

Intelligent IoT-based monitoring system for biological sample management

Assane DIOUF^{#1}, Abou Abdallah Malick DIOUARA^{#2}, Pape Abdoulaye FAM^{#3} and Idy DIOP^{#4}

Département Génie Informatique, Ecole Supérieure Polytechnique, Université Cheikh Anta Diop

Département Génie Chimique et Biologie Appliquée, Ecole Supérieure Polytechnique, Université Cheikh Anta Diop

*Département Génie Electrique, Ecole Supérieure Polytechnique, Université Cheikh Anta Diop
Dakar, Senegal*

¹assane9.diouf@ucad.edu.sn

²malick.diouara@ucad.edu.sn

³papeabdoulaye.fam@ucad.edu.sn

⁴idy.diop@esp.sn

Abstract— In biomedical research, biobanks are essential tools for collecting and storing bio-logical samples, providing researchers with valuable data such as medical histories or genetic profiles, which are crucial for personalized medicine. The management and monitoring of these biobanks represent a major challenge, particularly in developing countries such as Senegal, where resources and infrastructure are often limited. Continuous and strict monitoring of storage conditions is important for Senegalese biobanks. This monitoring is usually done with built-in thermometers and relies on manual checks and daily temperature reports. However, these methods also expose samples to risks of human error, data loss, and late detection of abnormal storage conditions. Recording data in laboratory logs complicates the centralization and rapid access to information related to our bioresources. This article proposes to design a smart monitoring system that control biological samples temperature in the biobank. The system uses sensors connected to a microcontroller to continuously measure temperature and transmit data to a local or cloud-based server via Wi-Fi and MQTT protocol. Data is also saved locally on an SD card to prevent losses in the event of network failure. Data visualization is managed by the Node-RED platform, which displays the latest measured temperature and facilitates real-time monitoring. A real-time alert system has been configured to automatically send emails to the administrator if the temperature exceeds critical thresholds. Thanks to these combined technologies and tools, our system allows for the remote monitoring of our various thermal chambers by visualizing temperature data in real time and recording this data in an electronic file.

Keywords— Biobanking, IoT, Remote Monitoring, Biological Samples.

I. INTRODUCTION

Biobanks play a crucial role in facilitating the collection, storage and management of biological samples for various studies, particularly in the context of biomedical research. They store various biological samples as well as associated data [1]. The first initiatives to preserve biological samples date back to the 1970s around 1990, with work on cryopreservation and human tissue banks [2], [3]. These samples offer a wealth of related datasets, including medical history and genetic profiles [4]. These datasets have the potential to unravel disease mechanisms, identify biomarkers for early diagnosis and prognosis, and personalize therapeutic strategies to improve patient outcomes [5].

However, effective management and monitoring of these samples remain a challenge, especially in developing countries such as Senegal, where infrastructure and resources can often be limited. Indeed, maintaining the stability of environmental parameters, especially temperature, is essential to preserve the integrity of biological samples. In terms of infrastructure, biobanks operate in an environment marked by power cuts, causing temperature drops. These temperature fluctuations can compromise samples, especially when backup devices such as power generators or solar systems are unavailable or operate intermittently. From a technological point of view, the lack of digital integration represents a remarkable limitation. In several biobanks, temperature monitoring is carried out manually or semi-automatically, limiting traceability and reactivity in the event of critical deviation. The lack IoT solutions or real-time analytics platforms

compromises the reliability of the monitoring process. This underlines the importance of an appropriate monitoring system and proactive management of biological resources.

The integration of IoT technologies into biobanks represents a breakthrough for automated and continuous monitoring of storage conditions. The Internet of Things (IoT) offers promising solutions to improve biobank management by enabling real-time monitoring and tracking of samples, [6].

This paper aims to design a remote monitoring system for biological sample management, based on IoT. This system offers biobanks considerable advantages over traditional monitoring approaches. It enables real-time monitoring through interconnected sensors that continuously measure critical parameters such as temperature. In addition, the use of automated temperature data collection eliminates the human errors inherent in manual entry and ensures full digital traceability of storage conditions.

Another major advantage is the retention of digital environmental data. Unlike paper ledgers, which are often fragmented and difficult to archive, IoT systems store information in local files or secure databases, making it easy to use and share. Indeed, the integration of surveillance systems is profoundly transforming the way biobanks are administered and operated, with significant scientific, health, economic and societal benefits. From a health perspective, an intelligent tracking system strengthens biosecurity and ethical compliance in the management of human samples. Automated monitoring reduces the risk of loss or alteration of rare or sensitive samples, often from long-term clinical studies [7]. This increased reliability improves the continuity of medical research programs, especially in the areas of public health, emerging infectious diseases or oncology, where the availability of quality samples is crucial for diagnosis, vaccine development or the implementation of targeted therapies. With this approach, we hope not only to strengthen local capacities for biobank management, but also to contribute to the development of biomedical research in West Africa.

The rest of the article is structured as follows: the first section presents the state of the art by reviewing previous work. The second section describes in detail the materials and methods used to design and implement this system. The third section is dedicated to the implementation of the proposed system, highlighting its architecture and functionalities. The fourth section deals with the results achieved. Finally, the last section offers a conclusion and opens prospects for future work.

II. RELATED WORKS

A. *Biobanks in Africa*

Biobanks in Africa provide researchers with local resources to conduct studies that are more relevant to the African context, providing a better understanding of the genetic, environmental and behavioural factors unique to the region. For example, Africa's genetic diversity, the largest in the world, offers unique potential for genomics research, which could lead to breakthrough discoveries for treatments and diagnostics that are better suited to local populations. The Stroke Investigative Research and Educational Network (SIREN) project aims to explore and unravel the genetic and environmental factors that interact to produce the phenotypic and clinical features of stroke observed in people of African descent, and to facilitate the development of new diagnostics, therapies and prevention strategies [8]. Initiatives such as the African Biobank Network support the development and coordination of biobanks across Africa, representing a major step forward in addressing health challenges while integrating the continent into the global scientific effort. Senegal is at the forefront of the development of biobanks in West Africa. Institutions such as the Institut Pasteur in Dakar have biobanks that contribute significantly to epidemiological and clinical research [9]. The Institut Pasteur biobank is a reference center for the storage of samples used in surveillance and research on infectious diseases, such as dengue fever and yellow fever, which are major concerns in West Africa [10]. The SEN project 'RT-Biobanking' of the GRBA-BE of the École Supérieure Polytechnique (ESP), which aims to establish a real-time management system for a national biobank, allowing the collection and storage of biological materials [11]. This system will allow for better governance and management of biological resources essential to research and public health. In the face of a multitude of human diseases, biological research continues to mobilize scientists. These studies, which are often prospective, require significant clinical and biological hindsight to allow retrospective analyses. It is in this context that the IRESSEF (Institute for Health Research, Epidemiological Surveillance and Training) is in the process of setting up a modern biobank capable of generating

quality biological samples (serum, plasma, PBMCs, whole blood, buffy coat) in collaboration with health structures and various partners [12]. The ambition of this structure is to become a modern sub-regional biobank, equipped with infrastructure and equipment to collect, conserve and make available to researchers a variety of quality biological resources.

In the field of genomics, Senegal is also involved in collaborative research projects aimed at exploring the genetic specificities of African populations to better understand the predisposition and response to diseases to treatment. This type of research not only contributes to developing more effective treatments for the local population but also contributes to global science by offering an African perspective on public health issues.

B. Traditional Biobank Monitoring Systems

Biobanks are vital for biomedical research but present distinct monitoring challenges. Important aspects of a typical monitoring system include:

- **Thermometers:** Thermometers play a fundamental role in the local control and spot check of thermal chambers. These instruments, often used as a reference or secondary control device, allow the temperature of the cryogenic medium to be measured directly without data transmission. Their primary function is to provide an accurate reading and provide manual monitoring in the event of a failure of the main device [13]. Unlike smart systems, these thermometers do not have storage or alerting features, their use requires manual reading and periodic recording of values, which can introduce a risk of human error or loss of information in the event of rapid temperature changes. However, their role remains essential as an independent verification instrument to confirm the accuracy of automated sensors and to ensure the redundancy of thermal control in critical environments [14].
- **Data Logger:** Measurements made with these thermometers are usually recorded on local media, most often in the form of paper registers or monitoring sheets, and then manually recorded by technical staff for archiving and later analysis.
- **Simple alarm systems:** Audible or visual alarms are used to signal anomalies (excessive temperature, open door, etc.).
- **Preventive maintenance:** Regular visits are made to check that equipment is working properly, and to carry out any necessary maintenance operations.

The figure 1 shows that the temperature of freezers is monitored by paper cards attached to the equipment doors. These documents allow for the manual recording of temperature readings taken at regular intervals by technical staff. This method, although operational, relies entirely on human intervention for reading, transcribing and archiving data.



Fig.1 Traditional recording system

Such an approach illustrates the traditional surveillance model still widely used in many biobanks, especially in resource-limited contexts. However, it has several constraints risk of human error, lack of digital traceability, lack of real-time tracking, and impossibility of issuing automatic alerts in the event of thermal drift. These limitations underscore the need for a transition to IoT-based smart monitoring systems that can ensure continuous and automated recording of environmental data.

C. *The Internet of Things and its Benefits for Biobank Monitoring*

The IoT makes it possible to improve the efficiency of the biobank management process in real time, enabling users to make considerable savings. IoT sensors can be used to monitor the cryogenic environment's internal temperature, pressure, power supply and more. Connected devices can provide data on the status of doors, such as whether they are open or poorly closed, enabling users to intervene at the right time. These sensors and RFID tags are key objects that fuel the concept of smart biobanking systems [15]. These objects connect biobanks to remote information systems and storage units via the IoT network. They are designed to work with several

communication technologies, such as Wi-Fi, Bluetooth Ethernet and others. The integration of these connected objects Considering this work, the application of these IoTs in the biobanking sector offers several advantages.

1) *Improved sample monitoring*: A major application of IoT in biobanks concerns real-time monitoring of sample storage conditions. Connected sensors enable continuous measurement and recording of the environmental conditions (temperature, humidity, pressure, etc.) in which samples are stored. This automation is essential to guarantee the integrity of biological samples (blood, tissue, plasma, etc.).

2) *Sample traceability*: Each sample can be fitted with an RFID tag or barcode, linked to an automated management system. This technology makes it easy to track sample stocks, manage incoming and outgoing samples, and quickly locate a specific sample in a large database.

3) *Inventory automation*: Automated inventories make the work of biobank managers simpler, as they no longer need to manually check stock levels or enter data into isolated systems. This improves operational efficiency and minimizes human error in data handling.

III. METHODOLOGY

At this stage, it is necessary to analyze the existing biobank system, identify and propose a framework for the acquisition of temperature data. The ESP biobank is chosen as a case study to collect all the data needed to design the new system. We have set up a new system based on DS18B20 sensors and PT100s to collect the temperature within the thermal chambers. These sensors are connected to the ESP 32 microcontrollers, which have a Wi-Fi module for connecting the node. We have configured the MQTT protocol for the transmission of data to the central server. To ensure long-term storage, we used a raspberry pi that hosts the MQTT broker for the recording of data from the various nodes. Moreover, this data is stored locally on an SD card to prevent loss in the event of a network failure. We used the Node-red platform to visualize data on its dashboard in real-time, generating alerts when critical temperature thresholds are exceeded.

IV. PROPOSED SYSTEM IMPLEMENTATION

The implementation environment for our sample temperature monitoring system based on IoT technology is shown in Fig.2.

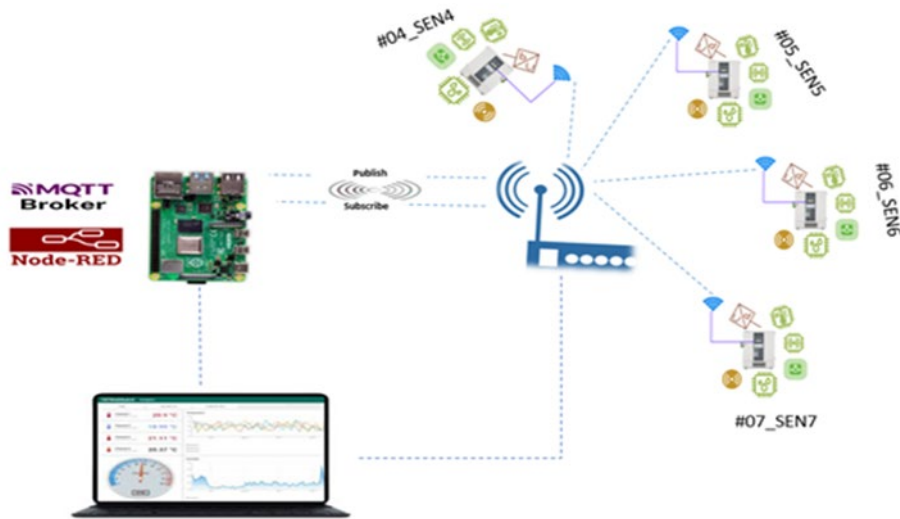


Fig. 2 Architecture of the proposed system

We have implemented a case study in which freezers are equipped with temperature sensors to monitor samples using wireless communication technology based on connected systems. Our proposed model aims to establish communication between the nodes and the server. An ESP 32 microcontroller, which acts as an IoT gateway, routes temperature measurements to the server, which in our case is a raspberry pi 5. The latter is responsible for processing requests and providing the acquired sensor data. The proposed system uses the MQTT protocol to establish a connection with peers. as shown in fig. 3.



Fig. 3 IoT module prototype

V. RESULTS AND DISCUSSION

A. Data visualization

The visualization of temperature data in node-red facilitates real-time monitoring, providing intuitive visual access to the biobanks' thermal environment. In Node-Red we display the last temperature measured, enabling us to quickly read the status of all our freezers, as shown in the fig. 4. In addition to this visualization, a real-time alert system has been configured to trigger automatic alerts to the administrator in the event of a critical deviation. It is based on a Node-Red function node that evaluates the temperature received at any given moment. If the measured value is out of range, an alert is generated by sending an email to the administrator. This reliable, scalable, and economical system provides comprehensive monitoring of our samples.

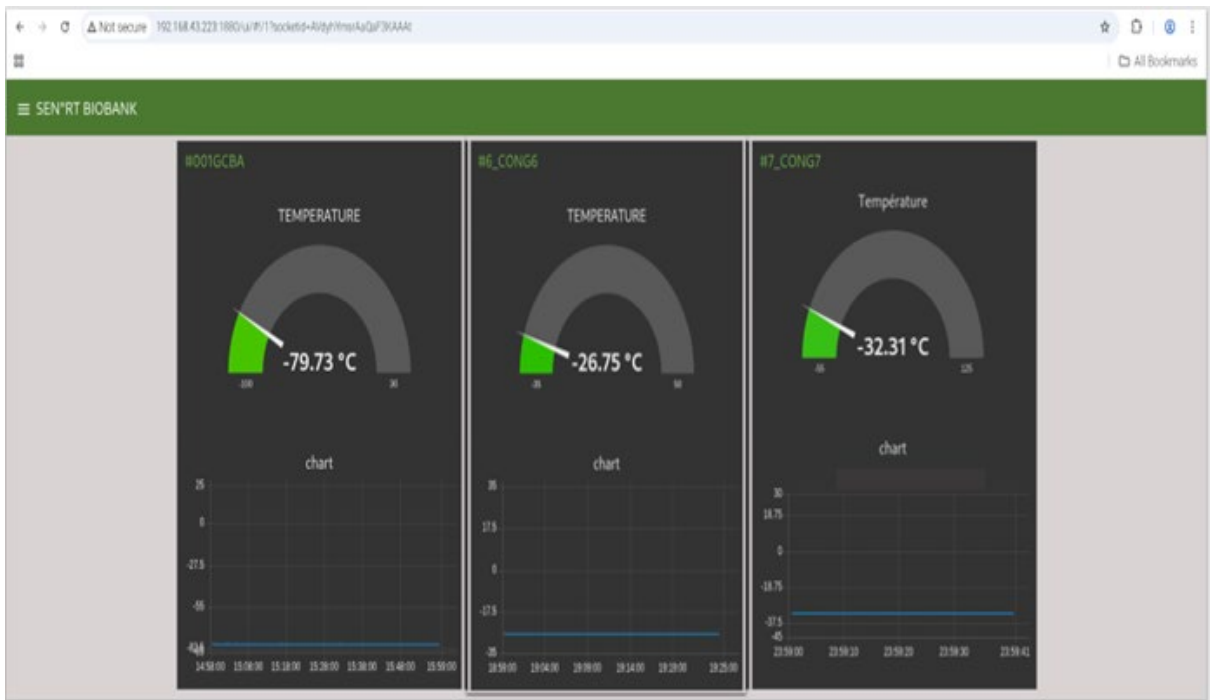


Fig. 4 Temperature visualization

B. Descriptive analysis

The data from freezer #07_CONG7 show very good thermal stability around -25°C , which corresponds to the usual requirements for the preservation of bioresources, particularly wastewater samples. This stability shows that the control system maintains the temperature within an optimal range, ensuring the viability of the samples and the reliability of the measurements. Compliance with the storage standard demonstrates that the control system is correctly sized, as shown in Fig. 5.

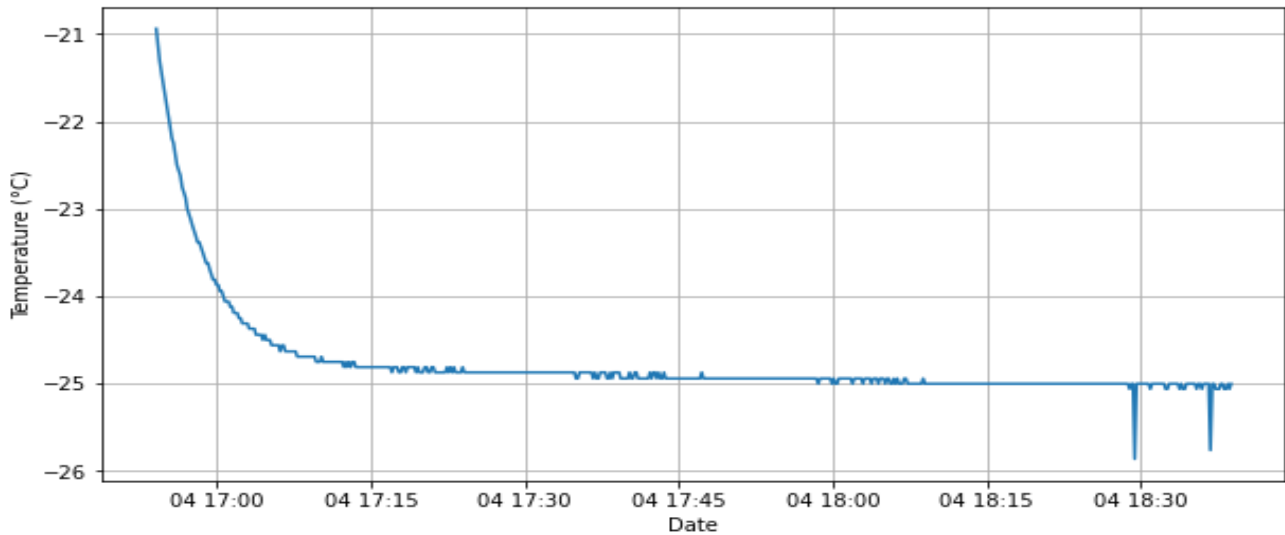


Fig.5 Temperature evolution over time of #07_CONG7

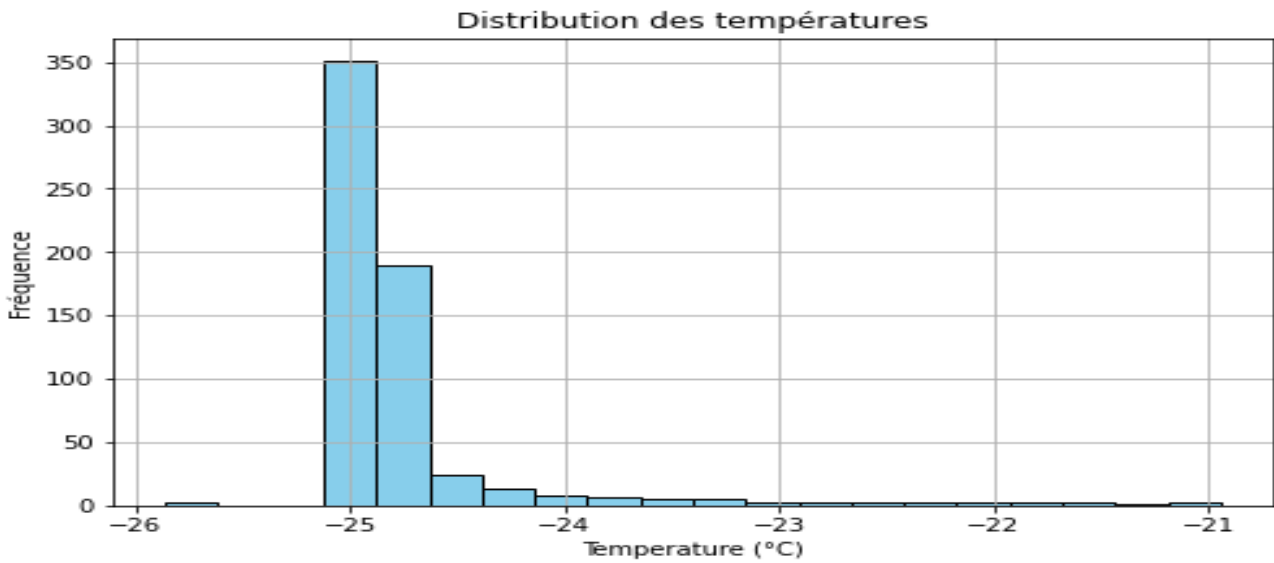


Fig.6 Temperature distribution for #07_CONG7

The low dispersion observed, with a standard deviation of 0.5°C , confirms the efficiency of the refrigeration system and the absence of significant temperature fluctuations that could alter the samples. This homogeneity reflects the stable performance of the control system. The maximum temperature, -20.9°C , appears to be a one-off anomaly, but is not representative of a real temperature rise. This is due to the response time of the sensor when immersed in a new cryogenic environment. In fact, it can take a few minutes for the sensor to stabilize before reaching equilibrium temperature. This illustrates an instrumental limitation and not a system failure. Furthermore, the histogram shows an asymmetrical graphical distribution on the right-hand side (as shown in Fig. 6). Of the 624 temperature measurements, almost all are concentrated between -25 and -24.5°C , confirming the thermal stability observed in Figure 5. A few higher values can be observed between -21 and -20°C , but they are rare and isolated due to the sensor's response time. These isolated deviations reinforce the idea of the system's structural stability.

For freezer #06_CONG6, out of 525 temperature readings, almost all values are between -29.7°C and -29.8°C (as shown in Fig. 7). This range corresponds perfectly to the recommended conditions for long-term storage of biological resources, thus guaranteeing their structural and molecular integrity [16]. This stability illustrates the effective design of the cooling system and its precise regulation.

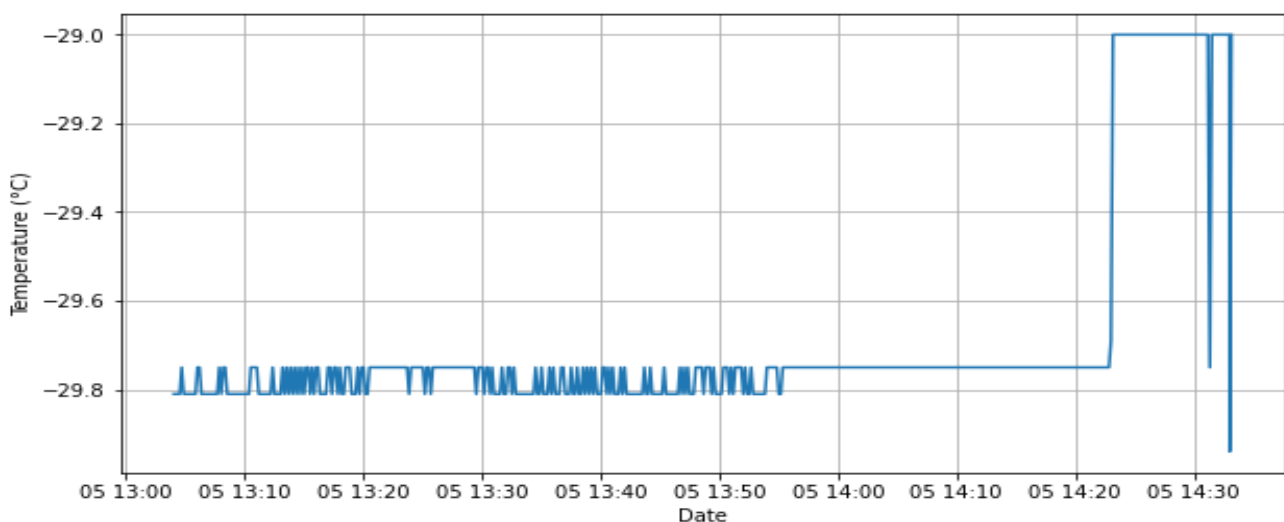


Fig.7 Temperature evolution over time of #06_CONG6

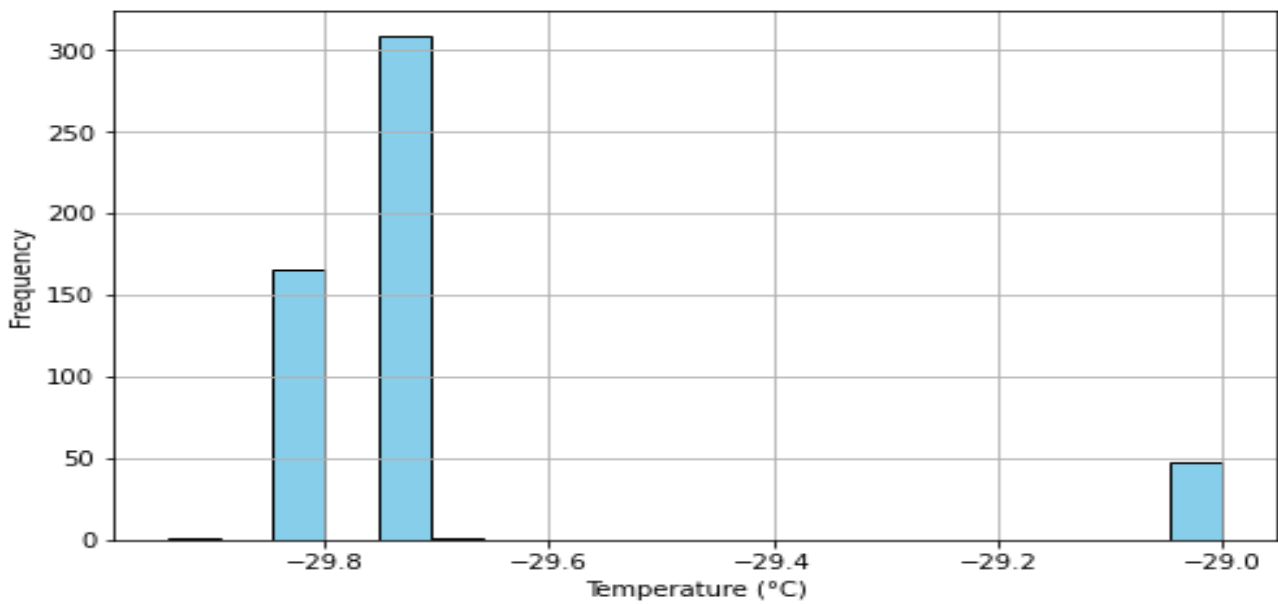


Fig.8 Temperature distribution for #6CONG6

The low standard deviation (0.22, see Table 1) confirms the efficiency of the refrigeration system. The maximum value is -29°C , with a very low frequency (as shown in Fig. 8). The data indicate excellent overall temperature control, with occasional slight drift that has no immediate impact on sample integrity.

In this freezer, #01_GCBA, three distinct phases are recorded (as shown in Fig. 9): before 5 p.m., the temperature is very stable, fluctuating around -80.5°C , which corresponds to the normal operation of the ultra-low temperature (ULT) freezer [17]. This phase illustrates the system's ability to maintain optimal conditions for blood and plasma samples. A rapid rise in temperature is then observed between 5:20 p.m. and 5:25 p.m., reaching -78.3°C . The visible fluctuations around this value indicate active but unstable regulation. Finally, a gradual return to normal is observed around 5:50 p.m. at -80.0°C . This 2°C increase may be due to frost formation or the door being opened to calibrate the sensor.

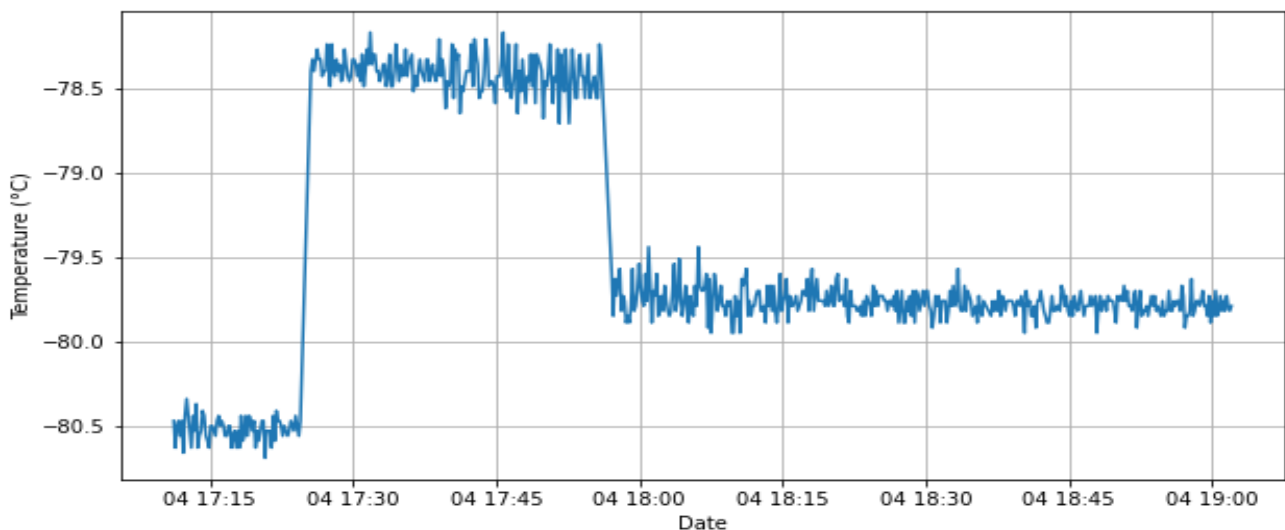


Fig.9 Temperature evolution over time of #001_GCBA

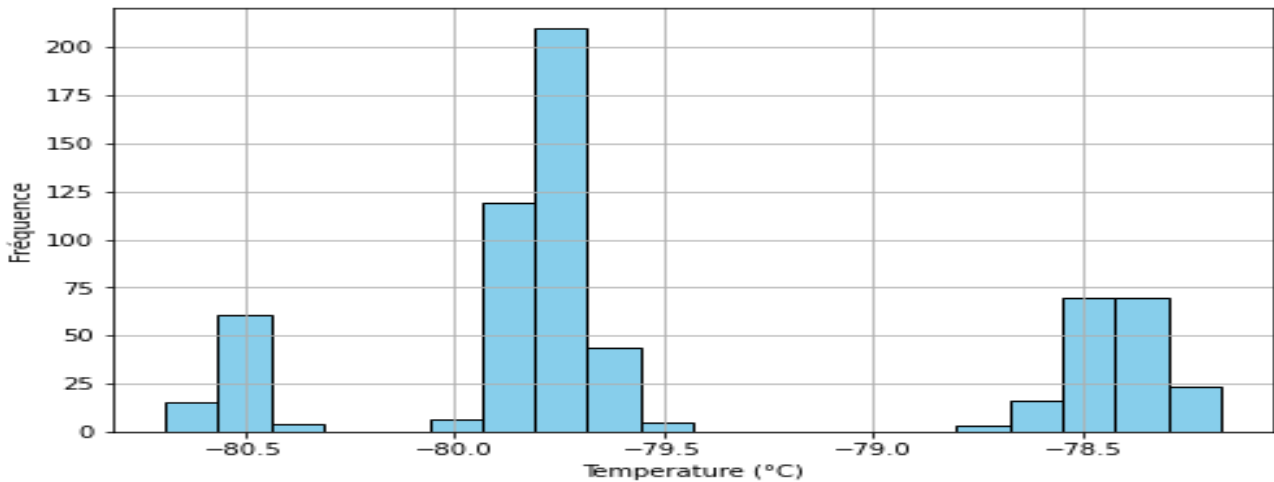


Fig.10 Temperature distribution for #001_GCBA

Although the temperature is above -78°C , this drop must be considered because, above this value, heat-sensitive samples, particularly those stored near the door, may be altered. However, the critical threshold has not been reached, and the frequency of these measurements is low, at around 100 measurements out of the 646 values taken (as shown in Fig. 10). Therefore, the samples still maintain their integrity according to long-term storage criteria [18].

TABLE I
TABLE I. SUMMARY OF TEMPERATURES MEASURED IN STORAGE UNITS.

ID	Count	Mean	Std	Min	Max
#07 CONG7	624	-24.7631	0.5668	-25.8600	-20.9400
#06 CONG6	525	-29.7006	0.2242	-29.9400	-29.0000
#001 GCBA	646	-79.4781	0.7180	-80.6900	-78.1700

The overall results obtained from the three storage units analyzed highlight the reliability of the deployed IoT monitoring system. The recorded measurements show remarkable thermal stability, with limited variations and a standard deviation of less than 0.5°C , attesting to the performance of the refrigerator and the accuracy of the sensor system.

VI. CONCLUSIONS

We have implemented an IoT-based smart monitoring system for the management of biological samples in our biobank. This technological approach guarantees the quality of biological resources in the face of the constraints of traditional monitoring methods. It enables real-time temperature monitoring through the Node-Red platform by generating automatic alerts in the event of thermal drift. This study confirmed the thermal stability of the equipment and normal refrigeration maintaining the required storage conditions. Although isolated measurements, such as temporary increases in temperature, were observed, the system was able to detect and analyze them, demonstrating its ability to identify occasional deviations without immediately impacting sample integrity. This modern surveillance system represents a major step forward in protecting valuable samples and ensuring their quality for future studies, marking an important step towards modernizing Senegal's health research infrastructure.

In our future work, we plan to integrate LoRa technology to overcome the limitations of Wi-Fi, especially in terms of autonomy and power consumption. To another extent, the integration of AI could revolutionize biobank management through the analysis of temporal data.

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