to integrate sensors capable of measuring additional parameters such as UV index, luminosity, and soil moisture. These supplementary factors hold substantial value as indicators influencing the sustainability of agri-food production.

B. IoT nodes for Production Monitoring Architecture

Using this approach, two types of nodes with different proposals were implemented: one for enclosed locations with pre-existing infrastructure (e.g., machinery room or warehouses), using WiFi, and another for remote and open spaces (e.g., open fields), using LoRa. Fig. 3 shows the characteristics of each developed node.

The selection of WiFi communication is based on its extensive usage in enclosed settings, such as factories or food warehouses, making it a viable choice for deploying nodes in such environments. Moreover, WiFi's installation simplicity is noteworthy as it eliminates the need for specialized gateways, unlike technologies like LoRa or Zigbee. On the other hand, the adoption of LoRa technology is driven by its capability for long-range communication in open areas (i.e. up to 10 kilometers [20] while Zigbee for example is limited to 300 meters [21]), coupled with optimized battery consumption.

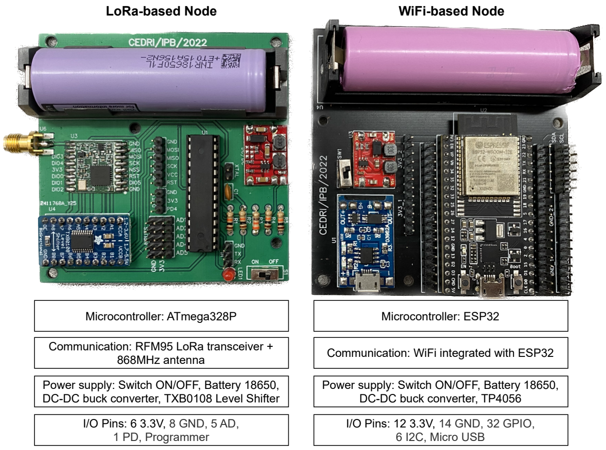

Fig. 3. Characteristics of each type of developed node.

This empowers the installation of nodes in remote locations, allowing for maintenance-free operation over prolonged durations.

The ESP32 was chosen as the microcontroller for the WiFi node due to its built-in WiFi functionality, which eliminates the need for extra modules and antennas. Moreover, the ESP32's large number of General Purpose Input/Output (GPIO) pins enables effortless integration with a wide range of sensors, assuring alignment with the system architecture. The ATmega328p microcontroller, on the other hand, was chosen for the LoRa node due to its favourable cost-benefit ratio, compatibility with the designated communication protocol, and low power consumption, contributing to the overall effectiveness of the system.

To address power management and supply requirements, both types of nodes utilized INR18650 3.7V batteries in conjunction with step-down DC-DC buck converters, which regulate the output voltage to the necessary 3.3V for microcontroller operation. However, it is crucial to note that the WiFi node's higher energy consumption, compared to the optimized LoRa node, necessitates a distinct power management approach. Consequently, the WiFi node is preferentially powered through a micro USB cable (5V/1A) connected to the TP4056 chipset, which delivers voltage to the converter and charges the battery. In the event of a power outage, the battery serves as a backup, ensuring uninterrupted node functionality for an estimated duration of approximately 60 hours.

The WiFi node is designed to support up to 12 sensors (analogue or digital). Additionally, it incorporates 6 pins dedicated to I2C communication (6 SCL and 6 SDA pins). The ESP32 microcontroller on the WiFi node can be programmed via the micro-USB connection provided on the board. On the other hand, the LoRa node is capable of supporting up to six sensors, along with one digital port and five analogue ports. To program the ATmega328p microcontroller on the LoRa node, the in-circuit serial programming (ICSP) pins can be utilized.

The LoRaWAN protocol, which leverages LoRa technology, incorporates built-in security measures to ensure the secure processing of collected data. Specifically, the protocol employs AES-128 encryption for robust data transmission security. In contrast, the WiFi node relies on the security measures implemented within the existing network, such as the security protocol supported by the router.

C. *Low-cost Purpose*

The cost analysis of the developed IoT nodes provides valuable insights into their viability and application in various agricultural settings. The WiFi node, which had a cost of 13.62 USD, offers a simplified implementation by leveraging the local WiFi infrastructure, thus reducing the hardware costs and deployment efforts. On the other hand, the LoRa node had a total cost of 24.25 USD and requires an initial investment in a LoRa gateway. However, this expense can be mitigated by the efficient long-distance coverage that LoRa provides.

Considering the benefits and limitations of each alternative, it is clear that the cost-effectiveness of the developed IoT nodes opens doors for wider adoption and integration of relevant data to the sustainability of agri-food production. By offering affordable and adaptable solutions, these nodes address the needs of both large-scale producers and small/family farmers, supporting inclusivity and promoting sustainable practices across varied agricultural contexts.

IV. EXPERIMENTAL RESULTS

The developed nodes were installed in the case study.

A. *Description of the Case Study*

The case study of interest of this work involves the practical implementation of the developed IoT nodes for monitoring key parameters relevant to the sustainability of agri-food production. Before the implementation of these IoT nodes, data collection in the selected locations relied on manual methods using analogue sensors and counters, or through commercially available solutions that incurred high costs.

The selected locations for the case study are a vineyard in the Monção region (Portugal), covering an approximate area of 64 hectares, and an apple orchard in the Alcobaça region (Portugal), with around 4 hectares.

In the vineyard, the parameters of interest to be collected are temperature, air humidity, soil moisture, precipitation, water and electricity consumption for irrigation. The implementation of cost-effective IoT nodes is an alternative to previously used commercial solutions, offering an economically viable alternative for sustainable grape production in terms of data acquisition. The developed nodes are strategically placed throughout the vineyard, as illustrated in Fig. 4. In this way, the LoRa-based node is the best option to ensure optimal coverage and data acquisition in this open and remote space.

Similarly, in the apple orchard, the installation of IoT nodes has enabled improved data collection practices, replacing the manual methods previously employed. The parameters of interest in this production are water and electricity consumption for irrigation. With pumps and electrical panel located in the machinery room, shown in Fig. 5, which already has an

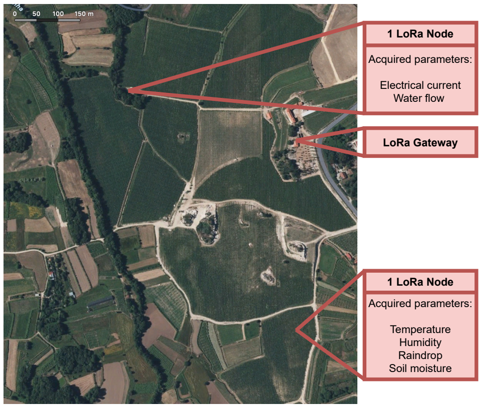

Fig. 4. Map of the case study installation in the vineyard.

existing WiFi infrastructure, the strategic approach is to utilize the WiFi-based nodes.

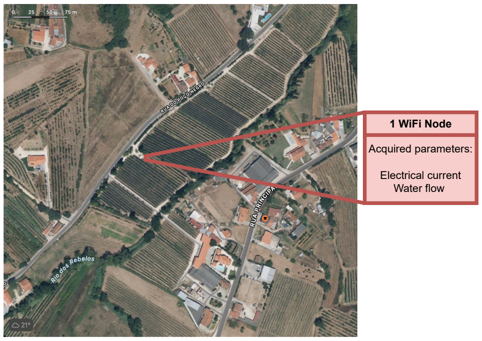

Fig. 5. Map of the case study installation in the apple orchard.

B. Experimental Tests

During the experiment conducted in the laboratory, the data from both nodes were transmitted via MQTT using their respective communication protocols and were received and stored in an SQLite [22] database using Node-RED [23] on a local host. To facilitate the analysis of the data collected during the experiment, a dashboard was created using the Grafana platform [24]. This allowed the user to easily access and visualize the data collected during the experimental phase.

Furthermore, the functionality of the nodes in transmitting data was evaluated, and the results were promising. During this test, the data transmission rates were set to 4 seconds per data transmission (for the WiFi node) and 12 seconds per data transmission (for the LoRa node), and the nodes demonstrated efficient data transmission. These data transmission rates are aligned with the expected performance for each respective communication protocol and can be adjusted according to the specific parameter being measured.

Additionally, battery tests were conducted to assess the performance of the nodes. Due to the use of distinct microcontrollers, components, and operational proposals of the nodes (one designed for extended battery life and the other for continuous power supply with battery backup), a direct comparison between the two types was not suitable. Instead, the focus was on analyzing whether the battery performance is aligned with expectations. Both batteries were fully charged, and continuously sent data for a 3-day test at the aforementioned transmission frequencies. After 60 hours, the WiFi node turned off due to battery depletion, and at 72 hours the LoRa node still had approximately 96.5% of the initial capacity.

The achieved results during the laboratory experiment provide valuable information about the successful operation of the nodes, their data transmission capabilities and battery performance. In this way, it was possible to proceed to the installation of the nodes in the case study.

C. Analysis of Results

The successful installation of the developed IoT nodes in the case study locations, as shown in Fig. 6, demonstrated their functionality and robustness in specific agricultural environments. These nodes effectively automated the data collection process, providing valuable insights for analyzing the sustainability of agri-food production. Importantly, the implementation of the IoT nodes offered a more cost-effective solution compared to existing alternatives in the area, while also significantly improving the efficiency and practicality of data collection compared to manual methods.

Fig. 6. IoT nodes installed in the case study.

The deployed IoT nodes showcased their capability to reliably gather and transmit data, supporting the analysis of key parameters related to sustainability. The dashboard, as shown in Fig. 7, provided a user-friendly interface for visualizing the collected data. This dashboard allowed an easy interpretation, enabling stakeholders to make informed decisions and optimize production practices accordingly.

Through the integration with the FIWARE middleware (https://www.fiware.org), described in [25], the data collected by the nodes is requested by an API and used as one of the terms (Environment category) that make up siBIO used to quantify sustainability of different producers. This approach allows the comparison of sustainability levels between producers with similar environmental conditions, producing similar products but using different amounts of resources.

V. CONCLUSIONS AND FUTURE WORK

Given the problem of food waste and the growing concern for sustainability, siBIO offers several interesting benefits for the agri-food sector, as it provides a sustainability index in

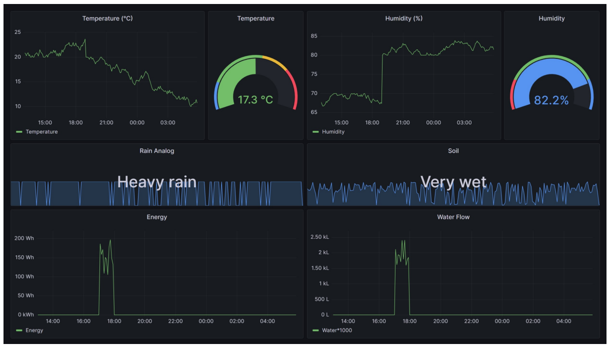

Fig. 7. Dashboard for visualization of collected data.

an innovative methodology that allows operators to exchange agricultural information in a reliable and standardised way. However, in order to calculate this index, parameters need to be collected more efficiently and at a lower cost.

This paper has presented an architecture made up of scalable, open source, low-cost, secure and reconfigurable IoT modules that contribute to more sustainable production and waste reduction, taking into account the use of different types of sensors to measure different parameters, whether environmental, operational or energy, as well as being able to communicate through different technologies, thus being adaptable to the installation site.

The IoT devices, components of the proposed architecture, are securely integrated through a middleware that allows the collection of data from heterogeneous sources belonging to the farm-to-fork chain, providing essential parameters for the quantification of the sustainability index and the subsequent visualisation and analysis of these data in an integrated way.

Operators, in particular agronomists, will be able to easily analyse the monitored information (through a simple, customisable and user-friendly interface), enabling them to make decisions and thus minimise wastage of resources.

The proposed general-purpose sensor board, whose modules are reusable and easy to maintain, provides a suitable approach to collecting, storing and transmitting data that can be easily scaled to meet production requirements, in addition to integrating modules that facilitate business-to-business operations without the need to purchase expensive hardware equipment.

Future work aims to install more sensors, covering the entire agri-food chain (production, transport and consumption), and to develop other applications for the data collected using AI.

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