Integrated Approaches to Monitoring GIAHS Territories: Requirements, Telematics, Sensorization and Intelligent Management Solutions

Joel Soares[1][a], Carlos Teixeira[1][b] and Ramiro Gonçalves[1,2,3][c]
[1]*AquaValor-Centro de Valorização e Transferência de Tecnologia da Água-Associação, Rua Doutor Júlio Martins nº1, 5400-342 Chaves, Portugal*
[2]*Institute for Systems and Computer Engineering, Technology and Science, 4200-465 Porto, Portugal*
[3]*School of Science and Technology, Universidade de Trás-os-Montes e Alto Douro, 5000-801 Vila Real, Portugal*

Keywords: GIAHS, Environmental Monitoring, IoT, Technological Architecture, Sensors.

Abstract: Globally Important Agricultural Heritage Systems (GIAHS) are models of sustainability, as they ensure a balance between human activity and ecosystem conservation. The Barroso region in Portugal is part of this network, as it follows traditional natural resource management and resilience practices by local communities. Given the threats posed by environmental degradation, it is urgent to adopt technological solutions for monitoring these conditions. Thus, throughout this article, the main threats to the integrity of these territories will be analyzed, and various methodologies and solutions for environmental monitoring will be presented. Based on the knowledge acquired, we will present an architecture for a digital solution that includes sensors, the Internet of Things (IoT), processing units, and platforms for real-time data visualization and alarm management.

1 INTRODUCTION

The United Nations Food and Agriculture Organization (FAO) created the Globally Important Agricultural Heritage Systems (GIAHS) initiative to identify and protect agricultural systems of exceptional global value (Koohafkan & Altieri, 2011).

Since the concept originated in 2002, GIAHS aims to ensure sustainability of dynamic systems where people and natural environment evolve together over generations (Arnés García et al., 2020).

In addition to their production function, GIAHS locations preserve landscapes and agro-biodiversity, significantly contributing to the development of rural territories, with a positive balance between field production and conservation of natural resources (Agnoletti & Santoro, 2022). They also preserve intangible cultural values, reinforcing identity and social cohesion through intergenerational transmission of knowledge and customs (Nan et al., 2021). Recently, GIAHS regions have gained global attention for their resilience and sustainability, withstanding climate and socio-economic changes without abandoning ancestral traditions and identities (Arnés García et al., 2020). Protecting these regions strengthens regional economic development by promoting sustainable tourism and consequently increasing work options for the individuals living in the area (Jiao et al., 2022). Despite their importance, GIAHS territories face increasingly complex threats to their integrity (Figure 1). Climate change, a mounting threat, increases extreme weather events, droughts, floods, heatwaves, directly reducing productivity and degrading ecosystems (Yadav & Jin, 2024). On the contrary, environmental decay, loss of biodiversity, habitat degradation, and pollution also threaten GIAHS sites, owing to the over usage of pesticides and fertilizers causing soil and water pollution, degrading their quality.

[a] https://orcid.org/0009-0000-6336-7158
[b] https://orcid.org/0009-0003-2982-5217
[c] https://orcid.org/0000-0001-8698-866X

Soares, J., Teixeira, C. and Gonçalves, R.
Integrated Approaches to Monitoring GIAHS Territories: Requirements, Telematics, Sensorization and Intelligent Management Solutions.
DOI: 10.5220/0013894400003982

In *Proceedings of the 22nd International Conference on Informatics in Control, Automation and Robotics (ICINCO 2025) - Volume 2*, pages 597-608
ISBN: 978-989-758-770-2; ISSN: 2184-2809

At the same time, industrial agriculture and globalization press GIAHS sites promoting monoculture and reducing agrobiodiversity, resilience and sustainability (Agnoletti & Santoro, 2022). Such problems are responsible for eroding the adaptive capacity, as well as ecological sustainability of the GIAHS sites.

Despite the need for monitoring, there is no harmonized framework, and each country defines its own protocols (Jiao et al., 2022). For this reason, there can be failures or gaps in the early detection of variations, which can make decisions for protecting these sites difficult, making integration with smart technology and digital monitoring solutions also relevant (Martins et al., 2022). To fend off this plague, advanced sensor-based systems with real-time analysis must be applied for designing more efficient and adaptive monitoring frameworks (Morchid et al., 2024). One of the strategies for minimizing this problem is by using smart, self-sustaining architectures to enable real-time monitoring, with the possibility to provide for automatic alerts for immediate action to be taken in the occurrence of emerging issues that impact quality standards.

For such issues to be tackled, an overall technological and information system design must be put in place with the capacity for answering the regions specific requirements. This system must include advanced environment sensing technology, smart data handling and processing, as well as sufficiently backed-up power systems (Mansoor et al., 2025).

Such requirements are in accordance with the dynamic conservation concept advocated by FAO, insofar as in leading the advancement of these regions not only through preservation, but through the proactive adaptive extension of GIAHS itself (Koohafkan & Altieri, 2011).

2 MONITORING REQUIREMENTS OF GIAHS TERRITORIES:

2.1 Characteristics GIAHS Territory

GIAHS sites are defined by their agricultural, cultural, and social diversity, contributing to environmental sustainability and socioeconomic resilience (Agnoletti & Santoro, 2022).

Beyond their biodiversity, GIAHS regions preserve traditional wisdom passed through generations. This ancestral knowledge includes cultivation and soil conservation practices that promote sustainability and rational use of natural resources (Koohafkan & Altieri, 2011). These territories feature distinctive landscapes shaped by long-standing community environment interaction.

These landscapes, in addition to their aesthetic value, are functional, as they support agricultural production and contribute to the biodiversity in the area. Adoption of diversified farming methods makes it possible for GIAHS to provide communities with food security, while boosting the local economy with products of commercial and cultural value (Agnoletti & Santoro, 2022). Such distinctive features of the GIAHS enhance socio-economic sustainability, an added value reinforced through the marketing of products with a positive impact in addition to enhancing local tourism with further benefit towards the continuity of traditional aspects, as well as the distribution of wealth in the community. For this to be achieved, it is worth emphasizing the adaptability these territories harbor, especially regarding climate change, in addition to environment variability, with an ability for the local communities to adapt their farming methods constantly (Lin et al., 2025; Mekouar, 2023).

These characteristics align with the FAO vision of vibrant conservation, merging adaptation and innovation, so GIAHS sites can address present and future challenges while preserving their heritage (Koohafkan & Altieri, 2011).

2.2 Indicators for Environmental Monitoring

The monitoring of a GIAHS location requires specific strategies, in tune with its peculiarities, as highlighted above. It requires receiving proper data regarding soil, air, and water quality (Martins et al., 2022; Jiao et al., 2022), as can be seen in Figure 1.

Water quality, essential for agriculture and community well-being, must be monitored for contaminants caused by agrochemical misuse, which can pollute water, affect health, and harm biodiversity (Zia et al., 2013). Conversely, physicochemical parameters like pH, conductivity, turbidity and dissolved oxygen also need to be monitored, as these are crucial quality indicators for everyday usage of the water. Nonetheless, water availability is also crucial for territorial sustainability and agriculture activity (Krklješ et al., 2024). Air quality is a highly important parameter in GIAHS jurisdictions and an important barometer for human health. Since there is an increased level of industrialization and pollution, there is an increased demand for regulating the rate of gases together with suspended particles, which cause respiratory issues (Borghi et al., 2023).

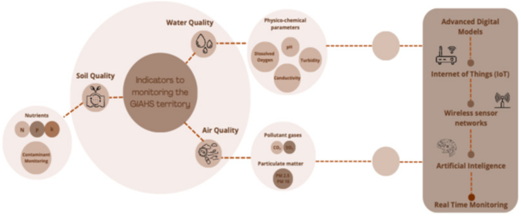

Figure 1: Integrated environmental indicators and digital technologies for real-time monitoring in GIAHS territories.

Soil quality is a key factor for the functionality and longevity of GIAHS sites. For this reason, systematic monitoring should detect pollutants like heavy metals and pesticide residues, which are toxic to ecosystems and human health. A complementary approach involves monitoring basic nutrients such as nitrogen, phosphorus, potassium and even organic matter, key indicators of soil fertility and the preservation of local balances in the ecosystem (Rashid et al., 2023).

However, to ensure real-time monitoring, it is also essential to implement intelligent digital models, such as wireless sensor networks, the Internet of Things (IoT), and artificial intelligence (Miller et al., 2025). This approach allows for the continuous collection of data on soil nutrients and pollutants, water quality and availability, pollutant gases concentrations (Musa et al., 2024), and the presence of suspended particles. This provides a clear overview of the ecological condition of the monitored area (Mansoor et al., 2025).

Incorporating these models within GIAHS sites is original, since it becomes possible to streamline environmental control procedures, providing added value to local products, assisting in fortifying the resilience of communities faced with external demands, for example, industrialization and over-use of toxic agents in agriculture (Martins et al., 2022). By connecting ancient wisdom with new technologies, adhering to the perception of dynamic conservation advocated by FAO, a solid and versatile model can be devised with a perspective that ensures cultural and ecological integrity preservation of the GIAHS, assuring a long-term sustainability.

2.3 Key Challenges to Effective Real-Time Monitoring

Digital ecosystems offer great potential for GIAHS monitoring but face significant challenges (Miller et al., 2025).

One of the main challenges is associated with the enormous technical and architectural complexity of these systems, since they are integrated systems based on the IoT, which require a multi-layered with each layer having a specific function (Maurya et al., 2024).

On the other hand, one of the major challenges of these systems is closely linked to the management of large volumes of data (Big Data). The large amounts of data from the sensors, images from satellites and meteorological data require acquisition, storage, processing and analysis processes that are often not available in this type of territory, due to a lack of technical capacity, specialized human resources and limited technological infrastructures. Due to these challenges, real-time monitoring of this data can often be compromised, thus interfering with the reliability and usefulness of the results (Miller et al., 2025).

Regarding the limitations of digital ecosystems, we highlight the difficulty for merging heterogeneous data from multiple devices and platforms, since efficient integration between geographic information systems, wireless sensor networks and data management platforms requires the adoption of standardized protocols (Pan et al., 2023). Another limitation to consider focuses on the economic sustainability of these digital systems, often identified as one of the most critical being also undervalued in the planning and implementation phases. Maintaining digital infrastructures, including sensors, communication networks, data storage and processing platforms, entails significant operating costs that can compromise long-term viability, especially in GIAHS territories located in rural or remote areas, where technical and financial resources tend to be more limited (Miller et al., 2025; M. Nawaz & M. Babar, 2025).

On the other hand, the limited availability of electrical infrastructure leads to a high dependence on renewable energy sources, such as solar panels, to power this type of digital monitoring solution. However, these methodologies present significant vulnerabilities, which may reduce system reliability in adverse conditions (Abdelhamid et al., 2025). Finally, one of the factors that could be a limitation for monitoring these territories is the acceptance and adaptation of local communities. Adopting new digital technologies requires training and technical skills, which poses a major challenge considering that the population is mostly elderly in these communities. Therefore, measures must, be taken to minimize the changes caused in local areas, and the population must be included as a central element of digital ecosystems creating a link between technological innovation and local knowledge (Zhang et al., 2024).

Although IoT-based digital ecosystems offer a promising model for real-time monitoring, it is important to recognize that they have limitations, so it is crucial to implement solutions that are adapted and customized to the location of interest.

3 TELEMATICS, SENSORIZATION AND INTELLIGENT MANAGEMENT SOLUTIONS

Effective management of GIAHS territories requires a precise, sustainable and technologically integrated approach. Nowadays, there are telematics solutions on the market offering a range of technological tools to improve the efficiency and effectiveness of monitoring and managing these territories, including high-resolution satellite images, unmanned aerial vehicles (UAVs) and environmental sensors deployed on site.

However, the effectiveness of these technologies increases significantly when integrated into advanced information management platforms, with data processing and analysis capabilities, as well as alarmist capabilities, thus facilitating the early identification of anomalies or trends (Shar et al., 2024).

3.1 Satellite Images

Environmental monitoring based on high-resolution satellite images has developed into a useful instrument in many scientific and operational applications in natural resource management, precision agriculture and natural disaster monitoring (Sishodia et al., 2020). Such a technique depends on the frequent scanning of the Earth's surface through the assistance of satellites equipped with special sensors. The environment is subsequently recognized, measured and quantified with a high degree of spatial and temporal precision (Shar et al., 2024; Sishodia et al., 2020).

For such a permanent and accurate observation, satellites such as Sentinel-2, Landsat-8 and WorlsView-3 are used with spatial resolutions ranging up to 0.5 meters and with adequate temporal repetition for the detection of climate change (Drusch et al., 2012). Such use is particularly beneficial in areas such as precision agriculture, surveillance of natural hazards and natural resource management (Segarra et al., 2020).

The data recording is based on sensors on the satellites, depending on the type of radiation the sensors are capable of recording. With regards to optical sensors, they can capture radiation being reflected in the near-infrared and the visible range, performing well in situations where the atmosphere is still and the conditions clear (Wulder et al., 2016).

Thermal sensors, in contrast, pick up emitted radiation and can estimate the temperatures at the surface, while the Synthetic Aperture Radar (SAR) sensors have the advantage of being independent of the presence or absence of the light conditions, or fog, ideal under unfavorable weather (Amitrano et al., 2021). Accordingly, by the employment of this type of technology, the evolution in the agricultural landscapes of GIAHS locations over a period of a few decades can be examined, and thus accurate discernment of changes in behavioral attributes in the land can be identified in a bid to reveal complex and seasonal dynamics.

However, before an analysis can be conducted on the images that have been captured, they are required to go through a pre-processing stage. In this stage, data will go through the process of radiometric and atmospheric correction through software such as Sen2Cor to remove the effect caused by atmospheres in order to retrieve more accurate surface reflectance (Main-Knorn et al., 2017). Concurrent with these atmospheric corrections is the function played by the radiometric calibration in the quality aspect of the results. It is typically conducted through the support of polynomial models whose results have coefficients of determination greater than 0.88 and root mean square errors (RMSE) lesser compared to 0.01 (Raut et al., 2019). With the radiation values properly corrected, we can now focus on the spatial correction of the images for them to possess geographical acuity. Orthorectification ensures accurate spatial correction with such errors lesser compared to 1 pixel in size. In addition, technologies such as pan-sharpening fusion are applied in the improvement of spatial resolution, particularly in panchromatic and multispectral sensors as used in WorldView-3 (Park et al., 2020).

Remotely sensed imagery is therefore a valuable tool in the surveillance of the territory as it has multiple applications. When in the agricultural area, they allow for one to monitor the status of the vegetation, making it possible for the pest to be identified early, assisting in the assessment of the water stress and in the making of the decision regarding fertilization and harvesting (Chattopadhyay et al., 2024).

From the environment standpoint, the method has proven effective in the analysis of illegal deforestation, assistance in the management of protected areas and analysis of the impacts of large infrastructure. Relating to the GIAHS areas, the utilization of time series of Sentinel-2 and Landsat imagery has proved extremely effective in the identification of phenological cycles and the analysis of the impacts of agricultural and environment policies.

Among the various associated advantages, global coverage stands out. However, there are significant limitations, such as decreased accuracy on cloudy days and the need for technical resources to process and interpret the acquired data. With the continuing development in the methods of artificial intelligence, it has been made possible to overcome some shortcomings through the utilization of convulsive neural networks assisting in the aspect of precision as well as the aspect of making analysis processes more automatic (Victor et al., 2024).

3.2 Unmanned Aerial Vehicles (UAVs)

Environmental monitoring by UAVs, also known as drones, has been a useful tool for the extraction of high spatial coverage data in a manner that facilitates observation, description and analysis of ecological and biophysical characteristics in spatial and temporal scales difficult to access through the utilization of other methods (Singh et al., 2024). UAVs have centimetric imagery offering the potential for extracting data in ultra-high spatial resolutions and customized cadences in such a manner that dynamics in natural habitats can readily be understood (Singh et al., 2024).

UAVs are multi-purpose platforms equipped with the latest RGB cameras, multispectral sensors, hyperspectral sensors and thermal sensors making it possible to collect images in very high resolutions in the range from 2 up to 5 cm/pixel depending on the installed flight altitude and the quality level of the installed sensor (Cao et al., 2021).

Sensors such as the RedEdge-P whose flight altitudes range to almost 60 meters offer centimetric resolution imagery marrying RGB and multispectral bands such as red and near-infrared. With such arrangements, it is possible to estimate accurately the spectral indices such as NDVI (Normalized Difference Vegetation Index) and NDRE (Normalized Difference Red Edge) useful for detecting water stress and vegetation health, with a specificity equal or superior to ground sensors (Bhagat et al., 2020; De Castro et al., 2021).

Alongside the above elements, the integration of thermal cameras in UAVs has been extremely effective in identifying temperature changes in vegetation and soil, with the ability to recognize thermal anomalies with a precision ranging from up to ±0.1 °C, particularly effective in the early identification of wildfires or in the delineation of soil temperature and humidity (Guan et al., 2022). The non-invasive capability provided by this form of remote sensing is matched by GNSS (Global Navigation Satellite System) navigation tools and also RealTime Kinematic (RTK) differential correction tools, which provide position precision levels below 2 cm, making them instrumental in applications where there is a need for high spatial precision (Niu et al., 2024). UAVs autonomy and range depend on the model, with models such as the DJI Matrice 300 RTK providing flight durations exceeding 50 minutes and real-time data communication where the distances go up to 15 km (Czyża et al., 2023).

Furthermore, various studies emphasize the potentiality for the use of UAVs in numerous areas of the environment domain, most notably the efficacy of this approach in the description of vegetation in mediterranean crop regions, making it possible for there to be multi-temporal analysis of land utilization where there is the possibility of detecting variations existing in crop dynamics and variations by season (Yeom et al. 2019). Conversely, UAV utilization in agricultural environments has been gaining popularity, most notably given the efficacy with which this method can monitor agronomic parameters in real-time. Such systems are increasingly applied in the early identification of nutritional deficiencies, for diagnosing water stress and in the identification of diseases where there can be the implementation of faster and more accurate measures contributing towards sustainable precision agriculture (Sharma et al., 2025).

The advancing development of UAV systems with increasing autonomy, decreased size and integration with sensors and machine learning approaches for automatic analysis of the gathered data enables new applications towards near-real-time observation of the environment at lowest operating costs and maximum flexibility (Tabassum, 2020). In such a manner, UAVs are receiving a vigorous large-scale response towards current environmental concerns with the optimum compromise between spatial resolution, accessibility and repetition frequency in the observation (Manjunath & Kumar, 2025).

3.3 Sensors Implemented in Situ

Sensors have proven to be effective in monitoring and managing rural areas, especially natural resources. Field deployed sensors monitor physical, chemical, and biological parameters with high temporal and spatial precision. Using of this type of approach is worthwhile particularly in remotely located areas with poor infrastructure where the traditional methods of monitoring are unsuitable or expensive (Abdinoor et al., 2025). Accordingly, in the remainder of this section we will consider some current solutions for the measurement of air, water and soil quality.

Meteorological monitoring uses industrial-grade sensors designed to withstand extreme temperatures, high humidity or heavy rainfall (Concas et al., 2021). A representative example of this type of device is the CWT-BY Outdoor Atmosphere Sensor (ComWinTop), which brings together, the ability to collect information such as ambient temperature, relative humidity, atmospheric pressure, noise levels, light intensity, particulate matter (PM2.5 and PM10) and carbon dioxide (CO2) concentration, all in a single module. This sensor module uses RS485 communication (Modbus RTU), is duly protected by an IP65 shield and has an accuracy of ±0.3 °C for temperature and ±2% for humidity accuracy. It is widely used in agricultural and forestry monitoring (Concas et al., 2021). Similarly, SenseCap sensors (Seeed Studio) offer precision, IP66 resistance, LoRaWAN, and up to 10 years of autonomy, ideal for remote or low-connectivity locations (González et al., 2020).

On the other hand, gas concentration monitoring in rural areas is increasingly important for assessing air quality. Carbon dioxide (CO_2), ammonia (NH_3), methane (CH_4), nitrogen dioxide (NO_2), ozone (O_3) and carbon monoxide (CO) are gases commonly linked to declining air quality and public concern. In the search for means of eliminating this pest, Libelium constitutes a formidable and multi-faced response in this regard in the sense that it has modular sensors for the above-mentioned gases and other gases on the basis of various principles of perception, namely electrochemical sensors, non-dispersive infrared (NDIR) and catalytic sensors according to the nature of the compound to be monitored (Hayat et al., 2019). The CO_2 NDIR sensor measures up to 5000 ppm and is widely used in greenhouses and compost facilities for CO_2 accumulation control (Pandey & Kim, 2007). Electrochemical NH_3 sensors detect below 5 ppm, ideal for livestock environments where exposure may harm animal and human health (Moshayedi et al., 2023).

By integrating these sensors into wireless communication networks, it is possible to efficiently monitor large areas, with high autonomy and low energy impact, promoting the implementation of sustainable strategies for environmental management (Concas et al., 2021). Other complementary examples include the MIPEX-02, a multi-gas sensor that is suitable for rural and industrial environments, where its architecture allows to combine the detection of CO_2 and CH_4 using dual-beam NDIR technology, guaranteeing reliable measurements, even in adverse conditions such as excessive dust or high humidity levels. On the other hand, sensors in the Aeroqual Series 500 range, which are compatible with various electrochemical and photoionization detection (PID) modules, enable mobile data collection in the field and are suitable for monitoring gas emissions and assessing air quality in forest areas (Mead et al., 2013; Whitehill et al., 2022).

Water monitoring is essential for assessing quality and availability, especially in areas prone to scarcity or contamination. To assess water availability, level sensors based on hydrostatic pressure are used, such as the Liquid Level Sensor For Water Level (Seed Studio) or the OTT Orpheus Mini probe, that measure the height of the water column with high precision (Whitehill et al., 2022). In addition, these sensors have IP68 protection, ideal for outdoor water monitoring using pressure transducers that convert column height into digital data (Whitehill et al., 2022).

When sites are difficult to access or susceptible to contamination, ultrasonic or radar sensors can be implemented, such as the VEGAPULS C 11, that performs measurements without direct contact (Wu et al., 2023). About water quality assessment, multi-parametric sensors such as the YSI EX02 or Proteus P35 can be implemented, which are made up of replaceable modules that make it possible to simultaneously measure pH, electrical conductivity, dissolved oxygen, turbidity and temperature, among others, with high precision and resistance to biofouling (Snazelle, 2015). In addition to these solutions, Seeed Studio integrates specific and independent modules for monitoring parameters such as electrical conductivity, pH, turbidity and water temperature, developed with the purpose of being integrated into real-time monitoring systems, making it possible to remotely and continuously collect essential data for the characterization and management of aquatic ecosystems.

Concerning soil quality, dielectric sensors for nutrients, such as the Soil NPK Sensor (Renke), are capable to collect data on the temperature, pH and electrical conductivity of soils, while also being able to estimate the concentration of nutrients such as potassium, phosphorus and nitrogen, all with response times of less than 1 second. In addition to these potentialities, it also has an IP68 protection rating, a decisive factor for its application in open field agricultural monitoring systems (Afridi et al., 2022). Another representative sensor is the Teralytic, capable of measuring pH, humidity, temperature, and NPK nutrients using LoRa for wireless data transmission, ideal for sustainable agriculture (Santos & Armstrong, 2024).

The wide range of sensors available today enables the development of robust systems that balance accuracy, sensitivity, durability, wireless integration, and long-term stability, thus operating reliably in harsh conditions with minimal human intervention.

Therefore, to meet these needs, it is important to use local processing units capable of interpreting the electrical signals generated by the sensors and, thus, performing basic pre-processing and communication operations, highlighting microcontrollers as essential units for these systems. Arduino, a device based on the ATmega328P microprocessor, is one of the most widely used, running at 16 MHz with 32 Kb of flash memory. These features make it ideal for low-complexity applications (Tukur Balarabe et al., 2019). The ESP32 is characterized by combining a 240 MHz dual-core CPU with Wi-Fi and Bluetooth connectivity and a low-power deep-sleep mode (<150 µA), which makes this system suitable for autonomous systems with low energy requirements (M. Broell et al., 2023).

The Raspberry Pi series, on the other hand, represents a more robust and versatile solution, including models ranging from the Model B (ARM single-core at 700 MHz, 256 MB RAM) to the Raspberry Pi 4 and 5, equipped with ARM Cortex-A72 quad-core processors up to 2.4 GHz, 8 GB RAM and multiple communication interfaces (USB 3.0, HDMI, gigabit Ethernet, Wi-Fi, Bluetooth), operating with a Linux system (Hosny et al., 2023).

In addition, the STM32, ARM Cortex-M microcontrollers, developed by STMicroelectronics, stand out for their high energy efficiency, good communication capacity (up to 72 MHz), multiple communication channels (USART, SPI, I²C, CAN) and robustness, being widely used in applications that require stability and low consumption over long periods of operation (D. Li et al., 2020).

With the adoption of these devices, it becomes possible to implement edge computing solutions, significantly reducing latency periods and the bandwidth required for data transmission, while increasing the resilience of these solutions in areas with limited connectivity (Dallaf, 2025).

But for everything to work, there must be protocols for the sensors and the control panels to talk to one another. I²C (Inter-Integrated Circuit) protocol is often used in compact systems due to its simplicity and low energy consumption, linking up to 127 devices by means of just two wires, the SDA (Serial Data Line) and the SCL (Serial Clock Line) lines. This protocol offers a range of speeds from 100 kbps (standard mode) up to 3.4 Mbps (high speed mode), but with limited range of up until about 1 meter. On the other hand, the SPI (Serial Peripheral Interface), a substitute protocol with higher data transfer speed (up until 10 Mbps) and lower latency can also be used in short-range systems like the previous one.

For applications requiring longer distances, RS-232 supports point-to-point communication of up to 15 meters at 20Kbps, however, it is sensitive to noise and does not support multiple devices on the same bus (Rajkumar, 2025). Alternatively, there is the RS-485 protocol which uses differential signaling, allowing speeds of up to 10 Mbps and coverage of over 1300 meters with the possibility of connecting up to 32 devices on the same bus (Scientific, n.d.). Its use in extensive agricultural networks has proven its robustness in the distributed collection of environmental data (water level, temperature, pH) over several hectares (Mo et al., 2022).

To overcome the limitations regarding the infrastructure in rural areas or in distant areas, long-range and low-power communications arise as leaders. Among these are considered LoRa, ZigBee, Wi-Fi, GSM/GPRS, NB-IoT, 4G and 5G. The LoRa (Long Range) stands out by the maximum range up to 15 km, by the transmission rates from 0.3 and 27 Kbps and by the low level of consumption in the order of 10 to 30 mW, ideal for remote and self-sustaining nodes (Duisebekova et al., 2019). On the other hand, ZigBee has a more limited range in the order of 10 to 100 meters and is suited in mesh architecture, being advantageous in environments with existing physical barriers (Fitriawan et al., 2017).

Wi-Fi provides bandwidths of more than 100 Mbps but requires greater energy consumption. On the other hand, technologies such as GSM/GPRS guarantee extended coverage, but the associated disadvantage is the lower data transmission rate, up to approximately 115 Kpbs (Hammami, 2019). Regarding NB-IoT, this protocol operates at rates of between 20 and 250 Kbps, with high signal penetration and energy efficiency (Waseem et al., 2025).

As for 4G and the emerging 5G, they guarantee high-speed transmissions of up to 10 Gbps, with low latency periods of less than 1 ms in the case of 5G, which is a determining characteristic for integrating this type of technology into applications that require real-time transmissions (Agiwal et al., 2016; Polak et al., 2024).

Finally, one approach that has been shown to be effective and amenable for integration in applications based on IoT monitoring has been the MQTT (Message Queue Telemetry Transport) protocol. With TCP/IP operation and publish/subscribe architecture usage, the MQTT protocol is a very effective solution in applications with limited bandwidth, varying latency or intermittent connectivity. As MQTT is compatible with Wi-Fi, 4G and 5G technologies, along with the availability of configurable Quality of Service (QoS) and bidirectional communications, results that the MQTT protocol is particularly effective in synchronizing sensors placed in the field with Cloud platforms with low energy requirements (Shilpa et al., 2022).

3.4 Visualization, Analysis and Alarming Tools

Visualization, analysis, and alert tools convert raw data into structured, user-friendly information, supporting efficient environmental management (Guerbaoui et al., 2025; Olatomiwa et al., 2023). These functions are generally integrated into digital platforms capable of real-time data acquisition, storage, and analysis with high scalability (Geldenhuys et al., 2021). In the field of visualization, platforms like Grafana and ThingsBoard offer interactive interfaces for intuitive data representation. Grafana supports dynamic dashboards with multiple data sources (e.g., InfluxDB, SQL), enabling time graphs, thematic maps, 3D modeling, and pattern detection (Singh, 2023). ThingsBoard, on the other hand, stands out for its object-oriented architecture and native integration of georeferenced maps, offering dashboards with alarm rules based on acquired parameter values (Chen, 2023). For analytics, Node-RED and InfluxDB stand out. Node-RED (IBM) is a low-code tool based on visual flows that facilitates the construction of data pipelines through configurable nodes. It integrates IoT sensors, preprocesses data (filtering, aggregation, transformation) and sends it to time series databases (Onwuegbuzie et al., 2024). InfluxDB is a database specialized in the efficient management of time series, which supports the integration of large volumes of continuous data, allowing for complex historical queries, which leads to the identification of trends, seasonal anomalies as well as the substantiation of mitigation strategies.

The alarming component complements these platforms by allowing the definition of alteration conditions based on static or dynamic limits, duly coordinated with sending channels such as e-mail, SMS, webhooks or internal notifications, reducing the response time to critical events (Filip et al., 2022). Integration with Node-RED or InfluxDB enables anomaly detection and predictive logic, improving failure anticipation and environmental response.

In addition, the *Infracontrol Online* platform (Icp - Infraestruturas Control Portugal, Sitowise Group) is an open cloud SaaS solution focused on the centralized management of urban infrastructures, such as street lighting, waste management and road signs, as well as the integration of real-time measured values of environmental parameters. It offers auto-generated alerts and georeferenced tickets for maintenance teams, plus real-time visualization and historical data access. It has an open, scalable architecture, permitting connectivity with IoT sensors and interoperability with SCADA/PLC systems, to foster an overall, integrated management of cities' operations.

Implementation of digital architectures driven by software like ThingsBoard, Note-Red, InfluxDB and Grafana has turned out crucial in constructing environmental monitoring systems, allowing for the collection, processing and visual representation of data in real time. Platforms such as Infracontrol offer robust mechanisms for operational visualization and alert management, so this platform can be used to supervise urban and environmental infrastructures, aiding decision-making and territorial coordination.

4 FUTURE PRESPECTIVES: PROPOSED TECHNOLOGICAL ARCHITECTURE AS A SOLUTION TO GIAHS MONITORING

One of the modern world's great anxieties, in the face of phenomena such as climate change, adoption of industrial agronomy and devastation of the environment, is the real-time surveillance of GIAHS regions - as has been stated in this review. Sophisticated technological systems should be implemented to enable these systems to be surveyed in real time in a permanent, precise and articulated way (Jiao et al., 2022). However, the adoption of these intelligent instruments has numerous constraints, which highlights the need for the design of a superior digital architecture able to interconnect two fundamental characteristics: autonomy and adaptation towards the territory. With this objective in mind, in this section we propose the adoption of an intelligent technological architecture, designed to offer a sound digital surveillance instrument. This proposal integrates environmental sensing, data processing, information management and user interaction components.

This system has been digitized for the collection and processing in real time of the data to facilitate the making of the required and strategic decisions as key factors in the proper management of the natural resources in GIAHS sites.

A technological architecture was conceived to remotely monitor a GIAHS site, in the Barroso area, in intelligent and integrated manner according to a modular and expandable model represented in Fig. 2.

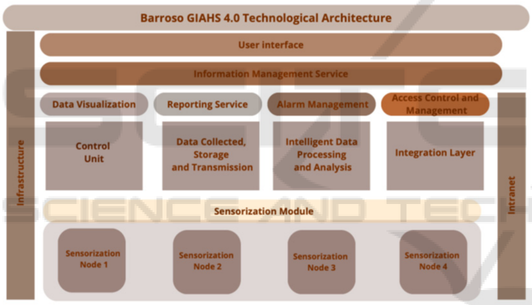

Figure 2: Technological Architecture Overview.

The system was designed to ensure proper collection of environmental data through intelligent processing devices which facilitate the distribution of the data in real-time to the various users and management entities.

At the center of the entire system is the Sensorization Module whose function is the extraction of desired environmental parameters on the soil, water, atmosphere and climatic conditions to accurately estimate the ecological condition of the area.

The main element in this architecture is the Control Unit where the flow of data from the sensors is directed and the entire operation of the sensor module is carried out. The control unit acts as the module manager for the data received from the sensors in such a way the received data is routed through the Data Collection, Storage and Transmission module where the data is formatted and sufficiently set up for local storage and subsequent transmission in secured mode back in the other system modules.

Received data is processed and correctly added into the Information Management Service with the capability for real-time visualization, generation of comprehensive graphic reports, and alarm management. Access Control and Management Module allows for the definition and management of the degrees of access with the purpose of preserving confidentiality and security of the data.

Finally, the User Interface is the central area in which the system and the different users communicate at, where there is visualization in real-time at a detailed level of the data, establishment of the alerts and reading the reports.

Briefly, the architecture represents a functional response towards the GIAHS regions observation difficulties. Beyond simplifying the local management, it is even transferable for other regions and show how the technology can offer concrete assistance in the conservation and the development of unique agricultural systems all over the world.

5 CONCLUSIONS

There is a requirement for customized digital architectures for effective monitoring and conservation of GIAHS sites. The use of real-time monitoring of environments with advanced technologies such as sensors, UAVs, and satellite images has the potential to enhance adaptive management as well as site resilience. Against this background, a technological structure for the development of an intelligent monitoring system for Barroso region, in Portugal, has been proposed being capable to integrate sensor networks, edge computing, data analysis and visualization tools, and user-focused alert handling systems.

Its biggest advantage is that it is repeatable and transferable so that it could potentially be applied to other areas of GIAHS with different realities and operational demands.

ACKNOWLEDGEMENTS

The authors are grateful to the Fundação “La Caixa” and FCT for the financial support through Project “Barroso GIAHS 4.0 - Ecossistema Digital de Monitorização e Gestão Ambiental do Barroso”, Projeto Piloto Inovador - Programa PROMOVE "O futuro do Interior", call 2022. J. Soares and C. Teixeira acknowledges national public funding through "Investimento RE-C05-i02 – Missão Interface N.° 01/C05-i02/2022", a project supported under the PRR (www.recuperarportugal.gov.pt), and financed by the European Union/Next Generation EU.

REFERENCES

Abdelhamid, M. A., Abdelkader, T. K., Sayed, H. A. A., Zhang, Z., Zhao, X., & Atia, M.F. (2025). Design and evaluation of a solar powered smart irrigation systemfor sustainable Urban Agriculture. Scientific Reports, 15(1), 11761.

Abdinoor, J. A., Hashim, Z. K., Horváth, B., Zsebő, S., Stencinger, D., Hegedüs, G.,Bede, L., Ijaz, A., & Kulmány, I. M. (2025). Performance of Low-Cost Air Temperature Sensors and Applied Calibration Techniques—A Systematic Review. Atmosphere, 16(7), 842.

Afridi, W. A., Akhter, F., Vitoria, I., & Mukhopadhyay, S. C. (2022). A technology review and field testing of a soil water quality monitoring system. International Conference on Sensing Technology, Agiwal, M., Roy, A., & Saxena, N. (2016). Next Generation 5G Wireless Networks: A Comprehensive Survey. IEEE Communications Surveys & Tutorials, 18, 1-1.

Agnoletti, M., & Santoro, A. (2022). Agricultural heritage systems and agrobiodiversity. Biodiversity and Conservation, 31.

Amitrano, D., Di Martino, G., Guida, R., Iervolino, P., Iodice, A., Papa, M. N., Riccio, D., & Ruello, G. (2021). Earth Environmental Monitoring Using Multi-Temporal Synthetic Aperture Radar: A Critical Review of Selected Applications. Remote Sensing, 13(4), 604.

Arnés García, M., Yagüe, J. L., de Nicolás, V. L., & Díaz-Puente, J. M. (2020). Characterization of Globally Important Agricultural Heritage Systems (GIAHS) in Europe. Sustainability, 12(4), 1611.

A., Igathinathane, C., Bandillo, N., & Flores, P. (2025). Optimizing integration techniques for UAS and satellite image data in precision agriculture—a review. Frontiers in Remote Sensing, 6, 1622884.

Bhagat, V., Kadam, A., & Kumar, S. (2020). Analysis of Remote Sensing based Vegetation Indices (VIs) for Unmanned Aerial System (UAS): A Review. Remote Sensing of Land, 3, 58-73.

Borghi, F., Spinazzé, A., De Nardis, N., Straccini, S., Rovelli, S., Fanti, G., Oxoli, D., Cattaneo, A., Cavallo, D., & Brovelli, M. (2023). Studies on Air Pollution and Air Quality in Rural and Agricultural Environments: A Systematic Review. Environments, 10, 208.

Cao, X., Liu, Y., Yu, R., Han, D., & Su, B. (2021). A Comparison of UAV RGB and Multispectral Imaging in Phenotyping for Stay Green of Wheat Population. Remote Sensing, 13(24), 5173.

Chattopadhyay, D., Balachandra, Y., P, A., Dutta, A., Sahu, T., Panotra, N., G, M., & Charitha, K. (2024). Precision Agriculture Technologies for Early Detection of Crop Pests and Diseases. UTTAR PRADESH JOURNAL OF ZOOLOGY, 15, 328-342.

Chen, K. (2023). An Adaptable IoT Rule Engine Framework for Dataflow Monitoring and Control Strategies.

Concas, F., Mineraud, J., Lagerspetz, E., Varjonen, S., Liu, X., Puolamäki, K., Nurmi, P., & Tarkoma, S. (2021). Low-cost outdoor air quality monitoring and sensor calibration: A survey and critical analysis. ACM Transactions on Sensor Networks (TOSN), 17(2), 1-44.

Czyża, S., Szuniewicz, K., Kowalczyk, K., Dumalski, A., Ogrodniczak, M., & Zieleniewicz, Ł. (2023). Assessment of Accuracy in Unmanned Aerial

Vehicle (UAV) Pose Estimation with the REAL-Time Kinematic (RTK) Method on the Example of DJI Matrice 300 RTK. Sensors, 23, 2092.

Dallaf, A. (2025). Edge Computing in IoT Networks: Enhancing Efficiency, Reducing Latency, and Improving Scalability. International Journal of Advanced Network, Monitoring and Controls, 10, 2025.

De Castro, A., Shi, Y., Maja, J. M., & Peña-Barragán, J. M. (2021). UAVs for Vegetation Monitoring: Overview and Recent Scientific Contributions. Remote Sensing, 13, 2139.

Drusch, M., Del Bello, U., Carlier, S., Colin, O., Fernandez, V., Gascon, F., Hoersch, B., Isola, C., Laberinti, P., Martimort, P., Meygret, A., Spoto, F., Sy, O., Marchese, F., & Bargellini, P. (2012). Sentinel-2: ESA's Optical High-Resolution Mission for GMES Operational Services. Remote Sensing of Environment, 120, 25-36.

Duisebekova, K. S., Sarsenova, Z. N., Pyagay, V. T., Tuyakova, Z. N., Duzbayev, N. T., Aitmagambetov, A. Z., & Amanzholova, S. T. (2019). Environmental monitoring system for analysis of climatic and ecological changes using LoRa technology. Proceedings of the 5th International Conf. on Engineering and MIS,

Filip, I.-D., Iliescu, C.-M., & Pop, F. (2022). Assertive, Selective, Scalable IoT-Based Warning System. Sensors, 22(3), 1015.

Fitriawan, H., Susanto, M., Arifin, A. S., Mausa, D., & Trisanto, A. (2017). ZigBee based wireless sensor networks and performance analysis in various environments. 2017 15th international conference on quality in research (QiR): International symposium on electrical and computer engineering, Food, & Agriculture Organization of the United, N. (2009). Globally Important Agricultural Heritage Systems. FAO.

Geldenhuys, M. K., Will, J., Pfister, B. J., Haug, M., Scharmann, A., & Thamsen, L. (2021). Dependable iot data stream processing for monitoring and control of urban infrastructures. 2021 *IEEE International Conference on Cloud Engineering* (IC2E),(pp.244-250).IEEE.

González, E., Casanova-Chafer, J., Romero, A., Vilanova, X., Mitrovics, J., & Llobet, E. (2020). LoRa Sensor Network Development for Air Quality Monitoring or Detecting Gas Leakage Events. Sensors, 20(21), 6225.

Guan, S., Zhu, Z., & Wang, G. (2022). A Review on UAV-Based Remote Sensing Technologies for Construction and Civil Applications. Drones, 6(5), 117.

Guerbaoui, M., el Faiz, S., Ed-Dahhak, A., Lachhab, A., Benhala, B., Bakziz, Z., Ichou, I., & Selmani, A. (2025). From Data to Decisions: A Smart IoT and Cloud Approach to Environmental Monitoring. E3S Web of Conferences,

Hammami, A. (2019). Smart environment data monitoring. 2019 International Conference on Computer and Information Sciences (ICCIS).

Hayat, H., Griuiths, T., Brennan, D., Lewis, R. P., Barclay, M., Weirman, C., Philip, B., & Searle, J. R. (2019). The State-of-the-Art of Sensors and Environmental Monitoring Technologies in Buildings. Sensors, 19(17), 3648.

Hosny, K. M., Magdi, A., Salah, A., El-Komy, O., & Lashin, N. A. (2023). Internet of things applications using Raspberry-Pi: a survey. International Journal of Electrical & Computer Engineering (2088-8708), 13(1).

Jiao, W., Yang, X., & Min, Q. (2022). A review of the progress in globally important agricultural heritage systems (GIAHS) monitoring. Sustainability, 14(16), 9958.

Koohafkan, P., Altieri, M., & Initiative, G. (2011). A methodological framework for the dynamic conservation of agricultural heritage systems. Geneva (Switzerland): Land and Water Division, The Food and Agriculture Organization (FAO) of the United Nations, 1-61.

Krklješ, D. B., Kitić, G. V., Petes, C. M., Birgermajer, S. S., Stanojev, J. D., Bajac, B. M., Panić, M. N., Radonić, V. M., Brčeski, I. D., & Janković, N. N. (2024). Multiparameter water quality monitoring system for continuous monitoring of fresh waters. IEEE Sensors Journal, 24(7), 11246-11260.

Li, D., Wu, T., Li, X., He, Q., & Cui, Z. (2020). A Wireless Multisensor Node for Long- Term Environmental Parameters Monitoring. Journal of Electrical and Computer Engineering, 2020(1), 8872711.

Li, J., Pei, Y., Zhao, S., Xiao, R., Sang, X., & Zhang, C. (2020). A Review of Remote Sensing for Environmental Monitoring in China. Remote Sensing, 12(7), 1130.

Lin, M., Wang, M., Lu, Y., Zhou, G., Shen, W., Yin, J., & You, J. (2025). Synergizing Conservation and Tourism Utilization in Agricultural Heritage Sites: A Comparative Analysis of Economic Resilience in Wujiang and Longsheng, China. Land, 14(4), 796.

M. Broell, L., Hanshans, C., & Kimmerle, D. (2023). IoT on an ESP32: Optimization Methods Regarding Battery Life and Write Speed to an SD-Card. In S.Goundar (Ed.), Edge Computing - Technology, Management and Integration. IntechOpen.

Ma, N., Yang, L., Min, Q., Keyu, B., & Wenhua, L. (2021). The Significance of Traditional Culture for Agricultural Biodiversity—Experiences from GIAHS. Journal of Resources and Ecology, 12.

Main-Knorn, M., Pflug, B., Louis, J., Debaecker, V., Müller-Wilm, U., & Gascon, F. (2017). Sen2Cor for Sentinel-2.

Manjunath, & Kumar, A. (2025). The Future of Autonomous Drones in Environmental Monitoring and Disaster Management. International Journal of Scientific Research and Engineering Trends.

Mansoor, S., Iqbal, S., Popescu, S., Kim, S., Chung, Y., & Baek, J.-H. (2025). Integration of smart sensors and IOT in precision agriculture: trends, challenges and future prospectives. Frontiers in Plant Science.

Martins, J., Gonçalves, C., Silva, J., Gonçalves, R., & Branco, F. (2022). Digital Ecosystem Model for GIAHS: The Barroso Agro-Sylvo-Pastoral System. Sustainability, 14(16), 10349.

Maurya, S., Pal, O., & Sarvakar, K. (2024). Layered Architecture of IoT. In (pp. 164-194).

Mead, M. I., Popoola, O. A. M., Stewart, G. B., Landshou, P., Calleja, M., Hayes, M., Baldovi, J. J., McLeod, M. W., Hodgson, T. F., Dicks, J., Lewis, A., Cohen, J., Baron, R., Sauell, J. R., & Jones, R. L. (2013). The use of electrochemical sensors for monitoring urban air quality in low-cost, high-density networks. Atmospheric Environment, 70, 186-203.

Mekouar, M. A. (2023). Food and Agriculture Organization of the United Nations (FAO). Yearbook of International Environmental Law, 34(1), yvae031.

Miller, T., Mikiciuk, G., Durlik, I., Mikiciuk, M., Łobodzińska, A., & Śnieg, M. (2025a). The IoT and AI in Agriculture: The Time Is Now—A Systematic Review of Smart Sensing Technologies. Sensors, 25(12), 3583.

Mo, C., Xie, Z., & Wang, J. (2022). [Retracted] Large-Area Saline-Alkali-Tolerant Rice Growth Environment Monitoring System Based on LoRa+UAV. Advances in Materials Science and Engineering, 2022(1), 9003753.

Morchid, A., El Alami, R., Raezah, A. A., & Sabbar, Y. (2024). Applications of internet of things (IoT) and sensors technology to increase food security and agricultural Sustainability: Benefits and challenges. Ain Shams Engineering Journal, 15(3), 102509.

Moshayedi, A. J., Khan, A., Hu, J., Nawaz, A., & Zhu, J. (2023). E-Nose-Driven Advancements in Ammonia Gas Detection: A Comprehensive Review from Traditional to Cutting-Edge Systems in Indoor to Outdoor Agriculture. Sustainability, 15.

Musa, P., Sugeru, H., & Wibowo, E. P. (2024). Wireless Sensor Networks for Precision Agriculture: A Review of NPK Sensor Implementations. Sensors, 24(1), 51.

Nan, M., Lun, Y., Qingwen, M., Keyu, B., & Wenhua, L. (2021). The significance of traditional culture for agricultural biodiversity—Experiences from GIAHS. Journal of Resources and Ecology, 12(4), 453-461.

Nawaz, M., & Babar, M. I. K. (2025). IoT and AI for smart agriculture in resource-constrained environments: challenges, opportunities and solutions. Discover Internet of Things, 5(1), 24.

Niu, Z., Xia, H., Tao, P., & Ke, T. (2024). Accuracy Assessment of UAV Photogrammetry System with RTK Measurements for Direct Georeferencing (Vol. X-1-2024).

Olatomiwa, L., Ambafi, J. G., Dauda, U. S., Longe, O. M., Jack, K. E., Ayoade, I. A., Abubakar, I. N., & Sanusi, A. K. (2023). A Review of Internet of Things-Based Visualisation Platforms for Tracking Household Carbon Footprints. Sustainability, 15(20), 15016.

Onwuegbuzie, I., Olowojebutu, A., & Kayode, A. (2024). Node-RED and IoT Analytics: A Real-Time Data Processing and Visualization Platform. 1, 1-12.

Pan, Y., Sun, J., Yu, H., Bai, G., Ge, Y., Luck, J., & Awada, T. (2023). Transforming agriculture with intelligent data management and insights. 2023 IEEE International Conference on Big Data (BigData).

Pandey, S. K., & Kim, K.-H. (2007). The Relative Performance of NDIR-based Sensors in the Near Real-time Analysis of CO2 in Air. Sensors, 7(9), 1683-1696.

Park, H., Kim, N., Park, S., & Choi, J. (2020). Sharpening of Worldview-3 Satellite Images by Generating Optimal High-Spatial-Resolution Images. Applied Sciences, 10(20), 7313.

Polak, L., Kufa, J., Sotner, R., & Fryza, T. (2024). Measurement and Analysis of 4G/5G Mobile Signal Coverage in a Heavy Industry Environment. Sensors, 24(8), 2538.

Rajkumar, P. (2025). Humidity and Temperature Monitoring System using Raspberry Pi via RS232 Networking. Array, 100464.

Rashid, A., Schutte, B. J., Ulery, A., Deyholos, M. K., Sanogo, S., Lehnhou, E. A., & Beck, L. (2023). Heavy Metal Contamination in Agricultural Soil: Environmental Pollutants Auecting Crop Health. Agronomy, 13(6), 1521.

Raut, B., Kaewmanee, M., Angal, A., Xiong, X., & Helder, D. (2019). Empirical Absolute Calibration Model for Multiple Pseudo-Invariant Calibration Sites. Remote Sensing, 11(9), 1105.

Santos, G., & Armstrong, S. D. (2024). Evaluation of Commercial Soil Probe (Teralytic NPK) Performance in Field Conditions. ASA, CSSA, SSSA International Annual Meeting,

Scientific, C. (n.d.). RS-232 and RS-485: Maximum cable lengths. Campbell Scientific. Retrieved July 23 from http://s.campbellsci.com/documents/us/technicalpapers/rs232-rs485-max-dist.pdf

Segarra, J., Buchaillot, M. L., Araus, J. L., & Kefauver, S. C. (2020). Remote Sensing for Precision Agriculture: Sentinel-2 Improved Features and Applications. Agronomy, 10(5), 641.

Shar, K., Boboy Singh, H., Kumar, P., Anand, S., & Mishra, R. (2024). Remote Sensing Applications in Agriculture: Monitoring and Decision Support. In (pp. 1-12).

Sharma, H., Sidhu, H., & Bhowmik, A. (2025). Remote Sensing Using Unmanned Aerial Vehicles for Water Stress Detection: A Review Focusing on Specialty Crops. Drones, 9(4), 241.

Singh, A. (2023). A Data Visualization Tool- Grafana.

Singh, K. K., Surasinghe, T. D., & Frazier, A. E. (2024). Systematic review and best practices for drone remote sensing of invasive plants. Methods in Ecology and Evolution, 15(6), 998-1015.

Sishodia, R. P., Ray, R. L., & Singh, S. K. (2020). Applications of Remote Sensing in Precision Agriculture: A Review. Remote Sensing, 12(19), 3136.

Snazelle, T. T. (2015). Evaluation of Xylem EXO water-quality sondes and sensors (2331-1258).

Tabassum, L. (2020). Environmental Monitoring Using AI-Powered Drones.

Tukur Balarabe, A., Sani, A., & Hassan, Z. (2019). An Arduino UNO Based Environment Monitoring System. 14(2), 4-09.

Shilpa, V., & Vidya, A. (2022). MQTT based secure transport layer communication for mutual authentication in IoT network. *Global Transitions Proceedings*, *3*(1), 60-66.

Victor, B., Nibali, A., & He, Z. (2024). A systematic review of the use of Deep Learning in Satellite Imagery for Agriculture. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing.

Waseem, M., López, A., Carro, P., Losada, M., Richards, D., & Aziz, A. (2025). Understanding the Potentials of Narrowband Internet of Things (NB-IoT) Cellular Technology: Salient Features, Architecture, Smart Applications and Quality of Service (QoS) Challenges. IEEE Open Journal of the Communications Society.

Whitehill, A. R., Long, R. W., Urbanski, S., Colón, M., Habel, B., & Landis, M. S. (2022). Evaluation of Cairpol and Aeroqual Air Sensors in Biomass Burning Plumes. Atmosphere (Basel), 13(6), 1-22.

Wu, Z., Huang, Y., Huang, K., Yan, K., & Chen, H. (2023). A Review of Non-Contact Water Level Measurement Based on Computer Vision and Radar Technology. Water, 15(18), 3233

Wulder, M. A., White, J. C., Loveland, T. R., Woodcock, C. E., Belward, A. S., Cohen, W. B., Fosnight, E. A., Shaw, J., Masek, J. G., & Roy, D. P. (2016). The global Landsat archive: Status, consolidation, and direction. Remote Sensing of Environment, 185, 271-283.

Yadav, K., & Jin, J. (2024). Exploring Sustainability through existing and potential GIAHS (Globally Important Agricultural Heritage Systems).

Yeom, J., Jung, J., Chang, A., Ashapure, A., Maeda, M., Maeda, A., & Landivar, J. (2019b). Comparison of Vegetation Indices Derived from UAV Data for Diuerentiation of Tillage Euects in Agriculture. Remote Sensing, 11(13), 1548.

Zhang, X., Yang, Q., Al Mamun, A., Masukujjaman, M., & Masud, M. M. (2024). Acceptance of new agricultural technology among small rural farmers. Humanities and Social Sciences Communications, 11(1), 1641.

Zia, H., Harris, N. R., Merrett, G. V., Rivers, M., & Coles, N. (2013). The impact of agricultural activities on water quality: A case for collaborative catchment- scale management using integrated wireless sensor networks. Computers and Electronics in Agriculture, 96, 126-138.