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Integrating IOTA's Tangle with the Internet of Things for Sustainable Agriculture: A Proof-of-Concept Study on Rice Cultivation

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Abstract: Addressing the critical challenges of resource inefficiency and environmental impact in the agrifood sector, this study explores the integration of Internet of Things (IoT) technologies with IOTA's Tangle, a Distributed Ledger Technology (DLT). This integration aims to enhance sustainable agricultural practices, using rice cultivation as a case study of high relevance and reapplicability given its importance in the food chain and the high irrigation requirement of its cultivation. The approach employs sensor-based intelligent irrigation systems to optimize water efficiency. These systems enable real-time monitoring of agricultural parameters through IoT sensors. Data management is facilitated by IOTA's Tangle, providing secure and efficient data handling, and integrated with MongoDB, a Database Management System (DBMS), for effective data storage and retrieval. The collaboration between IoT and IOTA led to significant reductions in resource consumption. Implementing sustainable agricultural practices resulted in a 50% reduction in water usage, 25% decrease in nitrogen consumption, and a 50% to 70% reduction in methane emissions. Additionally, the system contributed to lower electricity consumption for irrigation pumps and generated comprehensive historical water depth records, aiding future resource management decisions. This study concludes that the integration of IoT with IOTA's Tangle presents a highly promising solution for advancing sustainable agriculture. This approach significantly contributes to environmental conservation and food security. Furthermore, it establishes that DLTs like IOTA are not only viable but also effective for real-time monitoring and implementation of sustainable agricultural practices.

Keywords: agrifood sector; internet of things (IoT); distributed ledger technologies (DLT); IOTA tangle; rice cultivation; sustainability; real-time data recording; environmental footprint

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1. Introduction

The agrifood sector, a cornerstone of the global economy, sustains billions by providing food and livelihoods. Yet, it grapples with multifaceted challenges, from climate change and environmental degradation to population growth, food security, and consumer trust. Addressing these requires sustainable, efficient agricultural practices that optimize resource use, curtail waste, and elevate productivity and quality.

The Internet of Things (IoT) is emerging at the forefront of solutions. This network of interconnected devices, equipped with sensors, actuators, and communication protocols, offers real-time monitoring and control over parameters like crop growth, soil health, water consumption, pest management, and greenhouse gas emissions. Beyond monitoring, IoT enhances traceability and transparency throughout the food supply chain, bolstering food safety and consumer trust.

However, the integration of IoT in agriculture is not without challenges, especially concerning data management:

- Data Security: Ensuring data integrity and safeguarding against malicious tampering is paramount.
- Data Privacy: Stakeholders' rights and preferences necessitate stringent measures against unauthorized data access or disclosure.
- Data Scalability: As farms grow and technology adoption surges, systems must accommodate an increasing influx of data from sensors and devices.
- Data Interoperability: Seamless data exchange is crucial, especially when devices and systems employ diverse formats and standards.
- Data Cost: Efficient data transmission and storage are vital, particularly for frequent or low-value transactions.

Distributed Ledger Technologies (DLTs) and the IoT can address these challenges by offering a decentralized, immutable, and transparent platform for data management. However, while the blockchain, i.e., the most widely used form of DLT, has revolutionized data storage through cryptographically linked blocks, it is necessary to address scalability, transaction fees, energy consumption, and more limitations in the data-intensive IoT universe.

IOTA offers a fresh perspective on DLT with its Tangle, a directed acyclic graph (DAG) structure. Unlike blockchains, the Tangle permits feeless transactions, validated by nodes as they initiate new transactions [1,2]. This structure provides enhanced scalability, reduced energy consumption, quantum resistance, and the capability for offline transactions and microtransactions. Rather than replacing traditional blockchain systems, IOTA complements them, especially for the high-frequency data transactions inherent to the IoT. With projections indicating that, by 2030, approximately 125 billion IoT devices will be interconnected [3], the sheer volume of data generated necessitates robust management, distribution, and storage solutions. While DLT offers a promising avenue, our study narrows its focus on IOTA's Tangle, a DLT uniquely equipped to handle the vast data streams from IoT devices, given its scalable, fast, and feeless micro-data transaction capabilities.

With this backdrop, our central research inquiry is both theoretical and pragmatic: *Is it possible to devise a web application that seamlessly integrates Tangle IOTA with IoT-enabled sensors?* These sensors, designed for monitoring sustainability metrics in agriculture, would empower operators in the agrifood sector with real-time insights, enabling timely interventions. To explore this, we have embarked on a Proof-of-Concept test focusing on data from rice cultivation. Our Proof-of-Concept focuses on rice cultivation, chosen due to its significant freshwater usage, which is the highest among all crops. Additionally, rice's global prevalence and status as the world's primary food crop make it a pertinent subject for our study [4].

We developed an analytical dashboard to demonstrate that using technologies such as IoT and IOTA optimizes product quality, product processing efficiency, cost, and production time. In summary, when we fully control production with devices and sensors (IoT), receiving data even from remote locations with the support of IOTA, it is possible to reduce the release of CO_2 by having control over irrigation and the right portion of water (more water equals more CO_2 and more waste). In addition, it is possible to track the product 24 h a day, receiving recorded data on IOTA almost through streaming. Finally, the process is very green, reducing electricity consumption.

2. Background and Related Works

In this section, we first provide a general background on distributed ledger technology (DLT), including both blockchains and tangles like IOTA. Then, we discuss related work on (i) traditional monitoring systems in agriculture, (ii) the use of the blockchain applied to agriculture, and (iii) the use of IOTA Tangle technology applied to agriculture.

2.1. Background

DLT has become a transformative force in information technology, reshaping organizational collaboration and operation [5,6]. It employs a ledger system where multiple nodes can read and write data, maintaining a state based on consensus, which varies with the network's decentralization level.

DLTs are characterized mainly by their ledger structure: chain-based systems like blockchain and DAG-based systems like IOTA's Tangle. Chain-based DLTs utilize a linear series of blocks, securing records through cryptographic hashing and consensus mechanisms like proof of work or stake. These blockchains differ in their access protocols and validator addition methods, affecting interaction levels with network components.

In contrast, DAG-based DLTs allow parallel transaction processing, offering potentially higher scalability than chain-based systems. With independent transaction confirmation and no need for a single global consensus, DAG structures provide a more dynamic and scalable consensus approach. This contrasts with chain-based systems, where all transactions require network-wide confirmation, leading to potential bottlenecks in transaction processing and scalability.

2.2. Related Work

2.2.1. Traditional Monitoring Systems in Agriculture

Historically, agricultural monitoring has evolved through various traditional systems. Key studies in this field have explored different approaches:

- Wang et al. developed a low-cost, real-time remote environmental monitoring system combining wireless equipment and mobile phones that was powered by solar energy. This system was effective in collecting real-time information and fulfilling online acquisition needs [7].
- Dan et al. implemented a Greenhouse Environment Monitoring System using ZigBee technology, wireless sensors, and control nodes. This system focused on controlling environmental data for enhanced greenhouse management [8].
- Hashim et al. reviewed using an Arduino device for temperature and soil moisture control, managed via an Android smartphone. This study contributed to designing smart monitoring systems using an embedded micro-web server and IP connectivity, aiming to aid the agriculture sector in achieving quality production [9].
- Karim et al. developed an application for precision farming based on a wireless sensor network and IoT cloud. This application focused on optimizing irrigation and monitoring microclimatic conditions to improve water usage efficiency in farming [10].

2.2.2. Blockchain Technology and Sustainable Agriculture

Blockchain technology has significantly impacted the concepts of trust and efficiency in sustainable agricultural development. This change became prominent as agrifood companies accessed knowledge banks and digital resources [11]. Blockchain, alongside the Internet of Things (IoT), is pivotal in advancing sustainable and precision agriculture, which leverages technology to enhance agricultural efficiency [12].

- Lin et al. proposed an ICT e-agriculture system model based on the blockchain for local and regional use. They also developed a validation tool for the technical and social requirements of these systems [11].
- Patil et al. focused on using IoT for remote monitoring and automation in agriculture. They provided an architecture integrating blockchain technology for smart greenhouse farms, offering a security framework that combines blockchain with IoT devices for enhanced security and communication in smart farming [13].
- Munir et al. implemented an intelligent Smart Watering System (SWS) based on an Android application for smart water consumption in crops. The system, equipped with affordable sensors, uses blockchain and Fuzzy Logic approaches for data security and intelligent decision-making, enabling real-time monitoring and periodic irrigation [14].
- Baralla et al. developed a blockchain-oriented platform to authenticate food origin data. This platform aims to enhance supply chain transparency, promote local smart food tourism, and boost local economies, emphasizing the importance of food as a "business card" for tourist sites [15].

- Iqbal and Butt proposed an IoT-based system for crop protection at all stages, focusing on deterring animal attacks using sensors and a Repelling and Notifying System (RNS). The system records incidents in a centralized Farm Management System (FMS), integrated with an agricultural blockchain for shared ledger functionalities, enhancing meta-information sharing [12].
- Cocco et al. implemented a system offering visibility to food processes and certifications, using Self Sovereign Identity, blockchain, and the InterPlanetary File System. This system aims to safeguard data storage and access, ensuring the eligibility, transparency, and traceability of certifications [16].

2.2.3. IOTA Applied in Agriculture

IOTA's integration into agriculture showcases innovative projects combining IoT, AI, and DLT:

- Flores et al. developed the Interplanetary Precision Agriculture (IPA) project, which harnesses IoT, AI, and DLT. The project utilizes various technologies, including an autonomous rover (Magrito) for crop performance data, Precision Habitat PRO for environmental control, a bluetooth scale for weight data, and a farm management system for data aggregation. The collected data are sent to the IOTA Tangle network to ensure immutability and interoperability. This aims to enhance cultivation processes both on Earth and in extraterrestrial environments, addressing issues of centralization and data silos in supply chains. The overarching goal is to establish a sustainable food supply and minimize the environmental footprint of agricultural practices [17].
- Lamtzidis et al. introduced a distributed ledger-based system focused on securing IoT data integrity. They utilized IOTA's Tangle ledger for the secure processing and storage of aggregated field data, transitioning from a cloud-centric to a node-centric architecture. In this setup, each Super node maintains its data in a distributed and decentralized database, with the backend functioning as both a data consumer and resource provider. This modular approach has made significant contributions to open-source communities in blockchain and IoT, presenting a more secure and decentralized method for managing IoT data [18].

3. Design of the Study

The primary objective of this paper is to demonstrate how integrating IoT and IOTA technologies can optimize product quality, processing efficiency, cost, and production time in agriculture. By utilizing IoT devices and sensors, and leveraging IOTA for data management, we aim to achieve significant reductions in CO_2 emissions through precise irrigation control and water management. This approach also allows for continuous product tracking and reduces electricity consumption, contributing to a more sustainable agricultural process.

Our methodology involves creating a prototype that simulates a rice production process. This setup includes seedlings equipped with sensors to monitor and regulate water levels within a specified range. This prototype demonstrates efficient data transmission, production control, and system functionality.

The study heavily focuses on the impact of IoT in agriculture. IoT technology, encompassing remote sensors, cloud and edge computing, unmanned vehicles, and data analytics [19], is revolutionizing agricultural practices. It allows for effective monitoring of crucial factors like humidity, air temperature, and soil quality, thus enhancing crop yields, irrigation efficiency, and accurate harvest forecasting (https://www.appsforagri.com/en/news/impact-of-iot-in-the-agriculture/, accessed on 7 October 2023).

Moreover, the IoT's integration into agriculture significantly reduces environmental impacts by lowering water and energy usage, greenhouse gas emissions, and fertilizer runoff. Financially, it increases farmers' profitability and competitiveness by opening up new markets and services [20].

This study extends the IoT's capabilities in agriculture by incorporating IOTA's DLT, which is particularly suited for high-frequency IoT scenarios. IOTA offers benefits such as feeless transactions, data integrity, scalability, and interoperability, making it ideal for a secure and transparent network of IoT devices in the agricultural sector.

Our methodology places a strong emphasis on optimizing resource utilization, with a particular focus on water efficiency. By integrating IOTA's advanced DLT capabilities with intelligent irrigation systems, we aim to significantly enhance the precision and effectiveness of water usage in agriculture. Drawing insights from Mboyerwa et al.'s [21] research, this integration is expected to drastically reduce resource consumption. Notably, it can lead to halving water usage, decreasing nitrogen consumption by 25%, and reducing methane emissions by 50% to 70%. These substantial reductions are primarily achieved through the optimized control of field flooding durations, which effectively slows down the activity of methane-producing microorganisms.

The integration of IOTA plays a critical role in this process. Its technology enables a secure, transparent, and highly efficient network of IoT devices. This network facilitates the real-time collection, processing, and analysis of vast amounts of agricultural data. Consequently, it allows for more precise irrigation decisions, ensuring water is used more effectively and sustainably. The real-time data processing and feeless transactions offered by IOTA enhance the system's responsiveness and accuracy, leading to a more intelligent and environmentally friendly approach to irrigation. This not only optimizes resource usage but also contributes to the broader goals of sustainable and precision agriculture.

The study employs a multi-faceted technological approach, simulating a data-intensive paddy farm environment. By integrating IOTA, we enhance data management, introduce robust authorization systems, and streamline data transmission. The design covers three domains:

1. Local: Involves structuring, programming, and assembling a Raspberry Pi and its sensors.
2. Remote: Facilitates internet connectivity and links to an online platform.
3. Cloud-based server: Serves as the primary project hub.

Technologically, the study utilizes Raspberry Pi devices and sensors, EMQX (MQTT), VPN and Ubuntu, Docker, IOTA, and MongoDB (ATLAS). The programming spans across Python, NodeJs, Javascript, HTML, and CSS.

3.1. IOTA

IOTA stands out as a pioneering DLT tailored for the IoT landscape. Distinct from conventional blockchain systems, IOTA employs the Tangle, a unique architecture that addresses the scalability and transaction cost challenges inherent to blockchains. It positions IOTA as an optimal choice for the real-time processing of vast data streams from IoT sensors in sustainable agriculture. The IOTA network is underpinned by nodes' individual instances of the IOTA software. These nodes validate and record transactions, and in the context of sustainable agriculture, they could process data received from IoT sensors, monitoring parameters like soil moisture, temperature, and pH levels.

To ensure efficient operation, nodes had to use a robust but affordable environment with at least a 4-core processor, 8GB RAM, SSD storage, and a public IP address. Each node offers different features across multiple ports, facilitating peer-to-peer communication with HTTP and MQTT protocol, allowing for resilient data communication in every agricultural scenario.

IOTA nodes can manifest as Mainnet, Testnet, or Devnet nodes. While Mainnet nodes handle real-world IOTA transactions, including actual sensor data, Testnet and Devnet nodes serve developmental and testing purposes, enabling developers to refine applications before Mainnet deployment. There are two primary IOTA node software options: Hornet and Bee. Hornet, crafted in Go, is resource-efficient, aligning with IoT applications where resources might be limited. Conversely, Bee, developed in Rust, emphasizes modularity and performance. Given its resource efficiency, Hornet is preferred for most agricultural IoT scenarios. Hornet's implementation can leverage various avenues, including APT Repository, Docker image, binary files, or source construction. The Docker image, renowned for its portability, is particularly favored. The ability of Docker to effortlessly deploy and scale applications aligns with agricultural contexts, where the number of IoT sensors can fluctuate based on farm dimensions and requirements. Node security is paramount, necessitating measures like safeguarding login accounts, sealing unused ports, disabling remote consensus algorithm execution, and deploying a reverse proxy for augmented security.

The Docker image gohornet/hornet (https://hub.docker.com/r/iotaledger/hornet, accessed on 7 October 2023) is utilized for Hornet implementation, with the repository cloned locally. Configuration files (i.e., config.json and peering.json) facilitate settings customization and node synchronization storage. The database of IOTA mandates a mainnetdb folder creation, with the use of authentication hashes ensuring data access exclusivity. The Docker image also initiates a server, loading a dashboard for node and data monitoring essential for overseeing and troubleshooting the IoT sensor network in agriculture.

3.2. Raspberry Pi 4

In this rice production study, we use the Raspberry Pi 4, a capable computer equipped with an ARMv8 quad-core 1.5 GHz 64-bit CPU, dual-band wireless LAN, Bluetooth 5.0, and 1-2-4 GB RAM. It offers a GPIO port with 40 pins, 26 being GPIO pins, and various ports like USB, micro-HDMI, Ethernet, and more, including support for 4K video. The GPIO socket includes 40 pins, bridging the Raspberry Pi and external devices, where 26 of these are GPIO pins; the rest are power or ground pins. They are labeled in both physical and BCM numbering for convenience. Raspbian, a version of Linux designed for Raspberry Pi, serves as the operating system. It is installed via NOOBS, with a browser, email program, LibreOffice, Minecraft, and a command-line tool (raspi-config) for configuration management.

Sensors

Various sensors monitor and control environmental conditions, including humidity, temperature, flame detection, rain, pressure, and soil moisture:

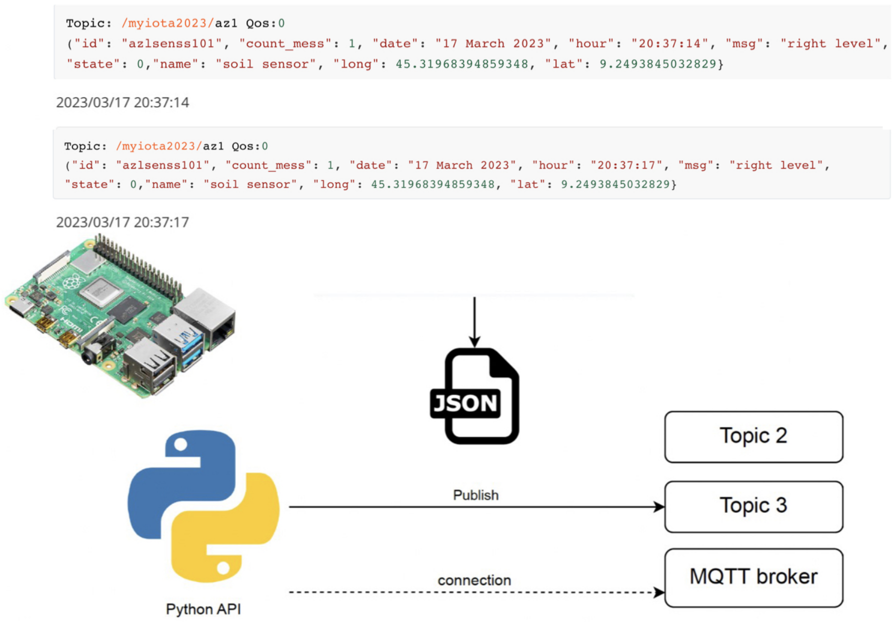
- The DHT11 is a temperature and humidity sensor with a digital output, allowing communication with a Raspberry Pi up to 20 m away. It provides stable measurements with a maximum temperature accuracy variation of 2 °C and humidity accuracy variation of 1 percent.
- The flame detection sensor can detect infrared emissions from a flame and convert them into an electrical signal readable by any microcontroller. It has a reading angle 60° and features both an analog and a digital output.
- The rain sensor detects the presence and concentration of water. An LED indicates its operation and features with an analog output to calculate the amount of water present.
- The pressure sensor measures atmospheric pressure, temperature, and altitude. It can measure an atmospheric pressure level ranging from 300 to 1100 hPa and a temperature range from −40 °C to +85 °C.
- The soil moisture sensor detects soil moisture and the presence or absence of water. It has a digital output that indicates the level of humidity. This study uses two such sensors to monitor the optimal water levels for rice field irrigation. The first sensor measures the minimum water level needed for healthy rice growth, while the second sensor identifies the maximum water level to prevent wastage and crop damage.

3.3. Sensor–Raspberry Pi communication

The communication between sensors and computers is ensured by a Python script, which sets the sensors with the correct configuration for reading. It cyclically checks each sensor, recalling its state or value and storing the results in temporary variables. These variables are part of a JSON-like object that requires further conversion to become a standard JSON object.

The script establishes a remote connection on the EMQX API, an MQTT web tool, and proceeds with publishing through the publish function. Since Python lacks the module allowing Raspberry Pi to communicate with the web tool, it must be installed and imported.

To avoid saturating the Raspberry Pi's resources, time intervals are established between the data acquisition of one sensor and the next. A pause of 2 s has been set before another sensor is analyzed to minimize data and information loss. The dialogue between the two technologies is summarized in Figure 1.



```
Topic: /myiota2023/az1 Qos:0
("id": "azlsenss101", "count_mess": 1, "date": "17 March 2023", "hour": "20:37:14", "msg": "right level",
"state": 0,"name": "soil sensor", "long": 45.31968394859348, "lat": 9.2493845032829}

2023/03/17 20:37:14

Topic: /myiota2023/az1 Qos:0
("id": "azlsenss101", "count_mess": 1, "date": "17 March 2023", "hour": "20:37:17", "msg": "right level",
"state": 0,"name": "soil sensor", "long": 45.31968394859348, "lat": 9.2493845032829}

2023/03/17 20:37:17
```

Figure 1. Sensor–Raspberry Pi communication.

3.4. MQTT and EMQX

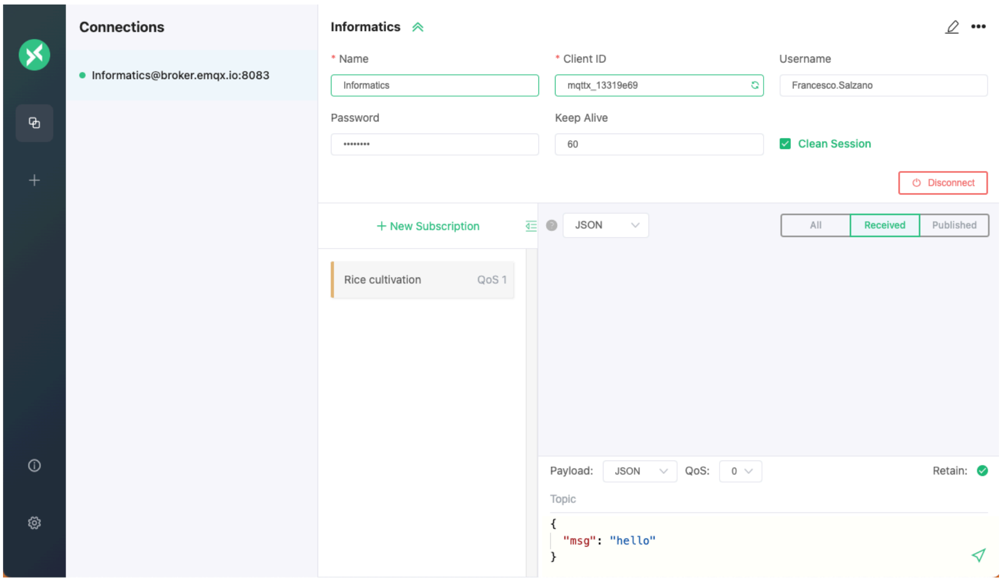
This project uses EMQX, a web socket implementation of MQTT, to facilitate remote IoT data collection. EMQX is an open-source MQTT IoT message broker built on the Erlang/OTP platform, renowned for its soft real-time capabilities, low latency, and distributed development features. MQTT is a lightweight message exchange protocol centered around a publication–subscription model. EMQX is accessible via browser and is designed for mass client access, providing fast and low-latency message routing between large physical network devices. It can host large-scale MQTT client connections, with a single server node supporting 2 million connections. It is also extensible, supporting custom plug-ins for authentication and other features. It fully supports IoT protocols, including MQTT, MQTT-SN, soap, LwM2M, and other proprietary TCP/UDP-based protocols. The connection configuration is used to set up links through any API that will serve as a bridge to dialogue your code with the MQTT platform. Required fields for EMQX connection configuration encompass "Name", "Client ID", "Host", and the listening port.

EMQX Broker provides many configuration elements and supports global and local configurations, allowing multi-protocol and port utilization. Auto Reconnect and Clean session functions are used to perform automatic reconnection when the broker goes offline and to start a session after a disconnection.

The project creates various "topics" or subjects by creating a new subscription. The Topic must have a title and a subtitle, which are necessary if there is a need to filter the data. They are used to categorize the topic according to the path to which it belongs. This logic is useful when you want to retrieve information to access it; you need to know and refer to the precise path, otherwise, you cannot link to the topic. Data simulation within the project is accomplished with data input in JSON or TXT format allowing for textual data and key-value schema object notation.

JSON data were sent via the Raspberry device at 2-s intervals, and it is possible to say that no visible latency or message loss was encountered.

Figure 2 displays the most important functionalities of this tool. Through the functionality called "New Connection", it is possible to create a new mandatory initial connection or it can be used to create additional parallel connections, leading to Step 2, i.e., the connection configuration. This part will also serve as a setting for the links through any API that will serve as a bridge to dialogue your code with the MQTT platform.


Connections
Informatics@broker.emqx.io:8083
Informatics
* Name: Informatics
* Client ID: mqttx_13319e69
Username: Francesco.Salzano
Password: ••••••••
Keep Alive: 60
☑ Clean Session
Rice cultivation QoS 1
Payload: JSON QoS: 0 Retain: ✓

```
{
  "msg": "hello"
}
```

Figure 2. EMQX: MQTT Websocket Toolkit.

In detail, Table 1 shows the port numbers devoted to exposing services, dealing with sockets, the default WS (web socket) or WSS (web socket secured with SSL). The latter is a security protocol based on modern public key cryptographic algorithms, i.e., TLS/SSL. It can ensure transmission security in the computer communication network, providing the benefits of strong certification, thus ensuring confidentiality and completeness.

Table 1. Protocol port.

Port Number	Description
1883	MQTT/TCP protocol port
11883	Internal port of MQTT/TCP protocol, used only for the local client connection
8883	MQTT/SSL protocol port
8083	MQTT/WS protocol port
8084	MQTT/WSS protocol port

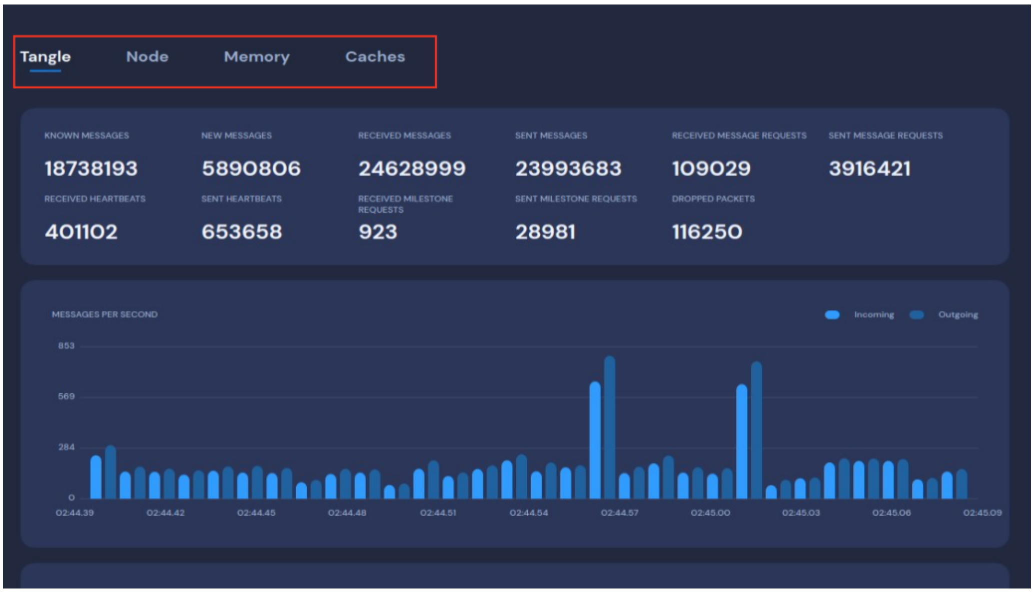
3.5. IOTA Dashboard

The IOTA environment provides a dashboard designed as a user interface that supplies real-time insights and control over the IOTA Tangle. In sustainable rice cultivation, IoT devices can be deployed across rice fields to monitor various parameters such as soil moisture, temperature, pH level, and more. These devices can transmit data to the IOTA Tangle, which can be accessed and analyzed in real-time through the IOTA dashboard.

The IOTA dashboard enables one to view the IOTA DLT state. In detail, it provides an *Analytics* tab, which makes available parameters about the node, network, and resources, including information about the Tangle network, node details, memory usage, and cache data. Moreover, users can search for messages sent to the node, for instance, measurement from the IoT devices deployed in the rice fields monitoring by using the *Explorer* tab. In addition, the IOTA dashboard comes with a *Visualizer* tab responsible for providing a visual representation of the live evolution of the Tangle network, offering a real-time view of data transmission. Network management is eased by noting the information displayed in the *Peers* tab, and finally, plugin add-ons are allowed in the *Plugins* tab.

Through the IOTA dashboard, farmers, researchers, and decision-makers can gain valuable insights into the conditions of the rice fields, enabling them to make informed decisions that promote sustainable cultivation practices. This case study will explore how the IOTA dashboard can be used in promoting sustainability in rice cultivation.

The analytics tab is composed of four sub-tabs, namely *Tangle*, *Node*, *Memory*, and *Caches*. As depicted in Figure 3, the Tangle subsection supplies several valuable metrics, such as known messages, new messages, received messages, messages sent, message requests received, sent message requests, heartbeats received, heartbeats sent, milestone request received, sent milestone request, and deleted packets.



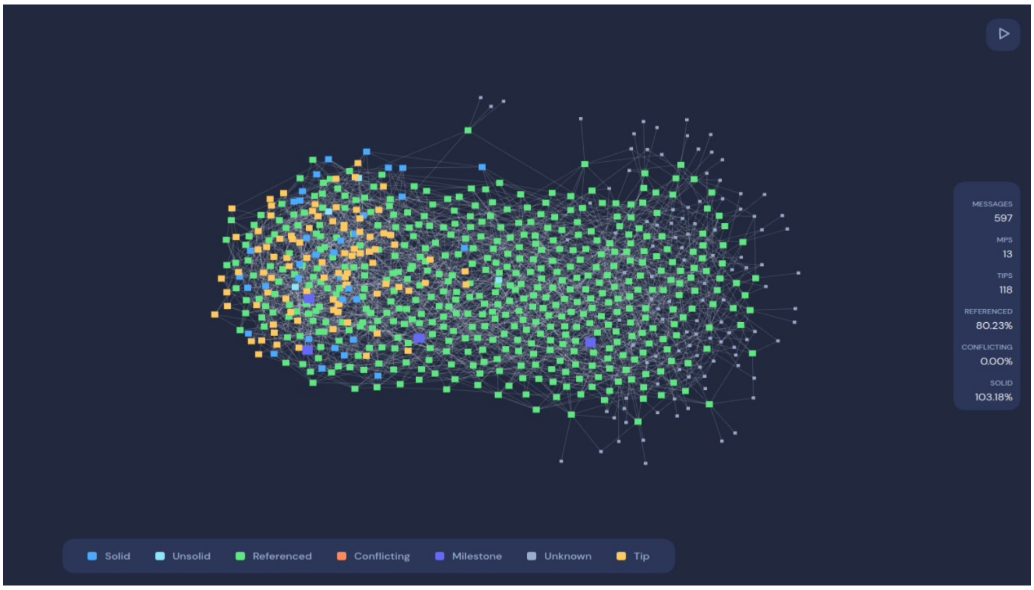
KNOWN MESSAGES 18738193
NEW MESSAGES 5890806
RECEIVED MESSAGES 24628999
SENT MESSAGES 23993683
RECEIVED MESSAGE REQUESTS 109029
SENT MESSAGE REQUESTS 3916421
RECEIVED HEARTBEATS 401102
SENT HEARTBEATS 653658
RECEIVED MILESTONE REQUESTS 923
SENT MILESTONE REQUESTS 28981
DROPPED PACKETS 116250

Figure 3. IOTA dashboard: analytics.

Between these analytics, it is possible to note a heartbeat signal. Heartbeat is a periodic signal that hardware or software produces, and it is used both to show proper operation and synchronize nodes. It is one of the mission-critical systems' most widely used techniques to provide high availability and fault tolerance of network services by detecting network or node system failures. Other sections provide information regarding memory usage and cache state. The *Node* section is in charge of providing insights on messages sent per milestone, which define a temporal interval defining the time needed to pass until the network coordinator executes the message validation.

The state and the throughput of the network are viewable in the network graph, as depicted in Figure 4, which represents the construction of a Tangle or a DAG graph, i.e., the distributed registry in which are stored all transitions. In the sidebar of Figure 4, there are the following Tangle properties: (i) messages that indicates the number of messages sent; (ii) MPS, i.e., the number of messages sent to the network per second; (iii) TIPS, i.e., the number of unapproved transactions; (iv) referenced, i.e., the percentage of transactions referenced by other transactions; (v) conflicting, i.e., the percentage of transactions with conflicts; and (vi) solid, i.e., transactions with their history.

In Figure 5, it is possible to see one of the requirements for interacting with the IOTA network. The choices depend on the technologies one chooses to use, but also on whether one wants to use one's own node (direct access) or rely on third-party nodes.



MESSAGES
597
MPS
13
TIPS
118
REFERENCED
80.23%
CONFLICTING
0.00%
SOLID
103.18%

Figure 4. Tangle graph.

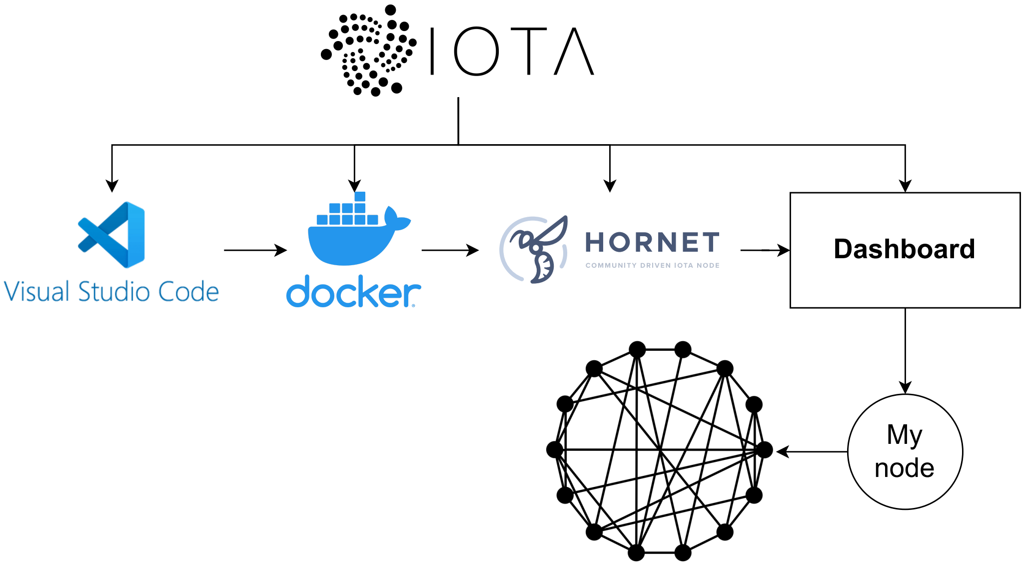


Figure 5. Dependencies and requirements of IOTA.

Constructing a personal node for network access is the optimal choice. The entire infrastructure can be raised using an editor (e.g., Visual Studio Code) or any other editor or IDE. Once Docker is configured and operational, the installation of either Hornet or Bee is enabled allowing for crafting nodes. Upon completion, the node may be launched via Docker. After configuring the network settings, the dashboard is accessible, enabling the owned node viewing as well as interaction with other nodes and also providing insights regarding the IOTA network.

MongoDB Atlas

Atlas uses MongoDB as a database, taking advantage of its scalability and flexibility and of its useful indexes and queries for data processing.

Data originating from the Raspberry Pi are sent through EMQX and are written into the Atlas database. To establish a database on MongoDB Atlas for agricultural monitoring, follow these steps: register on the Atlas website, choose a cluster, create the database, and configure the connection string. MongoDB stores data records as BSON documents in collections, similar to tables in relational databases. The document model based on

MongoDB is clear, easy to use, and supports various languages through its included drivers. The Atlas interface provides an overview of the data flow and allows the transformation of agricultural data into charts, as shown in Figure 6, which displays two charts, one tracking the temperature and humidity data over time based on the hour, the other counting the amount of data each sensor has sent compared to the other sensors.

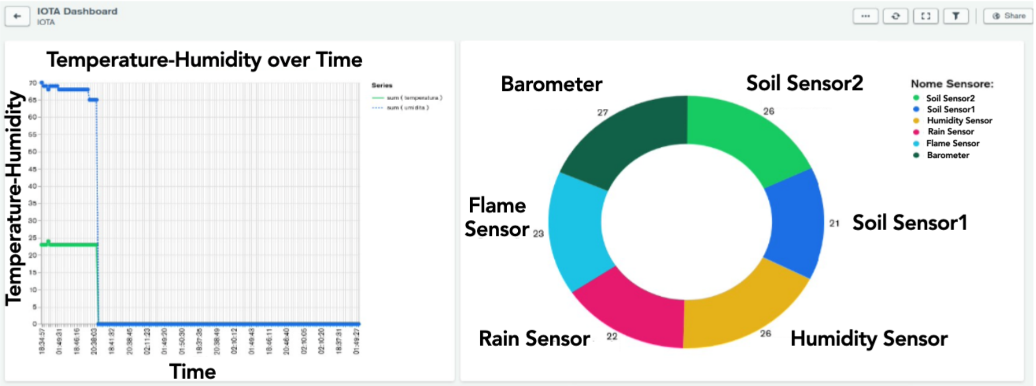


Figure 6. Atlas data charts.

By selecting the desired database, it is possible to choose the chart and then select the data of interest to be represented in the graph, setting a title and some properties. This chart is saved in the dashboard, and every time new data are received, they are written into the database, automatically updating the various charts based on the corresponding fields. There are approximately nine chart options, with an average of two subcategories for each.

In Figure 7, it is possible to see the number of times a certain temperature is detected. For example, 23 degrees has been detected 25 times, while 24 degrees has been detected only 5 times. The chart on the right displays the total count of temperature data. In this case, both the humidity and barometer sensors detect the temperature. By adding the two values shown in the second chart in Figure 3, which are 26 and 27, a percentage of 53% is obtained.

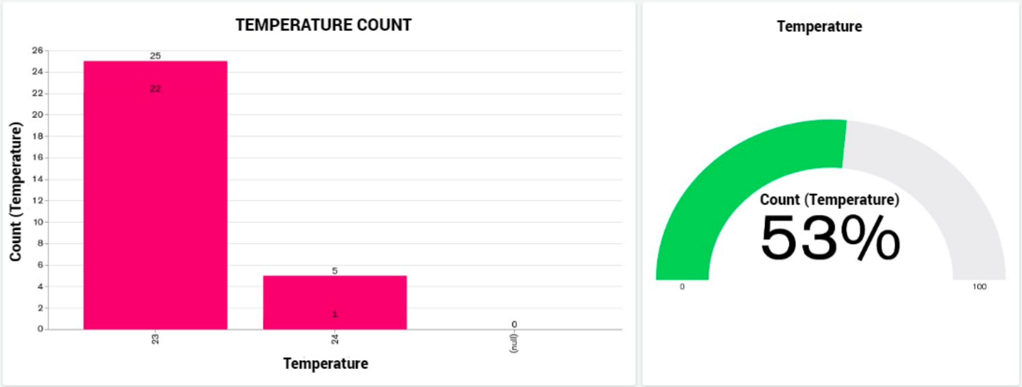


Figure 7. Temperature.

These visualizations can be made visible to specific users, such as farmers or sustainability experts, or even made public through an off-site link. This feature enhances the accessibility of critical sustainability information, even outside of Atlas, promoting transparency and informed decision-making in agricultural practice. Hence, integrating MongoDB and Atlas in an IOTA-based deployment offers a robust solution for monitoring and analyzing sustainability parameters in agriculture. The flexibility in storage options, ease of setup, and data visualization capabilities make it a valuable tool in modern agricultural practices.

Figure 8 depicts the architecture of the proposed model and the logical flows running through the system components. Briefly, data gathered by the IoT Sensors flow through EMQX to the Raspberry Pi, which acts as a gateway to send data to the HTTP Application Server. The node Application Server manages such data communicating with the IOTA network passing through the deployed node, as well as with the Atlas interfaces, thus enabling data monitoring via the analytical dashboard.

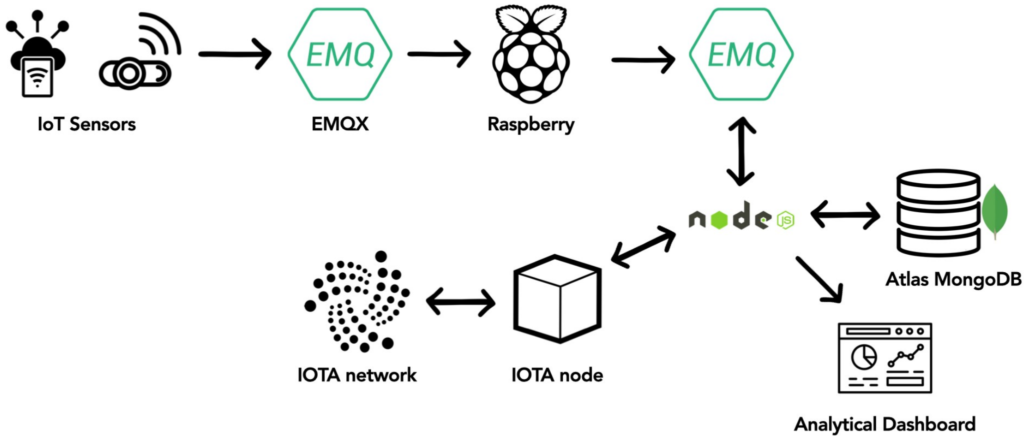


Figure 8. Architecture of the system.

4. Results

To monitor sustainability parameters in agriculture, MongoDB Atlas has been integrated into the IOTA-based deployment. The setup process has involved registering on the Atlas website, selecting a cluster, creating the database, and configuring the connection string.

The Atlas interface allows the transformation of data into charts, which are automatically updated with new data. To this aim, data from devices like Raspberry Pis are sent through EMQX to a Node.Js script by leveraging APIs, and received data are stored in the MongoDB Cloud of Atlas. Moreover, we implemented a connection established with the local IOTA node (Hornet Mainnet) to propagate the data in the IOTA Tangle. The created Node.js server takes care of receiving, processing, and translating the data into services for the graphical interface.

A lightweight Node.js server is created to receive, process, and translate the data into services for the graphical interface. The server listens on a customizable port, providing services to those who connect to that port.

Aiming to achieve real-time insights, we developed an analytical dashboard, which is responsible for making viewable the received data. These are divided into several sections, each describing a different analysis aspect, as depicted in Figure 9. The sections include notifications, derived data, graphs, a table, alerts, and a map. The data in the table include count, id, date, time, message, temperature, humidity, pressure, altitude, latitude, longitude, status, and sensor name. Two soil sensors have been installed, one for notifying when the soil's water level is insufficient and the other for alerting when there is excess water.

Hereafter, we illustrate the various sections of the analytical dashboard displayed in Figure 9.

- Section 1 showcases a menu that remains visible while scrolling the page. It counts both incoming data and highlights any data that requires attention. These particular data points are also tallied in the alerts.
- Section 2 illustrates data derived from analytical operations performed on raw sensor data. Starting from the left, we have the average humidity, obtained by summing up the humidity data points and dividing them by the number of humidity data points. Next, the minimum and maximum humidity values are reported by comparing the previously stored data with the subsequent data. Depending on the result, the old data may be overwritten. As in the case of humidity, it is possible that there are no

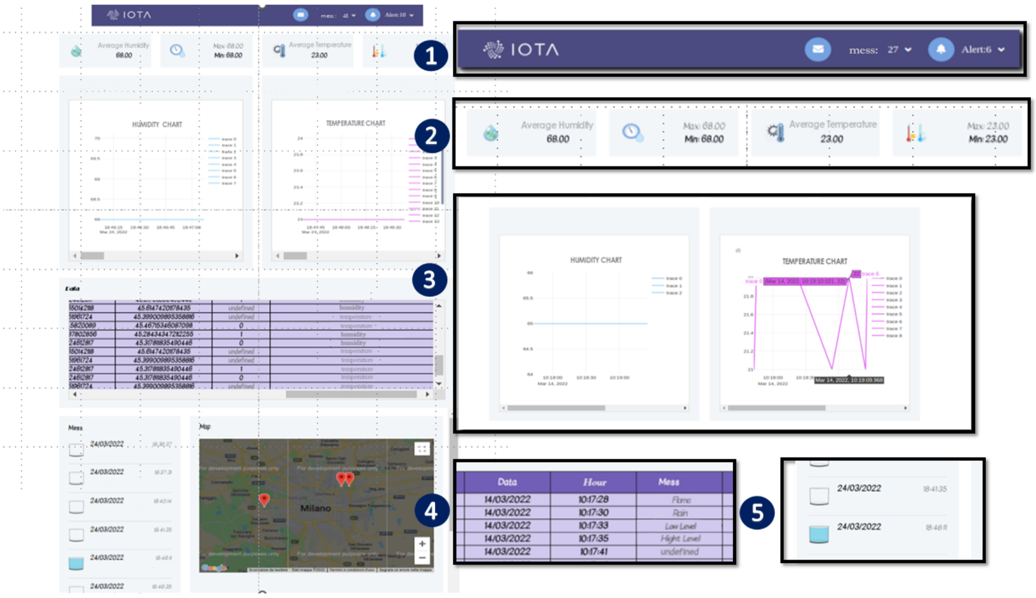
fluctuations in either an upward or downward trend, resulting in the “Min” and “Max” values being equal. “Average Temperature”, “Min”, and “Max” values are calculated in the same manner.

- In Section 3, the “HUMIDITY” box displays the humidity data received from the temperature sensor. Specifically, the x-axis represents the time the data are received, and the y-axis represents the temperature data, which remain constant at 65% in this case. Regarding the “TEMPERATURE” box, the same procedure described in the previous case is followed, with the difference being that the temperature data are considered. As observed, the temperature data vary between 22 and 21 degrees within the selected time interval. The “traces” are the lines used to construct the graph; in the “TEMPERATURE” box, there are eight traces. Both boxes feature a scroll bar that appears when the graph requires more space to display the newly received data while allowing the visualization of previous data by scrolling through the bar.
- Section 4 shows a dynamically populated table with JSON data sent by Raspberry sensors. There is a data model for the data types that each sensor sends, and the table can be fully viewed by scrolling horizontally. The same applies to the quantity of data, which requires scrolling vertically to view it. In detail, the data in the table include:
    1. Count indicates the number of times a specific sensor sends data;
    2. Id uniquely identifies each sensor;
    3. Date indicates the date the data was sent by Raspberry;
    4. Time indicates the time corresponding to the data sent by Raspberry;
    5. Message indicates additional information regarding the data;
    6. Temperature indicates the detected temperature;
    7. Humidity indicates the recorded humidity;
    8. Pressure indicates the identified pressure;
    9. Altitude indicates the measured altitude;
    10. Latitude and Longitude indicate the geographic coordinates of the sensor’s location;
    11. Status takes a value of 0 or 1 depending on the sensor;
    12. Sensor Name indicates the sensor’s name, which is useful for identifying the specific sensor being considered. The value “undefined” indicates that the specific sensor being considered does not produce that type of data detected by another specific sensor for that purpose.
- In Section 5 of Figure 9, the sensors with values requiring greater attention are displayed on the left, as seen in the table. Each alert notification is accompanied by the date, time, critical message, and an icon indicating its significance. At the top, the total number of alert messages received is shown. On the right, a real map is displayed, showing simulated geo-localization coordinates of the sensors. These data can either be pre-set or dynamically passed and plotted.

Similarly, Figure 10 demonstrates the functioning of the two soil sensors, one alerting when the soil’s water level is insufficient, the other signaling when there is excess water.

According to the works of Mboyerwa et al. [21] and Prem Kumar et al. [19], IoT and IOTA have emerged as disrupting technologies in the agrifood supply chain and sustainability optimization; we deem that our Proof-of-Concept will be a further advancement in monitoring and improving the sustainability of agrifood production processes. Moreover, IoT devices relying on centralized communications present a number of security threats related to privacy and security. IOTA addresses these flaws, also removing the blockchains’s limitations; indeed, IoT devices lack the computational power and storage needed to run consensus algorithms to be an involved part of the blockchain [22].

Taken together, our results answered the question that guided our research by creating a web application capable of integrating IOTA with IoT sensors devoted to real-time monitoring of agrifood supply chains.



Data	Hour	Mess
14/03/2022	10:17:28	Flame
14/03/2022	10:17:30	Rain
14/03/2022	10:17:33	Low Level
14/03/2022	10:17:35	Hight Level
14/03/2022	10:17:41	undefined

24/03/2022 18:41:35
24/03/2022 18:46:11

Figure 9. Analytical dashboard.

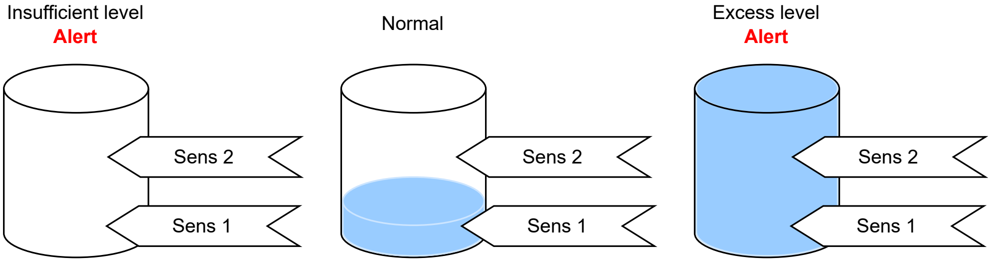


Figure 10. Functioning of the soil sensors.

5. Discussion

In this section, we discuss the obtained results.

5.1. DLTs in Agriculture—IOTA and Traditional Blockchains

We summarize here the main results of the Proof-of-Concept illustrated in the previous section to then put them into perspective in the trend of adoption of DLT and blockchain technologies in the agricultural sector and the role that IOTA can specifically play in this context:

1. Efficiency in Resource Utilization: This study shows that integrating IoT and IOTA can significantly reduce resource consumption. Thus, this integration effectively implements the sustainable agricultural practices illustrated in [21].
2. Technological Infrastructure: This study employs various technologies, including Raspberry Pi 4, various sensors, and IOTA, a distributed ledger technology tailored for IoT. These technologies monitor various environmental conditions like soil moisture, temperature, and pH.
3. Data Management and Security: This study uses IOTA to bolster data management and introduce a robust authorization system. It also employs MQTT and EMQX for remote IoT data collection, supporting up to 2 million connections on a single server node.
4. Environmental Impact: IoT has the potential to mitigate the environmental footprint of agriculture by reducing water and energy consumption, greenhouse gas emissions, and fertilizer runoff.
5. Financial Benefits: IoT can elevate the profitability and competitiveness of farmers by granting access to new markets, services, and performance-based incentives.

6. Real-Time Monitoring: The IOTA dashboard provides real-time insights into various parameters like soil moisture, temperature, and pH levels, enabling informed decision-making for sustainable agriculture.
7. Technological Toolkit: This study uses a diverse set of technologies, including Raspberry and its sensors, EMQX (MQTT), VPN and Ubuntu, Docker, IOTA, and MongoDB, and is programmed in Python, NodeJs, Javascript, HTML, and CSS.
8. Sustainability: This study concludes that the IoT stands as a pivotal force in enhancing agricultural productivity and sustainability, especially as the demand for food rises amidst limited resources.

Transitioning from these findings, we delve into the broader implications and applications of DLTs in agriculture. Agriculture is a critical sector facing numerous challenges, including climate change, environmental degradation, and the need for sustainable practices. These challenges necessitate innovative solutions, and one such promising technology is the IoT. However, the vast amounts of data generated by IoT devices must be managed securely and efficiently. Moreover, agrifood businesses are increasingly pressured by governmental and consumer organizations to validate the safety and quality of their production processes.

To meet these demands, DLTs offer a robust solution. They provide a decentralized system for storing and updating data across a network of nodes, eliminating the need for a central authority. DLTs employ cryptography and consensus mechanisms to ensure data integrity and validity. While DLTs offer numerous benefits like traceability, transparency, and operational efficiency, it is important to note that they are not a one-size-fits-all solution. Different DLTs have their own strengths and weaknesses, which we will explore by comparing three prominent DLTs in agriculture: Ethereum, Hyperledger Fabric, and IOTA. Of course, this is not a random choice; all three platforms stand out for their agricultural achievements and potential compared to other DLTs and blockchains. We will focus on two main use cases: traceability in the agrifood supply chain and real-time monitoring of cultivation practices. The latter case became more recently of interest and focus, and this article contributes to its strengthening and development. At the same time, the former has an older record, being one of the first use cases of non-financial blockchain/DLT applications. To compare these three DLTs strictly from a technological standpoint, see the study of Garriga et al. [6] instead, and the study of Dalla Palma et al. [23].

5.1.1. Traceability in the Agrifood Supply Chain

The agrifood supply chain is a complex network of multiple stakeholders: farmers, processors, distributors, retailers, and consumers. Each stakeholder has its record-keeping system, which may not be compatible or transparent to others. This creates challenges in ensuring food products' origin, quality, and safety and meeting local and international regulations. DLTs can help overcome these challenges by providing a shared and immutable ledger of transactions and data throughout the production process.

Ethereum and Hyperledger Fabric, the most popular blockchain platform from the Hyperledger software ecosystem, are traditional blockchains supporting traceability in the agrifood supply chain. Ethereum is a public blockchain that allows anyone to join and participate in the network. It supports smart contracts, i.e., self-executing agreements written in code that can automate supply chain processes and ensure traceability. Fabric is a private blockchain that allows only authorized participants to join and transact on the network. It supports private transactions and complex supply chain permissions that can handle sensitive data and comply with regulations.

Ethereum and Hyperledger Fabric have been used for various traceability projects in the agrifood sector. For instance, IBM Food Trust (https://www.ibm.com/blockchain/solutions/food-trust, accessed on 7 October 2023) is a platform built on Fabric that connects farmers, processors, distributors, and retailers to share data and track food products from farm to fork. Similarly, OriginTrail (https://origintrail.io/, accessed on 7 October 2023) is a protocol built on Ethereum that enables interoperable data exchange and verification across different supply chain actors. The articles by Cocco et al. [24] and Marchesi et al. [25]

discuss case studies and software development methodologies specifically in the context of blockchain-based food traceability systems.

5.1.2. Blockchains vs. IOTA DLT in the Agrifood Supply Chain

Among DLTs, the blockchain is a technology that can enhance the privacy and security of IoT-interconnected smart devices, as several papers have demonstrated [26,27]. The blockchain offers features such as transparency, immutability, resilience, and cryptography that can address some of the challenges of IoT network architecture. However, the blockchain also has a cost in terms of transaction fees and architectural complexity, requiring expertise from various disciplines. Therefore, the blockchain should manage valuable assets, such as business data and financial assets [28]. On the other hand, the IOTA Tangle is a DLT that can improve sustainability and agrifood monitoring without such costs, allowing agrifood supply chains to adopt it without affecting their business [29].

5.1.3. Real-Time Monitoring of Cultivation Practices

The other use case for DLTs in agriculture, treated explicitly in the previous section of this article, is real-time monitoring of cultivation practices. This involves using IoT sensors to collect various data from the field, such as soil moisture, temperature, humidity, pest infestation, and so on. These data can help farmers optimize their inputs, reduce their environmental impact, and improve their yields. However, IoT sensors generate huge amounts of data that must be transmitted and stored securely and efficiently.

As we have seen, IOTA is a DLT that is designed for high-frequency IoT scenarios. Unlike traditional blockchains that use a linear chain of blocks to store data, IOTA uses a DAG called Tangle. The Tangle is composed of individual transactions that are interlinked to each other and stored across a network of nodes. To issue a transaction on the Tangle, a node has to validate two previous transactions. This allows IOTA to overcome the cost and scalability limitations of blockchains.

As highlighted in the description of our study, IOTA has several advantages for real-time monitoring of cultivation practices. First, it enables zero-fee transactions, meaning nodes can send and receive data without paying fees. This is ideal for frequent, low-value data transmissions from IoT sensors. Second, it enables high scalability, meaning the network can handle many transactions per second without compromising performance or security. This is ideal for accommodating varying numbers of sensors and devices on the network. Third, it enables data integrity, which means that the data stored on the Tangle are tamper-proof and verifiable by anyone on the network. This is ideal for accurate decision-making based on real-time data.

Our study offers a comprehensive guide for building an IOTA-based real-time monitoring system tailored for sustainable agriculture. In this context, it complements Future Farm (https://future-farm.iota.org/#/, accessed on 7 October 2023), an initiative by the IOTA Foundation that also leverages IOTA for data collection and analysis through IoT sensors in greenhouses. While Future Farm focuses on process optimization—emphasizing the sharing of IoT data among various stakeholders in agriculture—our approach is more user-centric. Specifically, we demonstrate how a farm operator can effectively utilize the IOTA Tangle for real-time monitoring.

5.1.4. Complementarity: Technology and Business Perspective

Technology: The strengths and weaknesses of Ethereum, Fabric, and IOTA are summarized in Table 2 from a sustainable agriculture perspective standpoint. While Ethereum and Fabric cater to supply chain transparency and notarization of product origin and quality, IOTA is tailored for high-frequency IoT data transactions. However, these DLTs are not mutually exclusive. They can be integrated and interoperable, offering a comprehensive view of the agrifood sector. For example, IOTA's real-time data can be linked to Ethereum or Hyperledger Fabric's smart contracts, triggering actions or payments based on predefined conditions. Alternatively, IOTA's data streams can be hashed and anchored to Ethereum or

Hyperledger Fabric's blockchains, creating a secure and verifiable record of the data history. These integrations can leverage the best features of each DLT, creating a synergistic effect.

Table 2. Comparison of DLTs in agriculture: Ethereum, Hyperledger Fabric, and IOTA.

Capability	Ethereum	Hyperledger Fabric	IOTA
Traceability	Yes	Yes	Limited
Real-Time Monitoring	Limited	Limited	Yes
Transaction Fees	Yes	No	No
Scalability	Moderate	High	High
Data Integrity	High	High	High
Privacy	Limited	High	Moderate
Smart Contracts	Yes	Yes	Yes (limited)
Interoperability	Moderate	High	Moderate
Regulatory Compliance	Moderate	High	Moderate

Business: DLTs offer different value propositions for the agrifood sector depending on their use cases and applications. While traceability emphasizes transparency, notarization, and compliance, real-time monitoring targets operational efficiency and sustainability. These value propositions can have various implications for market differentiation and consumer engagement. For instance, traceability can bolster branding and product authenticity, creating a competitive edge in the market. Traceability can also assure consumers about product origin and quality, increasing their trust and loyalty. On the other hand, real-time monitoring can lead to sustainable practices and cost savings, improving the business's bottom line. Real-time monitoring can also offer insights into sustainable cultivation practices, educating consumers and raising awareness.

Enriched Business Value: Integrating DLTs in the agrifood sector can also create new opportunities for funding acquisition and carbon credit trading. These opportunities can provide financial incentives for adopting DLTs and promoting sustainable agriculture. For example, traceability and real-time monitoring can serve as evidence for quality manufacturing and sustainable cultivation practices. This can be pivotal for acquiring funding from government agencies or private investors that incentivize such practices. Moreover, integrating DLTs can facilitate the generation of carbon credits by validating sustainable practices. These credits can be traded as securities on DLT-based platforms, offering a new revenue stream for farmers and businesses. On the other hand, Ethereum and Hyperledger Fabric can leverage the capability of inter-enterprise transactions of their smart contracts to go beyond traceability to boost supply chain efficiency and profitability, as shown in [30,31].

Summing up, Ethereum, Hyperledger Fabric, and IOTA are three prominent DLTs that can revolutionize the agrifood sector. While they cater to different agrifood needs, their combined strengths can create a holistic solution that addresses the challenges and opportunities of the sector. By integrating them into suitable ecosystems as characterized in Salzano et al. [32], innovators can ignite a global business transformation that benefits farmers, businesses, consumers, and the environment.

5.2. Reapplicability of Our Model

Our research demonstrates a flexible and adaptable model, where the specific components we used can be substituted with equivalent alternatives to suit different requirements.

- Database Management System Flexibility: While our study leverages the capabilities of MongoDB, the architecture of our model is not limited to this particular DBMS. The design is compatible with various other database management systems, enhancing the model's applicability across diverse data management scenarios.

- Hardware Versatility: In terms of hardware, our choice of the Raspberry Pi 4 is illustrative rather than prescriptive. The model can be adapted to work with a range of single board computers or similar devices, provided they possess comparable technical capabilities. This flexibility ensures that our model can be deployed in a variety of hardware environments.
- Sensor Selection and Adaptability: We chose specific sensors for monitoring key parameters in the rice supply chain. However, this selection is not rigid. Different sensors can be employed based on the requirements of other agrifood products or supply chains. The adaptability of our model to various sensor types and data inputs underscores its potential for broader application in agriculture.
- Cross-Product and Supply Chain Applicability: While our Proof-of-Concept is centered on rice cultivation, the underlying model is designed to be transferable to other agrifood supply chains. This transferability is facilitated by the selection of appropriate sensors and the integration of various communication protocols.
- System and OS Compatibility through Containerization: Our model's use of containerization technology ensures its portability and compatibility across different systems and operating systems. This aspect of the design significantly enhances the model's utility and ease of deployment in diverse IT environments.

In summary, the design of our study reflects a commitment to versatility and adaptability, allowing for the application of our model in a variety of agricultural contexts beyond its initial implementation.

6. Conclusions

This research project has been centered around exploring the transformative impact of IOTA, in synergy with IoT technologies, on enhancing sustainable agricultural practices. Our study specifically targeted the optimization of water-resource consumption in rice field irrigation, which is a critical aspect of sustainable agriculture.

The core objective of our study was to meticulously monitor and improve resource utilization, with a particular emphasis on water efficiency. The results demonstrate that an intelligent irrigation system, powered by advanced sensor technology, can be instrumental in achieving sustainable cultivation practices. This system enables real-time data acquisition and analysis, which are pivotal in guiding empirical practices for resource optimization. Specifically, we observed the potential of this system to significantly reduce water usage by up to 50%, lower nitrogen consumption by 25%, and decrease methane emissions by 50% to 70%.

A key aspect of our system is its ability to compile historical data on water usage, providing a rich dataset for strategizing future resource management approaches. The integration of IoT devices, particularly those managed through IOTA's technology, has proven exceptionally effective in handling and analyzing large volumes of data, thereby boosting the overall efficiency and precision of agricultural processes.

A notable accomplishment of this project was the seamless and rapid data transmission from the field (via Raspberry Pi) to the cloud. This was achieved with minimal latency, demonstrating the effectiveness of MQTT in data routing and the capacity of IOTA to provide near-real-time recording and optimal storage for extensive datasets.

Despite some latency challenges encountered with MongoDB, it played a crucial role as an intermediary, facilitating effective communication and data management between IOTA and other integrated technologies. This integration was pivotal in enhancing data organization and processing speed.

Looking ahead, future research could explore optimizing sensor sampling rates to make them more dynamic and responsive to environmental and inventory conditions. Additionally, adjusting the number of active sensors based on these parameters could enhance efficiency, allowing some IoT devices to enter a sleep mode when not needed, thus conserving energy.

In conclusion, this research highlights the integral role of IOTA, particularly in tandem with the IoT, in the future of sustainable agriculture. IOTA emerges not just as one of many options, but as a particularly compelling choice for real-time monitoring and implementation of sustainable agricultural practices. Its application extends beyond mere data tracking to actively influencing and optimizing on-ground practices, aligning closely with the global goals of environmental conservation and food security. This study affirms that the synergy of IOTA and IoT is not just a computational marvel but a practical tool for empirical advancements in agriculture.

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Conflicts of Interest: Remo Pareschi and Roberto Carlini were employed by the company BB-Smile Srl. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

DAG	Directed Acyclic Graph
DBMS	Database Management System
DLT	Distributed Ledger Technology
ICT	Information and Communication Technology
IA	Artificial Intelligence
IoT	Internet of Things

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