Design and Development of an Affordable Laboratory Incubator with Data Logging

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Abstract

Background: Laboratory incubators recreate an artificial environment necessary for the microorganisms to grow. Of all other conditions, temperature plays a vital role in their cultivation; a minor change can alter the result. Before the invention of laboratory incubators, scientists developed their cultures in temporary enclosures or small rooms. With time, laboratory incubators evolve to become complex systems from a simple temperature-controlled chamber, which significantly helps scientific research in pharmaceuticals and microbiological studies.

Methodology: The functional prototype was developed at NED University, Pakistan, in 2024. This incubator's temperature remains constant at 37 °C. The critical components used are a PT100 sensor for precision in temperature measurement, a relay module for driving high-power devices, NODEMCU for wireless data transfer, an LCD for data visualization, and heaters to increase the temperature. The first step was to create a working prototype, which verified the system's performance and the results' stability. Upon validation of the results, a final incubator with data-logging and wireless data transfer was to be built along with improvements to the functionality.

Results: The device developed would hold the required temperature to some decent degree of accuracy. Real-time data is wirelessly transmitted through WiFi and can be visualized on cell phones. The device was much more cost-effective if compared to the commercially available products.

Conclusion: The proposed IoT-enabled, advanced laboratory incubator is a significant development in scientific instrumentation. This study found that the experimental device provides a highly accurate, reliable, efficient, and cost-effective alternative to the various commercially available options in today's market.

Keywords

Cost-Effective, Data Logging, Incubator, Temperature Monitoring.

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Introduction

Laboratory incubators are devices used to create controlled environments required while studying microorganisms. The device controls temperature, humidity, and gas composition to obtain test accuracy[1-3]. These microorganisms have specific attributes that dictate their growth to changing environmental variables, making their environment controlled for different research studies[4]. One critical factor that affects the proliferation of microorganisms the most is temperature. A range of temperatures is critical in the growth of different microorganisms such as bacteria, moulds, and yeast[5]. Such minor variations within these temperature ranges can lead to extreme outcomes and thus demonstrate how paramount controlled temperature conditions are for the propagation of such organisms[6].

Laboratory incubators have undergone many evolution processes throughout their history. Laboratory incubators evolved from simple chambers with temperature control to systems that controlled the environment precisely. They became imperative for scientific research and provided the basis for reproducible experimental conditions in the mid-20th century[7-8]. These devices have become indispensable tools for various applications throughout scientific research in pharmaceutical development, clinical diagnosis, quality control, and microbiological research[9]. Laboratory incubators provide regular conditions for biological samples, cell cultures, and microbial cultures and ensure the quality and reliability of the experiment's data.

With the invention of laboratory incubators, scientists could still maintain stable and constant conditions for the experimental material. They used to work with some temp enclosures or even small rooms where the temperature varied pretty much, and, therefore, conditions could not be kept stable. The emergence of laboratory incubators supported a considerably new approach to experiments, particularly in microbiology and medical research[10-11]. Technological advancements in laboratory incubators have introduced features including gas regulation, improved temperature stability, and humidity control. These innovations enhance the precision and reliability of experimental outcomes, driving scientific research and technological innovation. These innovations enhance the precision and reliability of experimental outcomes, driving scientific research and technological innovation[12]. This project aimed to provide a cost-effective solution for maintaining stable temperatures. By making these tools more accessible, the project will contribute to scientific research, ultimately improving the general well-being and quality of life of people around Pakistan.

Methodology

Designed System

The functional prototype was developed at the Department of Biomedical Engineering department, NED University of Engineering and Technology, Pakistan, in 2023.

Working Principle

The laboratory incubator was designed to function at the surrounding temperature of 37 ° C and in a loop enabled by a PT100 sensor, relay module, and environmental controller, which was programmed and monitored by the Arduino IDE for data logging[13-16].

Construction

The construction of the laboratory incubator included planning, research, component selection and programming to make the components work together. Validation and testing were done to ensure optimal performance and functionality. Here is a detailed look at the construction process:

- ***Component Selection:*** Component selection was the first and most significant part since it would determine whether or not the incubator offers good functionality, efficiency and compatibility. The main components include a PT-100 sensor for accurate temperature measurement, PTC heaters for rapid, stable, and safe heating, a 2-channel relay module for running high-power devices such as heaters, NODEMCU for wireless data transfer, and a 20x4 LCD for real-time data visualization (Figure-1).

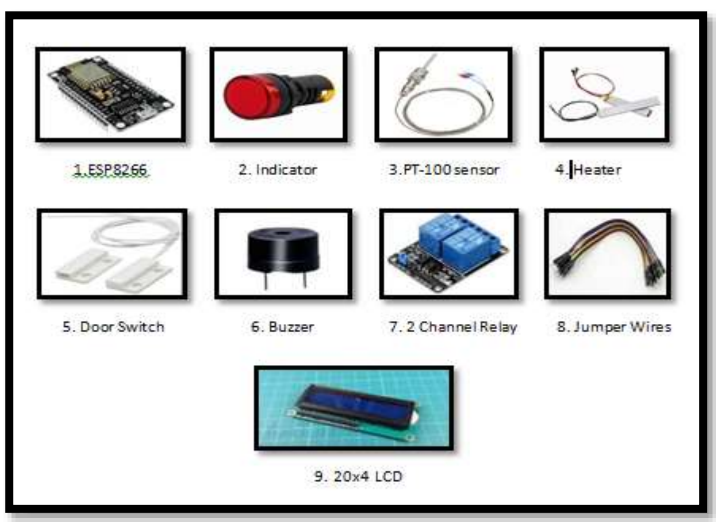

Figure-1 Components used in the construction of the prototype

- ***Prototype Development:*** Before making the final laboratory incubator, the functional prototype was built and programmed to test the working of the components and validate the system's performance[17]. This prototype served as the basis of our work. It facilitated the final product's design refinement and addressed potential issues before moving to the final construction phase.

- ***Circuit Design:*** Once the correct connections were ensured, a detailed circuit diagram was made to map all the connections of the laboratory incubator. It was started by specifying the wiring and then by mentioning each component's input and output connections and the signal flow of the entire circuit.

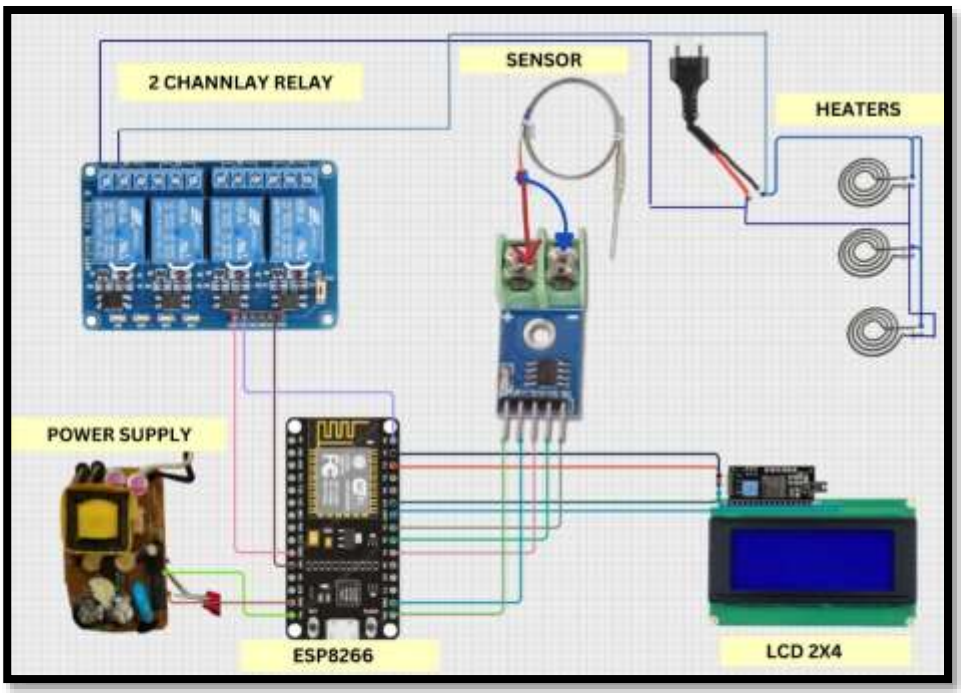

Figure-2 Circuit diagram of the laboratory incubator

- ***Programming:*** The Arduino software to program the incubator was used. The programming included a temperature control part to maintain a steady temperature, data logging for real-time monitoring, IoT connectivity credentials for wireless data transfer and other user interface interactions such as LCD. The last step was to optimize the programming for increased efficiency, reliability, and compatibility with our hardware components.

- ***Integration and Testing:*** The integration included connecting all the components according to the earlier circuit diagram. During the testing and validation phase, the main focus was observing whether the incubator provides controlled temperature conditions then its data logging capability and IoT connectivity were assessed. The testing phase included placing the incubator at different temperatures and monitoring the system's response to various environmental conditions.

- **IoT Integration:** The IoT was one of the most essential elements of the incubator since it allowed for easy data transmission. The process involved using the NODEMCU to connect with WiFi and sending data to Google Sheets for real-time data transfer and monitoring[18-20].

- **User Interface Design:** The user interface was designed to be responsive and user-friendly. The 20x4 LCD was programmed with the help of NODEMU to provide continuous temperature readings. The intelligent IoT interface allowed users to access and monitor the incubator's temperature using smartphones remotely. This enhanced accessibility and convenience for a better user experience[21-23].

- **Final Assembly:** The final assembly was completed after integrating and testing the components and the incubator. The components were secured and finalized in their place, and the wiring was organized to avoid any inconvenience while taking inspiration from the standards. The temperature control evaluated the incubator's ability to maintain the desired temperature range consistently. The design of the laboratory incubator integrates all the mentioned components for optimal functionality. The components include:
  - ***A PT100 sensor for accurate temperature monitoring.***
  - ***A 4-channel relay module for controlling heaters.***
  - ***An intelligent controller for data transmission.***

  All the components were programmed through the Arduino IDE for seamless and effective operation.

Results

The developed laboratory incubator demonstrated maintaining a constant temperature of 37°C. Two main parameters were used to judge its performance: rise and fall time.

- ***Rise Time***: The rise time is the time the incubator requires to reach the desired temperature. In the laboratory incubator, the desired temperature was 37°C, and the time needed to get it was 13 minutes. This indicates the incubator's efficiency and quickness in reaching the set temperature.

- ***Fall Time:*** Fall is the time taken for temperature to return to room temperature. In this case, it was observed to be 9 minutes, reflecting the efficiency of the laboratory incubator for rapid temperature adjustments, as shown in Table-1.

Table-1 Validation Metrics	
Validation Aspect in room Temperature	**Deviation/Time**
Temperature Rise	13 minutes
Temperature Fall	9 minutes

In addition, the stability of the temperature readings was also monitored and analyzed. Figure-3 shows temperature readings over a specific time interval. The temperature values remained consistently around 37°C, demonstrating the strength of the incubator.

Figure-3 Data points showing the incubator's temperature at a specific time interval

Moreover, the incubator successfully transferred the values to Google Sheets, demonstrating its data logging capability to share data wirelessly. Figure-4 shows the constant stream of values received on the Google Sheets, indicating continuous data transfer without error.

	A	B	C
1	Running Date	Running Time	Temperature
2	6/3/2024	12:25:00	34.75
3	6/3/2024	12:25:04	34.75
4	6/3/2024	12:25:08	34.75
5	6/3/2024	12:25:12	34.75
6	6/3/2024	12:25:17	34.75
7	6/3/2024	12:25:21	34.5
8	6/3/2024	12:25:25	34.5
9	6/3/2024	12:25:29	35
10	6/3/2024	12:25:33	35
11	6/3/2024	12:25:37	35
12	6/3/2024	12:25:41	35
13	6/3/2024	12:25:56	35.25

Figure-4 Google sheets showing the continuous transfer of temperature values along with date and time

The results confirm the incubator's efficiency in effectively maintaining stable temperature conditions. The consistent temperature readings prove PT-100 reliability, as shown in Table-2, while the data logging feature enhances functionality. As shown in Figure 5, the LCD screen and the TES-1310 show the exact temperature, validating the accuracy of the results. Additionally, no missing data points were observed, as the chart shows a complete temperature recording throughout the running time[24].

Figure-5 Testing and validation

Table-2 Validation and Performance Metrics of the Prototype	
Parameter	**Performance Metric**
Sensor Accuracy	± 0.5°C
Average Incubation Time	13 minutes
Accuracy (compared to reference)	± 0.1°C
Completeness (missing data points)	0
User Input Response Time	≤ 1 second
Incubation Efficiency	90%
Temperature Control Efficiency	99.5%

The final product can be seen in Figure-6, showcasing its stainless steel body.

Figure-6 Final product

- ***Costing:*** The laboratory incubator, when compared to commercially available alternatives, has proven to be at least four times more cost-effective due to the utilization of locally available materials for its manufacturing[28].

Discussion

This study evaluated the performance of the laboratory incubator, comparing it with other systems[18]**,** focusing on the main aspects. The PT-100 sensor proved highly accurate, with a deviation of ±0.5°C from the desired temperature. The system's reliability was tested using the calibrated reference thermometer, the TES-1310[25-26]. The user interface proved highly responsive, taking less than a second to respond to the user input. This, combined with the LCD, enhances the user experience.

The efficiency of 90% highlights the incubator's rapid processing, and the temperature control efficiency of 99.5% highlights its ability to maintain a consistent temperature throughout the running time[27]. Upon evaluation, the incubator proved to be significantly cost-effective compared to commercial alternatives, highlighting its affordability and accessibility. Furthermore, in the market, some devices are high-cost but not portable, while our device is mainly designed for user comfort and wireless compared to existing devices. This achievement aligns with our overarching goal of broadening access to laboratory technology, particularly in low-resource settings where high initial costs pose significant barriers[9,14]. Despite the efforts, the incubator shows some limitations. The prototype has yet to be tested for long-term stability and durability. Hence, it will likely have a shorter lifespan than an average laboratory incubator or commercially available one. Therefore, future research should include testing for long-term testing to analyze the incubator's stability. Moreover, the incubator also has limited functionality. Integrating features like laminated air or CO_2 control can help increase its application scope, especially for microorganisms that require precise environmental control.

These findings can significantly contribute to the field of laboratory equipment development. The efficient control, user-friendly interface and data logging features can make it a valuable tool for numerous scientific applications. Further work may involve decreasing the size of the incubator for better portability.

Conclusion

The construction of our advanced laboratory incubator with IoT integration signifies a leap forward in scientific instrumentation. With precise control, real-time monitoring, and user-friendly interfaces, this system promises to revolutionize research and healthcare practices, paving the way for enhanced efficiency and innovation.

Acknowledgments
None.

Conflict of Interest
None.

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None.

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AUTHORS' CONTRIBUTION

The following authors have made substantial contributions to the manuscript as under:

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Acquisition, Analysis or Interpretation of Data: Mujib DM, Rao AZ, Fatima J, Jawed N, Habib M, Mazhar SM

Manuscript Writing & Approval: Mujib MD, Rao AZ, Hasan MA

All the authors agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.