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Climate Change Mitigation Tool Implemented through an Integrated and Resilient System to Measure and Monitor Operating Variables, Applied to Natural Wastewater Treatment Systems (NTSW) in Livestock Farms

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Abstract: In this study, the main elements that can make up a Natural Treatment System for Wastewater (NTSW), its most important parameters and properties of operation and design, have been analyzed, as well as the environmental problems derived from the generation of large amounts of slurry. The objective of this paper is to propose a methodology to improve the operation of these systems, associated with small and medium-sized livestock farms, in insular and isolated systems such as the Canary Islands. An Integrated and Resilient System (IRS) for monitoring and measuring operational variables quasi-continuous and in situ is proposed. Low-cost technology and open source hardware are employed, as well as application of the IoT (Internet of Things) strategies to share and analyze the information collected in the cloud. In view of the high degree of resilience and the simplicity of this type of technology, as well as its low cost, it is concluded that it is feasible to create a measurement system with these characteristics that can be used for NTSW parameterization, and other purposes. Satisfactory results were obtained for several parameters (ambient temperature, relative humidity, UV radiation, atmospheric pressure). It is presented as a novel proposal based mainly on low-cost technology and free software with which to improve the NTSW operation process.

Keywords: wastewater; IoT; Arduino; natural treatment; monitoring

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1. Introduction

In recent years, there has been an increase in intensive farming, mainly due to the global increase in meat consumption [1]. Outdoor grazing is commonly being replaced with indoor feeding systems, often with totally or partially slatted floors. Such a system generates large amounts of manure, forming a heterogeneous mixture of solid and liquid excrement, feed remains and water, that is often difficult to assimilate with the available farmland [2–4]. This growth in the number of heads of cattle per farm means that manure has gone from serving as fertilizer for the land to becoming a waste that must be managed correctly, since there is not as much surface area available [5,6]. Especially, slurry of pig origin are the ones that present the most problems when it comes to correctly managing said waste due to its properties [7]. In general, pig manure is characterized by a high degree of hydration, a high chemical and biochemical oxygen demand (COD and BOD), and a high content of fertilizing macronutrients (nitrogen, phosphorus, potassium). In addition, due to the diet, traces of iron, zinc, and copper can be found in its composition, which can be polluting elements for the soil [3,8–10]. As can be seen in Figure 1, excess slurry without proper treatment can cause contamination of: (i) surface and groundwater due to the presence of nutrients such as nitrogen and phosphorus in high concentrations; (ii) the atmosphere, due to the significant amount of emissions of greenhouse gases, including methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (N_2O); (iii) the land, as high concentrations of elements such as heavy metals, antibiotics, and nitrates, can have detrimental effects on the properties of the land, exposing the soil to a risk of contamination and reducing crop yields [6,11–15]. In recent years, various materials and components have been proposed for wastewater treatment, composite materials are gaining attention for various uses including wastewater treatment due to their specific functionality, cost-effectiveness, and efficiency in articles reported by the Awual group [10,16–19]. These studies have investigated materials such as bamboo, which have suitable characteristics and morphology for the removal of heavy metals from wastewater.

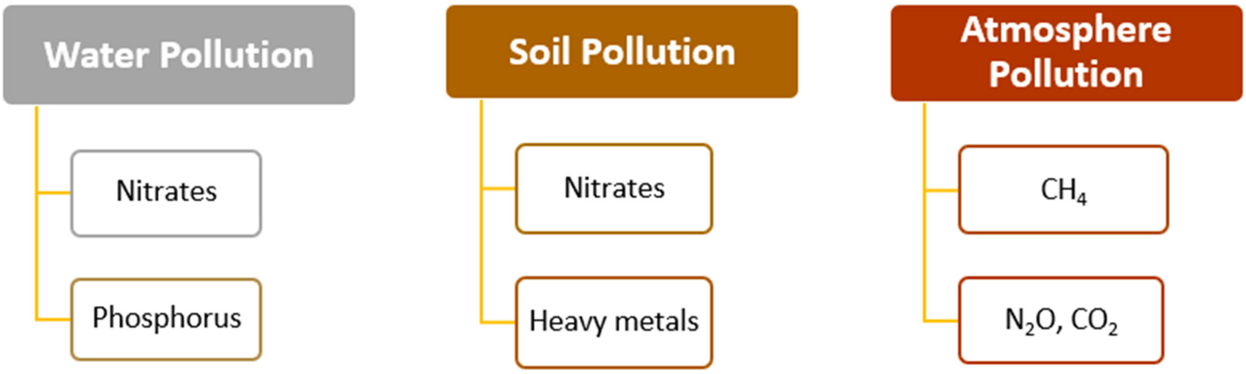

Figure 1. Pollution by the composition of pig livestock waste in the different environments.

In Gran Canaria (Canary Islands, Spain), small pig farms represent almost 90%, however, 10% of these intensive farms account for almost 75% of the total number of animals on the island. These farms generate a large amount of waste, since they represent around 1000 to 1500 animals in a closed cycle in a year of production. In addition, 79% of these animals are concentrated in just three municipalities: Telde (35%), Teror (31%), and Agüimes (13%) [20,21]. Figure 2 shows the geographical location of the island of Gran Canaria.

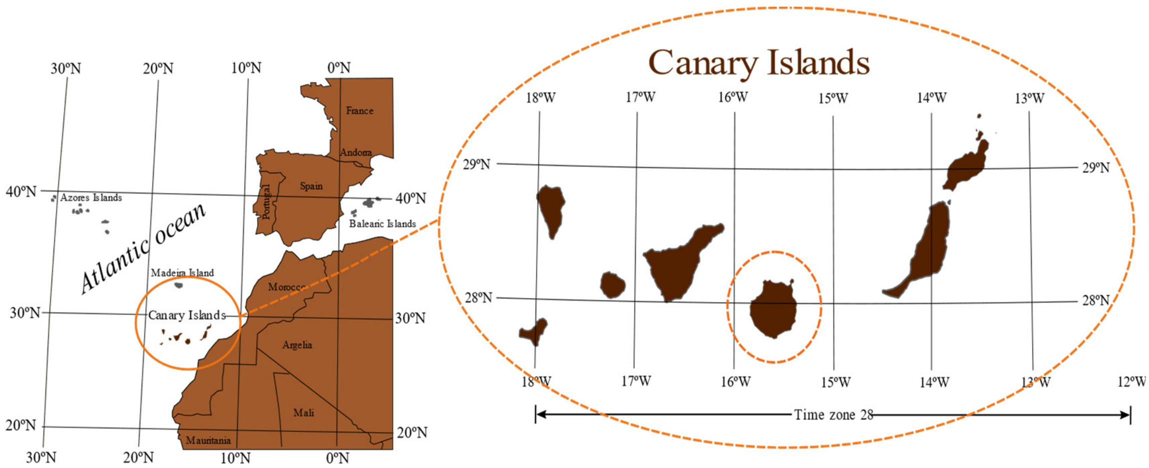

Figure 2. Gran Canaria (Canary Islands, Spain) location.

Given that a large part of the territory of Gran Canaria belongs to protected areas, approximately 42% is under one of the protection categories of the Canarian Network of Protected Natural Areas, it can be considered that the island is vulnerable to contamination due to poor slurry management. Figure 3 shows the island territory considered as protected land [22].

As reported in different studies, one way of treating said waste is to employ a Natural Treatment System for Wastewater (NTSW) on the livestock farm itself, either through anaerobic digestion or the use of constructed wetlands and lagoons [23–26]. However, it has been studied that these systems generally operate in less-than-optimal conditions, mainly due to the lack of online data of the operating parameters, which translates into lower performance. In addition, as a consequence of the lack of information about each stage of the process, undesired organic overloads and unexpected interruptions of the process or accidental addition of toxic substrates can occur [27–29].

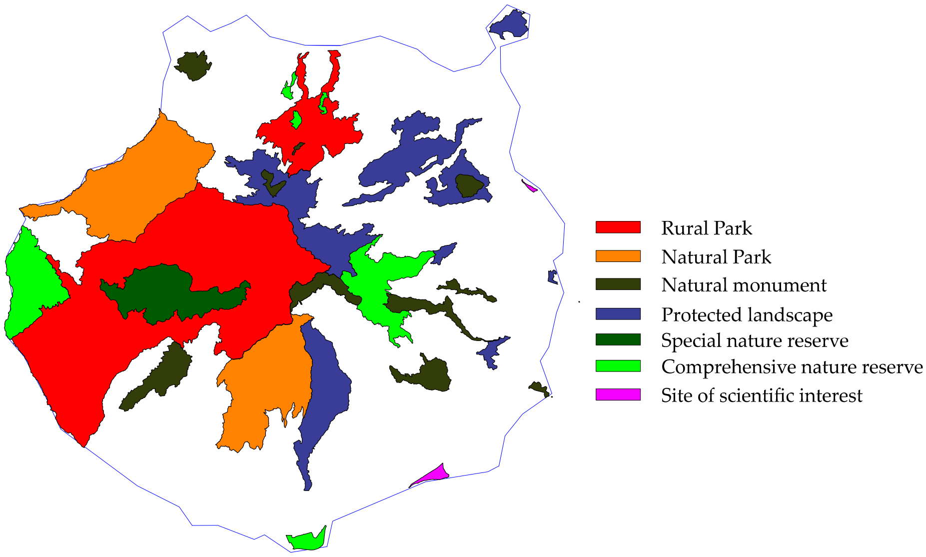

Figure 3. Protected Natural Areas, and Biosphere Reserve of Gran Canaria [18].

It should be noted that in Gran Canaria, the non-existence of previous execution projects, environmental studies, or management reports of pig farms is by no means uncommon. The computerized control of the animals, the production, as well as the manure handling process is very scarce, with the systems that are in place requiring significant updating and modernization [21,30]. It can reasonably be argued that the monitoring and control of slurry management processes, from a technological point of view, are poorly developed. Process parameters should be available online and there should be far less of a need to rely on human intuition or intervention.

It can therefore be said that the development of monitoring systems is crucial if the aim is to have control over the entire sludge treatment process and increase process performance. These should be easy-to-use systems that do not compromise the potential and quality of the information they sample. This is potentially possible due to the application of sensor technology and appropriate process modeling for each system [31–36]. Sophisticated hardware solutions should be avoided, and robustness and simplicity should necessarily be part of the monitoring design [28].

The aim of this work is to propose a methodology for improving NTWS operation associated with small and medium-sized livestock farms, in insular and isolated systems such as the Canary Islands. The methodology is based on the design and implementation of an Integrated and Resilient System (IRS) to monitor and measure operating variables through low-cost technology and open hardware (sensors, data loggers, control systems, etc.), and the application of Internet of Things (IoT) strategies to share and analyse the information collected, serving as a climate change mitigation tool. Removal technology is developed based on selectivity, sensitivity, and cost-effectiveness in similar studies [37–41].

2. Materials and Methods

2.1. Analysis of the Operating Parameters and Design of the NTSW

2.1.1. Anaerobic Digester

Anaerobic digestion (AD) is a complex biochemical process, in which microorganisms break down organic matter in the absence of oxygen and produce biogas. According to the literature [42–47], temperature is one of the main parameters that need to be taken into account in the design of anaerobic digesters. Anaerobic processes are highly dependent on temperature as it strongly affects the AD rate. As the growth rate of microorganisms increases, the digestion process speeds up, producing more biogas. However, violent temperature variations in the digester can damage the process. The temperature is related to the Hydraulic Retention Time (HRT), which is the time that the biomass must remain inside the digester to complete its degradation. The higher the temperature, the shorter the retention times, and so a smaller volume of reactor is required to treat the same amount of biomass [48–51].

The pH values also need to be taken into account, with this being a determining factor in both biogas production and composition. The anaerobic process must be maintained at pH values between 6.0 and 8.0 [42,52–54]. Its value is especially critical in AD, significant amounts of protons may be released if the pH values are too low (<6.0) which can lead to acidification and accumulation of volatile fatty acids (VFA), reducing the yield of the process. In contrast, if the pH values are high (>8) there will be an increase in the formation of ammonia, which is an inhibitor of microbial growth in very high concentrations. Therefore, the measurement and control of pH are important to ensure a good process performance [33].

Other parameters also need to be taken into account including, among others, the amount of suspended solids (SS) present [55,56], the type of organic matter that is used, substances that may inhibit the methanogenic process, and the C/N ratio [42–44].

2.1.2. Constructed Wetlands and Lagoons

Constructed wetlands and lagoons are types of systems especially suitable for tropical and subtropical countries since radiation and ambient temperature are key factors in the performance of their processes [57,58]. Wetland plants can improve water quality through the uptake of nutrients, metals, and other contaminants. The distribution and morphological characteristics of the roots, and the efficiency of contamination removal will depend on the type of plants used. In studies [59,60], bamboo was used to achieve efficient encapsulation of toxic copper thanks to its porous structure, larger surface area, thermal stability, and governable morphology.

Intense summer radiation results in warmer conditions and higher evapotranspiration. Winter radiation is less intense and results in cooler temperatures with less evapotranspiration. Other variables that affect the process are humidity and precipitation [61,62], in addition to other parameters such as pH, dissolved oxygen (DO), depth or stratification [63–67].

2.2. Monitoring Techniques to Control the Anaerobic Process and/or Water Quality

There are several methods to monitor the liquid and gas phases of AD. These include gas chromatography, pH titration, high performance liquid chromatography, or near and mid-infrared spectroscopy. However, laboratory analysis or offline monitoring of control parameters are often associated with potential errors due to improper sampling and analysis techniques, as well as human bias [28,68].

All these aforementioned methods suffer from certain disadvantages with respect to sample preparation. While mid-infrared and near-infrared spectrometry have been shown to be a viable option, they require advanced automated sampling, sample transfer, and filtering to allow sufficient sampling. Additionally, ultrafiltration of the reactor samples is necessary to produce a clear, particle-free liquid for spectroscopy [69,70]. It can be said that these methods are often expensive, time-consuming, and commonly tested manually. Furthermore, they generally require complex equipment and/or extensive maintenance. The literature reviewed reveals that process monitoring is the best option to achieve better system stability and higher conversion efficiency in digestion [71–74].

2.3. Methodological Proposal to Control and Improve the Performance of NTSW

Process monitoring is the first step and constitutes a crucial component of any automatic control system. Advances in instrumentation make it possible to monitor in real time the critical parameters in the wastewater treatment process. Such instruments serve to provide warnings if disturbances occur that may impair the process, thus decreasing the performance [75]. There are three basic elements in any control system: sensors, controller, and communication software [68].

Below, a methodological proposal is offered to improve NTSW operation, using low-cost sensors and implemented with Arduino technology (Figure 4). The objective is to provide a cheap and easy-to-use tool for the control and improvement of the slurry purification process. The idea is to develop a system that can be extrapolated to the treatment of different types of wastewater and livestock farms.

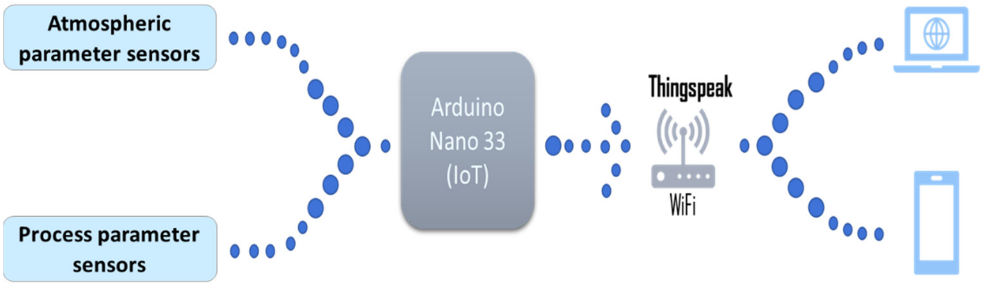

Figure 4. Generic diagram of the system employed.

2.3.1. Sensors

It is proposed to use low-cost sensors (Figures 5 and 6) compatible with Arduino technology to monitor different parameters and variables of an NTSW. It is important to monitor parameters such as ambient temperature, relative humidity, radiation, or the speed of the incident wind in the area. It is important to control operating parameters such as pH, temperature of the aqueous medium, dissolved oxygen, conductivity, gas concentrations (CO_2, CH_4, H_2), pressures, or redox potential.

Atmospherics Parameters Sensors

- BME280 sensor. This precision sensor can measure relative humidity from 0 to 100% with an accuracy of ±3%, barometric pressure from 300 Pa to 1100 hPa with an absolute accuracy of ±1 hPa, and temperature from −40 °C to 85 °C with an accuracy of ±1.0 °C. It can also estimate altitude with an accuracy of ±1 m.
- ML8511 sensor. It is proposed to use the ML8511, an easy-to-use ultraviolet light sensor to measure ultraviolet radiation. It works by emitting an analog signal relative to the amount of ultraviolet light detected in a 280–390 nm wavelength range.
- TSL2561 sensor. It is proposed to use the TSL2561 module, a digital output sensor to measure intensity of light. This sensor is highly accurate and can be configured with different gains and acquisition times. Its internal architecture contains two light detectors, one in the visible light spectrum and the other in the infrared light spectrum. It can be configured for different gain/integration time ranges to detect light ranges from 0.1 to 40,000 Lux. By having an I2C communication port, it facilitates its integration with different embedded systems.

Process parameters sensors

- pH sensor. As previously mentioned, pH is one of the factors with the greatest impact on the AD process. It is proposed to use Atlas Scientific's EZO-pH integrated circuit with its corresponding probe to measure pH. This is a module that allows high-precision measurements for a relatively small cost, compared to traditional equipment [76]. The connection with the microcontroller can be made in UART or in I2C.
- Oxygen Reduction Potential sensor (ORP). ORP probes are extremely versatile measurement systems for monitoring biological reactions in wastewater treatment plants, as they can indicate whether acceptable biological activity is taking place [77]. It is

proposed to measure this parameter using Atlas Scientific's integrated circuit EZO-ORP, which allows to take measurements of great precision. The ORP probe has a platinum tip that is connected to a silver wire, surrounded by silver chloride. The connection with the microcontroller can be made in UART or in I2C.

- DO sensor. Oxygen is a key factor for wetlands and lagoons, so it is essential to know the DO concentrations of dissolved oxygen in each of the different stages. Different studies have shown that digesters can support limited amounts of oxygen and can even lead to better reactor performance and methane generation, and contribute to H2S removal [78,79]. It is proposed to use the Atlas Scientific EZO-DO module for DO measurement, as it offers accurate readings in mg/L and percent saturation, without having to perform chemical titration tests to check that the readings are correct [80].
- Conductivity sensor. It is proposed to use the Atlas Scientific EZO EC, a circuit to measure conductivity the integrated circuit, in addition to the conductivity of water which also measures salinity as well as the amount of total dissolved solids in ppm. It will indicate all dissolved minerals, salts, chlorides, metals, organic compounds, and other contaminants found in the water.
- Temperature sensor. The internal temperature of the biodigester chambers is a determining factor for the development of the anaerobic process, as previously indicated, as well as the water temperature in wetlands and facultative lagoons. It is proposed to use the Atlas Scientific EZO™ RTD (Resistance Temperature Detector) module. This integrated circuit records high-precision measurements using a generic temperature probe. The EZO-RTD circuit can work with any class of 2-, 3- or 4-wire platinum RTD probe and has a sensing range of −126 to +1254 °C.
- Gas sensor. It is proposed to use the Grove-Multichannel Gas Sensor, an environmental detection sensor with a built-in MiCS-6814 that can detect different types of gases (carbon monoxide, nitrogen dioxide, hydrogen, ammonia, methane, ethanol, propane, or isobutane) These gases can be measured simultaneously due to its three channels. This sensor can work with Arduino directly with I2C interface [81].

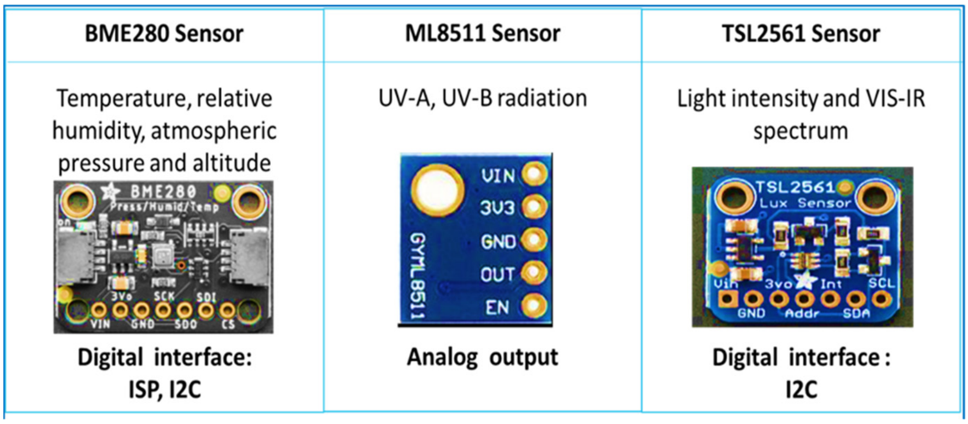

Figure 5. Atmospheric sensors.

2.3.2. Control System and Circuits

Arduino is an open source electronic platform that allows the construction of scientific instruments, using open source hardware and software, thereby reducing the cost of research. It has been used efficiently to monitor and control experimental equipment in automation processes by the scientific community [82–87].

It should be noted that livestock farms may be located with difficult access to the electricity grid or local area connections (Ethernet, Wi-Fi, etc.). Therefore, an efficient and economical way needs to be devised to maintain communication with the established system.

With this in mind, the Arduino Nano 33 (IoT) microcontroller was used for this study (Figure 7). The main processor on the board is a low power 48 MHz Arm Cortex-M0 + SAMD21 processor with 256 kb of flash memory and 32 kb of SRAM memory. This microcontroller offers Wi-Fi and Bluetooth connectivity through a u-blox module, the NINA-W102, a low-power chipset with an internal 2.4 GHz antenna. In addition, secure communication is guaranteed through an ECC608 cryptographic microchip. This device is chosen for its low cost and the suitability of having an integrated Wi-Fi module for communication with the server, which simplifies the installation. This microcontroller allows communication through the I2C protocol via pins A4 (SDA) and A5 (SCL). In addition, it can be connected in UART protocol (Rx and Tx pins) and in SPI protocol (pins 10 (CS), 11 (MOSI), 12 (MISO), and 13 (SCK)).

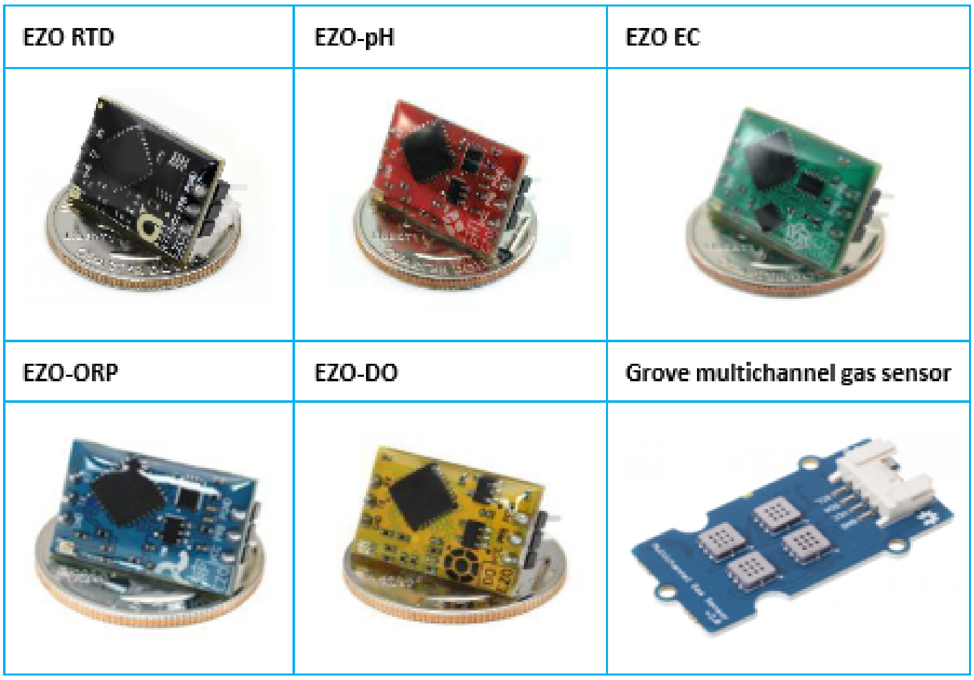

Figure 6. Process parameters sensors.

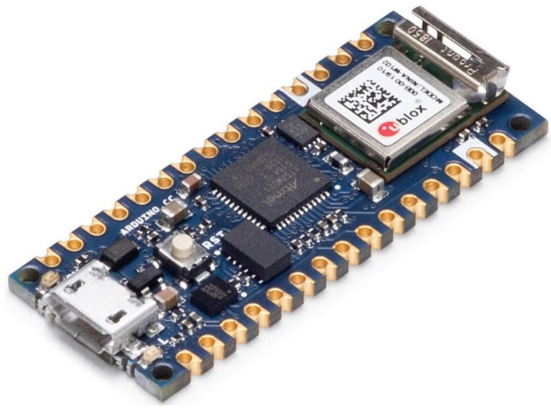

Figure 7. Arduino nano 33 (IoT).

To obtain data, a communication between the sensors and the Arduino Nano 33 IoT microcontroller is used. The ML8511 sensor was connected to the analog output A7 of the Arduino. Figure 8 shows the assembly of the circuit with atmospherics sensors and the microcontroller.

2.3.3. Communication System

Once the system is in operation with the sensors taking readings of the different parameters to be studied, this information has to be accessible. The communication module used offers the possibility of sending the data to a web platform where it can be analysed in real time (Figure 9).

The power of cloud computing and the increased connectivity of devices (with low-cost elements) are an emerging trend in which many embedded devices are connected to the IoT Internet [88–91]. Table 1 shows a list of the most commonly used platforms at present.

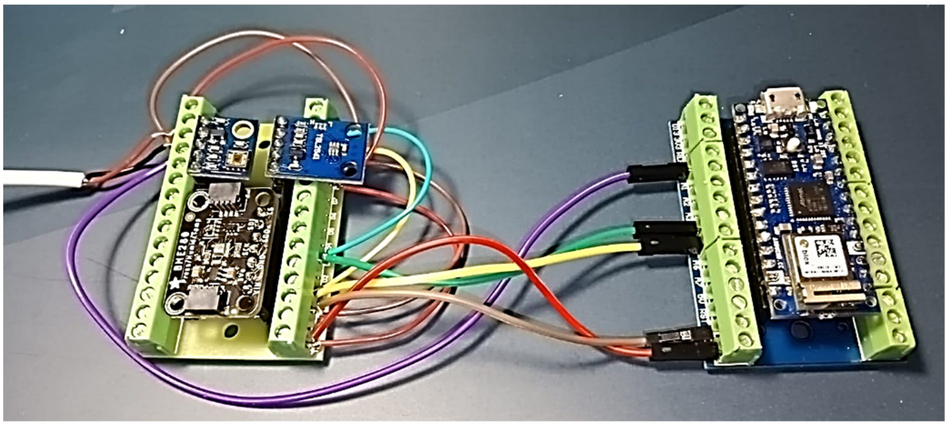

Figure 8. Circuit assembly.

Table 1. Main IoT software.

Platform	Description
ThingSpeak [92]	Open source software written in Ruby that allows users to communicate with Internet-enabled devices. Has integrated MATLAB applications for data analysis and visualization.
Google IoT Core [93]	Managed cloud service that lets you easily and securely connect, manage, and transfer data from millions of devices around the world.
IBM Watson IoT Platform [94]	A fully managed and cloud-hosted service suitable for device registration, connectivity, control, rapid visualization, and data storage. It uses communications based on open standards such as MQTT and HTTPS.
Datadog [95]	The SaaS (Software as a Service) platform integrates and automates infrastructure monitoring, application performance, and log management to provide real-time, unified management.
AWS IoT Analytics [96]	Fully managed service that collects, processes, stores, and analyzes data from IoT devices at scale. Customers can also use their own custom analytics. Processing, data storage, running queries, and running custom analytics are charged for separately.
Blynk IoT Platform [97]	A fully integrated suite of IoT software. It offers device provisioning, sensor data visualization, remote control with mobile and web applications, firmware updates, secure cloud, data analysis, user and access management, and alerts.
Thingsboard [98]	Open source IoT platform for data collection, processing, visualization, and device management. It allows device connectivity through MQTT, CoAP, and HTTP protocols.

For this study, we decided to use ThingSpeak (Table 1), an open source data platform for the IoT, which enables the aggregation, visualization, and analysis of online data flows in the cloud. It makes it easy to access, retrieve, and record data by providing one application programming interface (API) per project, for both devices and websites. It also provides users with free storage of time series data in up to four channels, where each channel can include a maximum of eight data fields. Access is also available to online technical support, private channel sharing, and MQTT (Message Queuing Telemetry Transport) subscriptions, with this being a Machine to Machine (M2M) communication protocol, widely used for the IoT.

We used the free license that allows up to 4 channels with 8 fields each and 3 million messages per year (~8200 messages/day). In addition, it allows the user to automatically act on data and communicate through third-party services such as Twilio® or Twitter. The channel will have a unique identification address used to communicate with it. In addition, two "API keys" are created:

- Write API key. Used to write data to the channel.
- Read API key. Used to give permission to third parties to view the feed and graphics of the private channel.

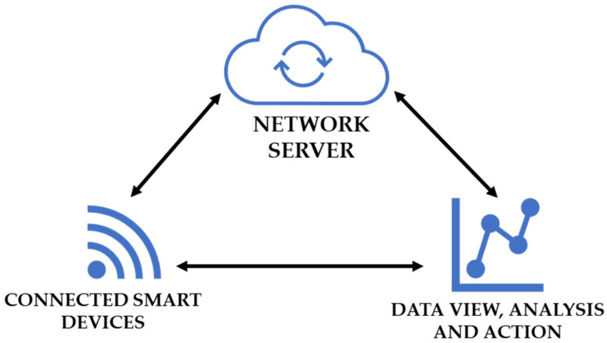

Figure 9. Network server operating diagram.

Figure 10 shows the channel created, with the different atmospheric variables for which the data will be collected.

Once the channel has been created and the corresponding fields assigned, the code to connect the microcontroller to the cloud is created. To do so, it is necessary to use three specific libraries, "ThingSpeak.h", "WiFiNINA.h", and "SPI.h" in addition to those used for the configuration of each sensor [99–105].

The ThingSpeak.h library is responsible for linking to the cloud, "WIFININA.h" allows the NINA module to connect to a Wi-Fi network, and the "SPI.h" library allows the SAMD21 microcontroller to communicate with the NINA module through the SPI communication protocol. The program created to take the measurements and send the data to the network server is represented in Figure 11. TheBME280, TSL2561, and ML8511 sensors are programmed in Arduino IDE. An alarm is also programmed from the ThingSpeak platform itself that provides notification via Twitter when data has stopped being received.

Different analyses of the results were carried out using a mathematical calculation tool, MATLAB, reading the data directly from the ThingSpeak cloud thanks to the read and write APIKEYS. Normality tests of the humidity and temperature fields were carried out to check if the data samples taken presented a normal distribution The mean and standard deviation of the data samples were also obtained, as well as the maximum and minimum values and the date they were obtained. In addition, frequency histograms were made to observe the most repeated values of the samples studied.

Name: Atmospheric measurements
Channel ID: 1501363
Access: Public
Read API Key: 2NX3PF6BTYSRJVEE
Fields:
1: Humidity (%)
2: Temperature (ºC)
3: Visible
4: IR
5: Atmospheric pressure (Pa)
7: UV (nm)
8: Illuminance (lux)

Figure 10. Channel created to store the readings collected by the sensors.

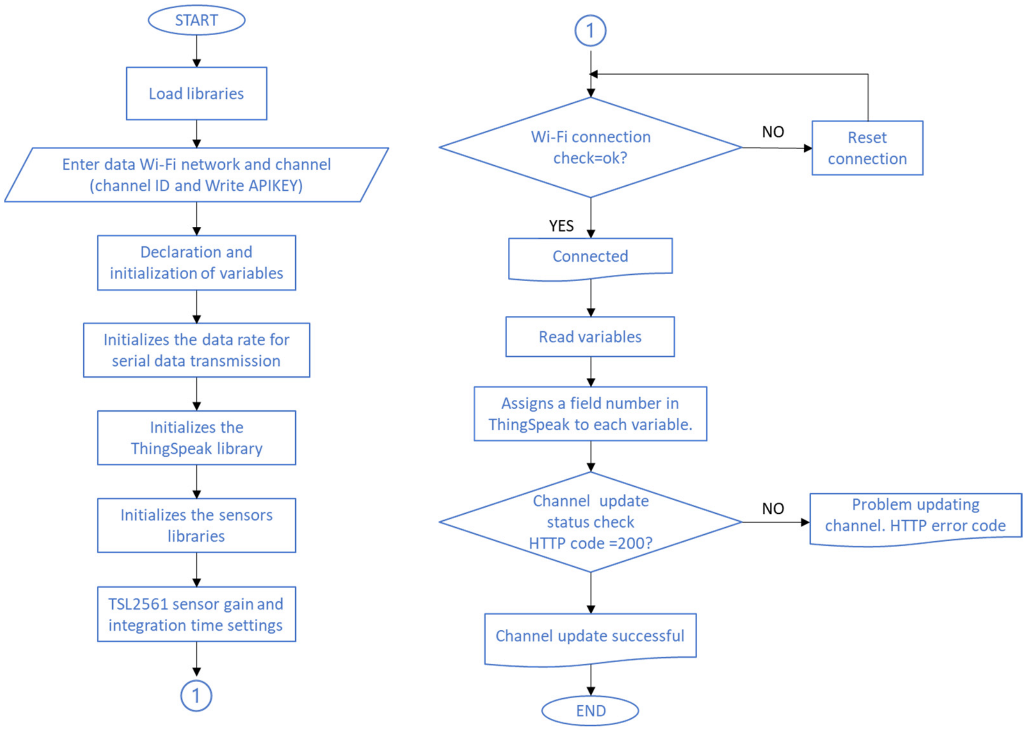

Figure 11. Program flowchart.

3. Results

Once the program is compiled in the Arduino IDE, it is uploaded to the board and the data is sent to the cloud. This data can be accessed from the display screen of ThingSpeak, where different settings can be chosen (number of results, time scale, average, median, title, number of results, etc.) in a personalized way for each of the fields. Figure 12 shows the different options available to configurate each field, and in Figure 13, we can see the data sent by the different sensors. Sensors sent data back for the time period from 20 September 2021 to 28 January 2022.

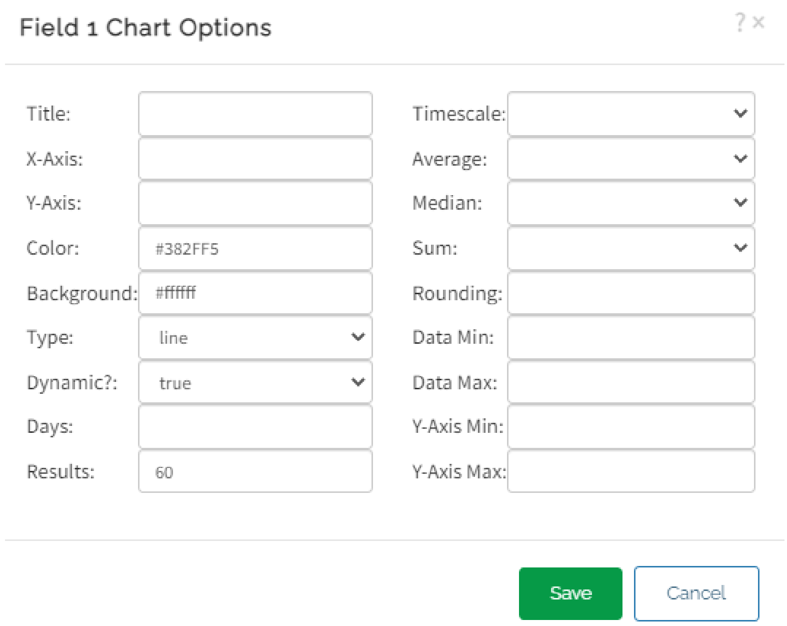

Figure 12. Field 1 Chart Options.

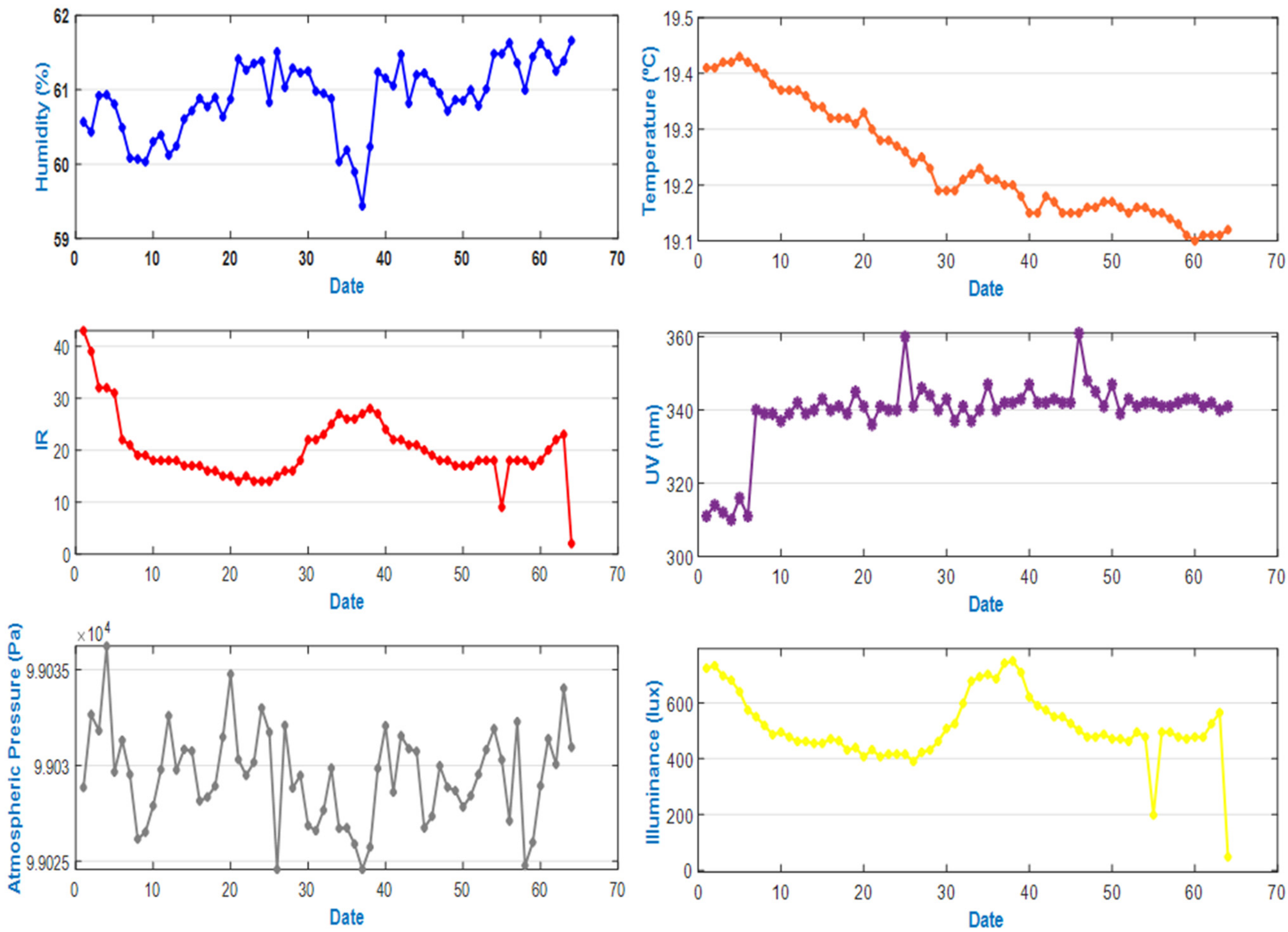

Figure 13. Feed of different parameters.

In total, 285,521 data entries of humidity, temperature, IR and UV radiation, atmospheric pressure, and illuminance were registered with 44,948 discarded as channel test entries. The ThingSpeak server limits the number of points returned to a maximum of 8000. We had to adjust our ranges or make multiple calls to analyze more than 8000 data points. We decided to analyze the hourly values of the temperature, humidity, and UV radiation fields, and for this, we uploaded the selected data to a new channel. In this way, we will work with 1435 data for each field. Figures 14–16 show the results obtained regarding temperature, humidity, and UV radiation.

A test was carried out to warn the user in case the system stops receiving data for a certain time. This could mean that the system may have lost power or some error has occurred that needs to be corrected. The system was disconnected from the electrical network for a short period of time to check the alarm created to provide a notification that no data is being stored. In our case, we chose Twitter as the communication channel. Figure 17 shows the alarm received.

Table 2 shows the results obtained on the mean, the deviation, and the minimum and maximum values.

These alerts can be especially useful in the AD process, where relatively sudden changes in pH, for example, are likely to alter the performance of the process. In this way, by means of control elements, action can be taken almost immediately without the need to be physically present at that moment.

This tool offers a wide range of possibilities when viewing and processing the collected data in a simple and fast way, allowing the creation of a large information bank in the cloud. The results obtained show us relevant information about the parameters studied that can help improve the AD and NTSW processes, since they allow data to be obtained in real time and hence offer the possibility of acting on the system almost immediately. Currently, as has been commented throughout the study, this is one of the problems presented by these types of wastewater treatment systems, so research in this field is crucial. The application of this type of system in small and medium-sized livestock farms can be used as a climate change mitigation tool, improving control of the NTSW process.

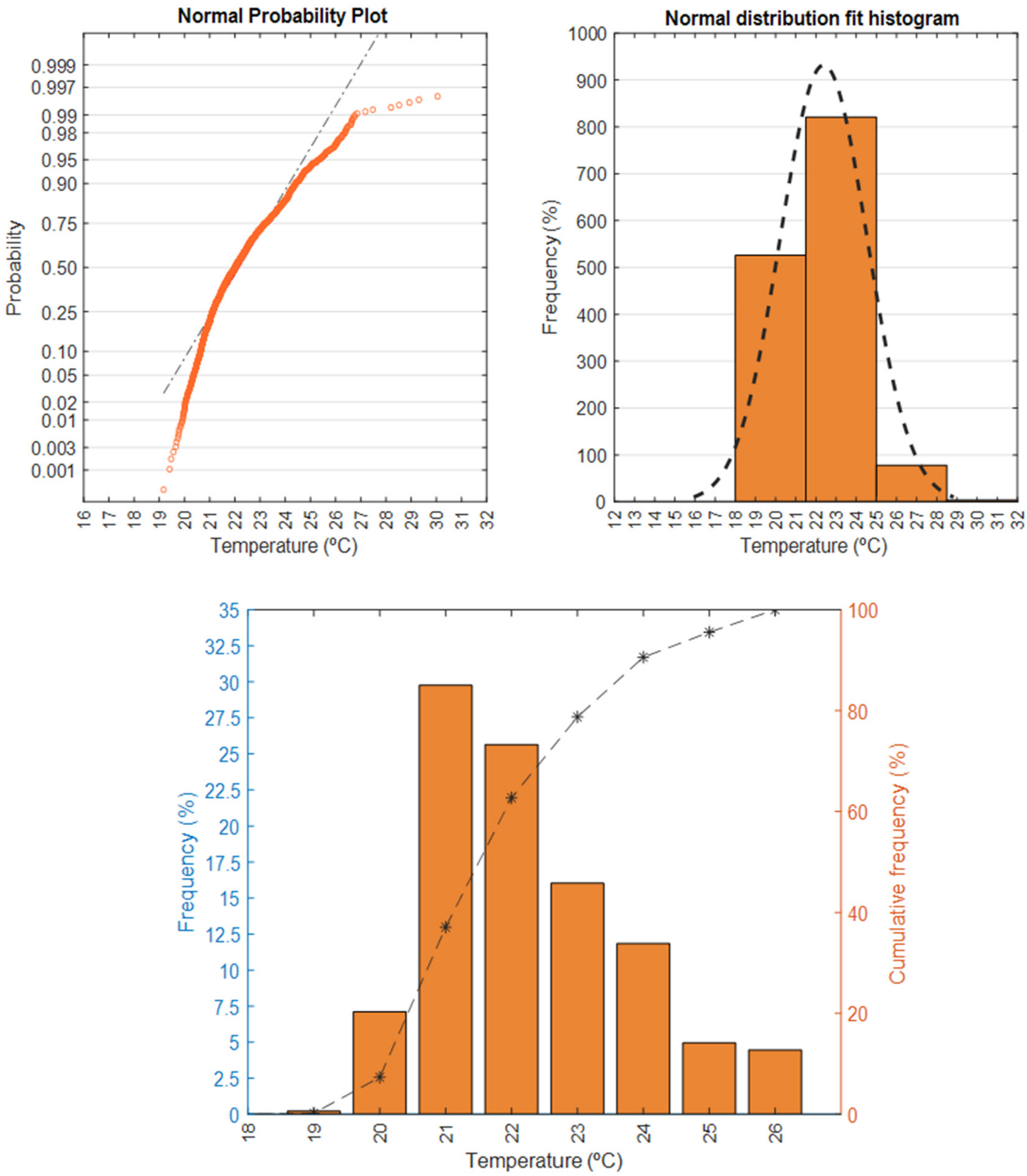

Figure 14. Temperature results.

Table 2. Results obtained for Temperature, humidity, and UV radiation.

	Mean	Standard Deviation	Maximum	Data of Value	Minimum	Data of Value
Temperature (°C)	22.38	2.15	52.13 *	22-January-11:58:13	19.17	22-January-09:58:11
Humidity (%)	62.32	10.86	85.38	21-December-20:01:07	12.43 *	22-January-11:58:13
UV Radiation (nm)	302.13	10.98	420	16-December-12:00:20	266 **	08-January-13:00:07

* These results were obtained by providing heat from an external source to the temperature and humidity sensor.
** This result was obtained by keeping the radiation sensor inside.

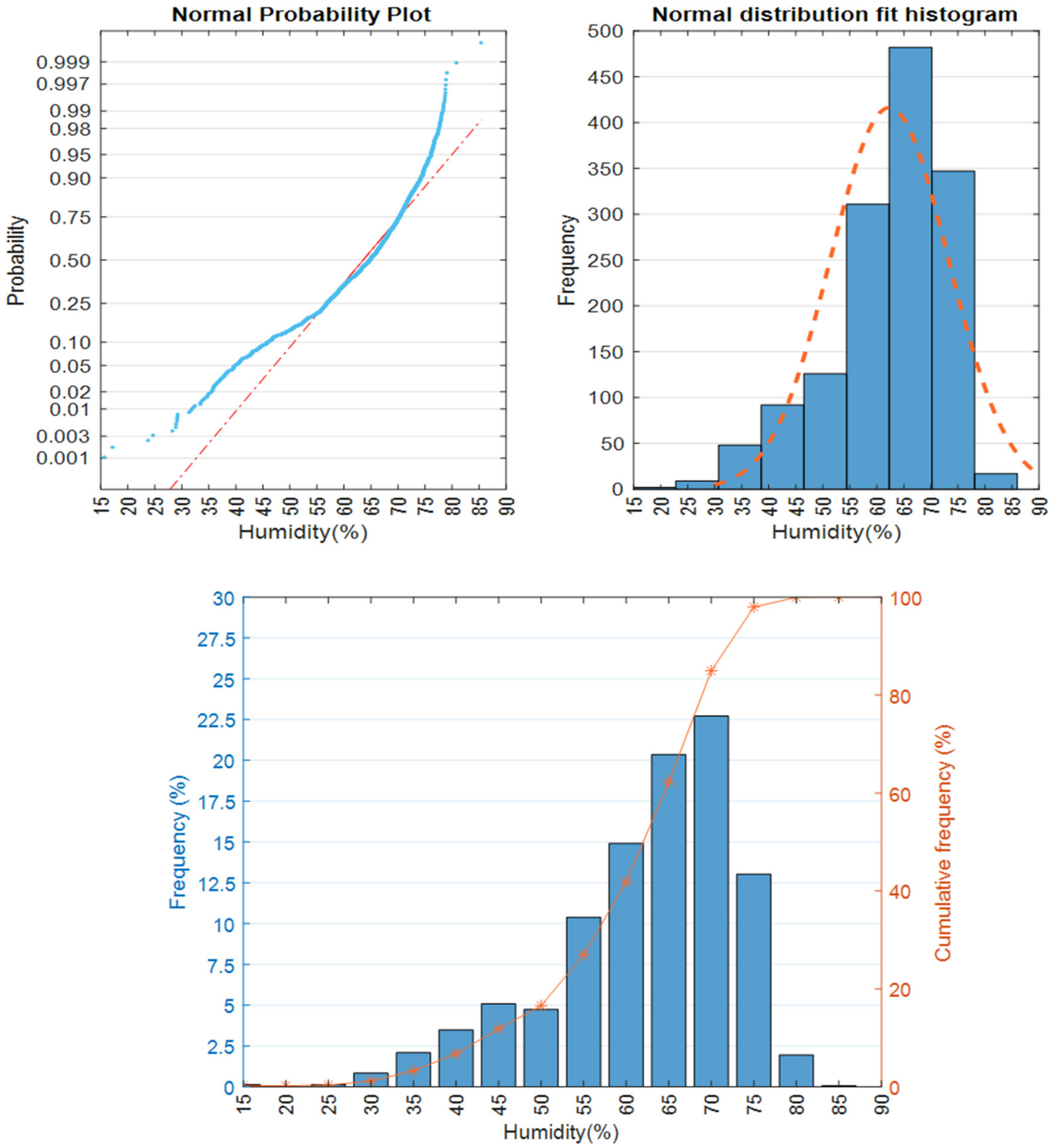

Figure 15. Humidity results.

It is also important to point out that renewable energies could be used to give autonomy to the system. Any system can become autonomous by incorporating a battery based on its consumption and a device capable of taking advantage of renewable energies to recharge said battery, such as a photovoltaic installation. The data can then be taken from places located in rural settings where there is difficult access to power lines.

The combination of Arduino technology with the IoT is a real option for the supervision, control, and acquisition of data not only for natural purification systems, but indeed, any system, given the programming simplicity and the low price of the components. It is thus possible to create with relative ease an online data network of several wastewater treatment plants since, thanks to cloud servers, the information can be universally accessible. Such information can be consulted from a computer or mobile phone, allowing the simultaneous management of a large amount of information, which would not be possible otherwise. The cost of the Arduino Nano 33 (IoT) microcontroller, the BME280 sensor, the TSL2561 sensor, the ML8511 sensor, and the various connections is approximately USD 50 [106–109].

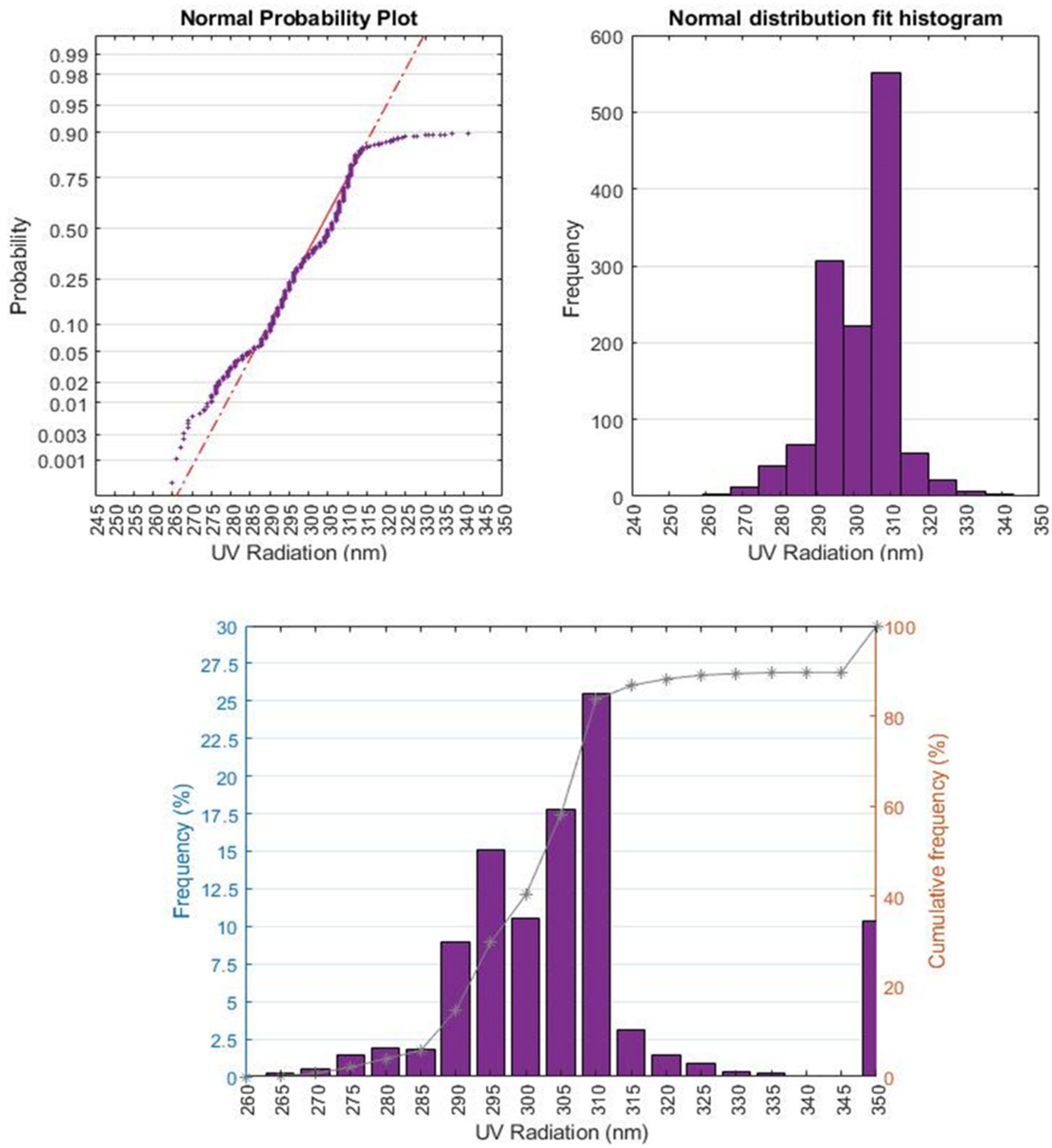

Figure 16. UV Radiation results.

Figure 17. Alert received.

4. Discussion

Similar results have been obtained by other authors: In study [110], research was developed to design and implement an IoT (Internet of Things) system to optimize biogas digesters by providing accurate information in real time using sensor technologies in Rwanda (Africa). The system comprised two temperature sensors connected to the Arduino Esp8266 module. The microcontroller collects the data from the sensors and sends it over Wi-Fi to the data center. This system aims to integrate several biogas digesters on a single platform, thus helping to redesign its structure and improve its mechanical and economic efficiency. In study [111], an automated system was developed capable of the online monitoring of some AD process indicators in the liquid phase (pH, temperature) and gas phase (pressure, methane yield, biogas volume) using the Arduino platform and some low-cost electronic components. The authors concluded that the construction of the device was feasible for the proposed work, highlighting its economic viability.

In study [87], a waste-to-energy system was created, using the AD of mixed manure from poultry and pigs to produce biogas for cooking, power generation, and organic fertilizers for domestic and agricultural uses. A monitoring unit comprising an Arduino Uno microcontroller that is connected to a pressure sensor, a pH sensor, and a temperature sensor to measure the process parameters was incorporated into the system. The results obtained validate the direct relationship between the organic load index and biogas production and shows the interaction between temperature and pressure, temperature and pH, and pH and pressure. The work was able to lay the foundations for studies of biogas production through sensors and continuous monitoring of parameters.

In study [112], a low-cost portable device was built to measure the methane content of biogas samples. The core component of the device was an MQ-4 methane sensor. This sensor, along with humidity, temperature, and pressure sensors, were interfaced with an Arduino Uno microcontroller. Measurements made by the sensor were compared to analyses made using a gas chromatograph, showing an average absolute error of just $0.69 \pm 0.55\%$. This device was assembled for a price of USD 37.

In study [113], based on ultraviolet spectrophotometry, the authors proposed an online remote measurement method to measure groundwater quality parameters: COD, TOC, NO3–N, and turbidity. For this, a control system based on a STM32 microcomputer, a communication module via RS232 serial port, and a GPRS transmission module were used. Absolute measurement errors of COD, TOC, and NO_3-N were less than 5.0%, while those for turbidity were less than 5.4%, meeting the requirements for online measurement of groundwater quality in China.

In study [114], the methane content of biogas from an online digester was measured by modifying an offline measurement device, previously built by the authors, using a hydrocarbon sensor (MQ-4) and a pressure/temperature/humidity sensor (BME-280) integrated with an Arduino Uno. This modified online sensor was programmed to automatically measure methane composition by self-regulating biogas sample introduction and evacuation of the device. Measurements made by this device agreed within a mean absolute difference of $0.81 \pm 0.58\%$ with measurements conducted by using a gas chromatograph. The total cost of this system was less than USD 140.

In study [115], the development of a simple and low-cost water quality measurement device was developed for real-time monitoring of water temperature and turbidity using IoT technology and the Arduino UNO open source platform. The authors used the Kolora mobile application to monitor the data obtained. The study highlighted the potential for the real-time early detection of water contamination. It should also be noted that these types of tools are becoming increasingly necessary given the restrictions in movements that have been imposed as the result of the COVID-19 pandemic. The study carried out demonstrates the potential of this type of low-cost tool to measure and monitor the variation of the most important AD and NTSW parameters, in this way, contributing to improving the performance of the water treatment process and biogas quality.

5. Conclusions

The feasibility of a novel, simple, low-cost and highly versatile monitoring and measurement system with these characteristics described in this study has been shown for

NTSW parameterization applied to small and medium-sized livestock farms. It is concluded that the AD and NTSW operation process could be improved thanks to this technology, using the information obtained to improve efficiency.

Through this study, it has been possible to demonstrate the high versatility of low-cost microcontrollers such as Arduino combined with IoT. It is shown that with low-cost devices, it is possible to take readings of multiple variables in real time. Data were taken and analyses of different atmospheric parameters such as temperature, humidity, and UV radiation were carried out, obtaining relevant information for the control of the NTSW process. This has the advantage of not needing traditional measurement equipment that is associated with high costs and that also requires highly qualified personnel for its use. These characteristics facilitate the integration of this type of technology in rural environments, with small and medium-sized livestock farms and where highly qualified personnel are not available, allowing better management of the slurry generated. The application of this novel system as a climate change mitigation tool in these livestock farms can improve the control of the AD and NTSW process applied to manure, favoring the reduction of its high contaminant load. It should also be noted that flexible and easily accessible free software has been used to develop the code and send the data to the cloud. Although paid software was used to carry out the subsequent analyses, another numerical analysis tool could have been used, such as Scilab, which is free and open source. The system provides a solid foundation for future expansion work in the same category.

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