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Low-Cost and Accessible Scale Body Maceration Control System: Integration of Internet of Things-NodeMCU with Arduino-IDE

Sistema de Control de Maceración Corporal a Escala Accesible y de Bajo Costo: Integración de Internet de las Cosas-NodeMCU con Arduino-IDE

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SUMMARY: The rapid advancement of the Internet of Things (IoT) has transformed our lives by connecting objects and creating an intelligent environment that drives automation and massive data collection. IoT has overcome challenges through remote monitoring, robotics, and sensors, with powerful wireless technologies opening up possibilities in various fields, including anatomical techniques. The objective of this study is to demonstrate the feasibility and benefits of integrating IoT technology into the body maceration process by developing a low-cost, accessible, automated maceration control device compatible with the Arduino IDE programming environment. Using an open-source NodeMCU system based on the ESP-12E chip, which employs the LUA programming language and is compatible with Arduino IDE, we incorporated a microSD card reader module for data storage, a digital temperature sensor (DS18B20), a clock module (DS3231), a magnetic stirrer, and an aquarium heater controlled by a digital thermostat with relay (W1209). To validate the device, we conducted maceration tests on C57BL mice, comparing two groups: Control (n=5; weight=17g) subjected to maceration in 4 liters of water at 10°C without agitation; Experimental (n=5; weight=17g) exposed to maceration in 4 liters of water at 35°C, with agitation at 1500 r/min and water flow renewal at a rate of 900 ml/h. Specimens were evaluated for their degree of maceration, cleaned, weighed, and photographed. The maceration time for the control and experimental groups was 730 hours and 60 hours, respectively. In the experimental group, no foul odors, damage, or bone demineralization were detected. The device cost was 60 USD, and programming through the Arduino IDE environment was straightforward. The focus on hardware contributed to accessibility and time savings. The system operated with a conventional power supply and required a water supply, making it adaptable to various configurations with greater capacity. Under this configuration, we effectively controlled the variables (temperature, agitation, and water flow). The NodeMCU-based bone maceration system improved the performance and adaptability of existing systems and increased accessibility by reducing costs, complexity, and foul odors.

KEY WORDS: Anatomy; Internet of Things; Anatomical Technique; Maceration; Arduino; Automation.

INTRODUCTION

The rapid advancement of digital health technologies has significantly transformed various fields within medical sciences, notably through the integration of Internet of Things (IoT) applications. These advancements have been predominantly observed in clinical settings such as orthopedics, robotic surgery, and cancer care, where IoT facilitates real-time data collection, monitoring, and analysis to improve patient outcomes (Sadoughi *et al*., 2020). However, the field of anatomy, a cornerstone of medical education, has been slow to adopt these technological innovations, largely relying on traditional cadaver-based teaching methods (Aghdam *et al*., 2021; Wickramasinghe *et al*., 2022). IoT technology has been indispensable for monitoring and automating industrial processes, commonly used by tech companies but rarely in biological experiments (Parks *et al*., 2022). An IoT-based monitoring system can collect, transmit, analyze, and supervise data in real-time (Zhang *et al*., 2024). In the discipline of anatomy, the use of this technology has been limited. Maceration for osteotechnique presents an ideal candidate for IoT integration as it is a technique that has not reached higher complexity levels in terms of equipment used and data collection.

Maceration, a relevant process in osteology and anatomical preparation, traditionally involves manual cleaning and degreasing of bones, often leading to inconsistencies and prolonged processing times. Integrating IoT technology presents an innovative approach to optimize this process by enabling precise control and monitoring of variables such as temperature, agitation, and water flow (Parks *et al*., 2022; Zhang *et al*., 2024). Bridging the gap between traditional anatomical practices and modern digital

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techniques by developing an IoT-based system to streamline and improve the bone maceration process is an unaddressed challenge. In this study, we have optimized the practice of bone maceration by designing and building a system that incorporates data acquisition and storage, as well as control of agitation, temperature, and water flow. Using cost-effective technological resources such as Arduino-type modules and sensors, and NodeMCU development boards programmable via Arduino IDE software (Matuska *et al*., 2022), we have created a system that significantly accelerates the maceration process. This system not only allows remote monitoring but also facilitates the adjustment of key variables during decomposition by regulating the activity of components responsible for heating and agitating the water.

The importance of this study lies in the innovation it represents for osteotechnique and anatomy in general, providing a modern tool that enhances the efficiency and precision of the bone maceration process on a scalable level. A review of the literature reveals a gap in the application of advanced technologies such as IoT in anatomy, particularly in anatomical techniques, highlighting the need for studies that explore and validate their use. Therefore, the objective of this study is to demonstrate the feasibility and benefits of integrating IoT technology into the bone maceration process by developing a low-cost, accessible, automated maceration control device compatible with the Arduino IDE programming environment, setting a precedent for future research and applications in anatomy and other biological disciplines.

MATERIAL AND METHOD

Maceration bucket and device case. All electronic components (Table I) were mounted and organized within a "control box" (IP55; SAIME SG) measuring 187 mm x 187 mm x 105 mm. Initially, holes were drilled into the box to accommodate the various components necessary for the system. The macerator consisted of a 10-liter bucket with a hermetic seal lid (1H2/Z1.2/120/*/RCH/P.HADDAD), which included an inlet and outlet for water, a transparent plastic window, and a PG-7 cable gland (3.5 mm-6 mm) for the heater cable. Additionally, connections for the water inlet and outlet were incorporated (Fig. 1). A bottle with a chlorine tablet was connected to the water outlet hose to eliminate odors from the waste water.

Electronic components. A generic ESP8266 NodeMCU V3 module, based on the ESP-12E chip, was used with an open-source NodeMCU system, employing the LUA programming language and compatible with Arduino IDE, allowing data transmission via WiFi. This system was complemented with a microSD card reader module for data storage. The control

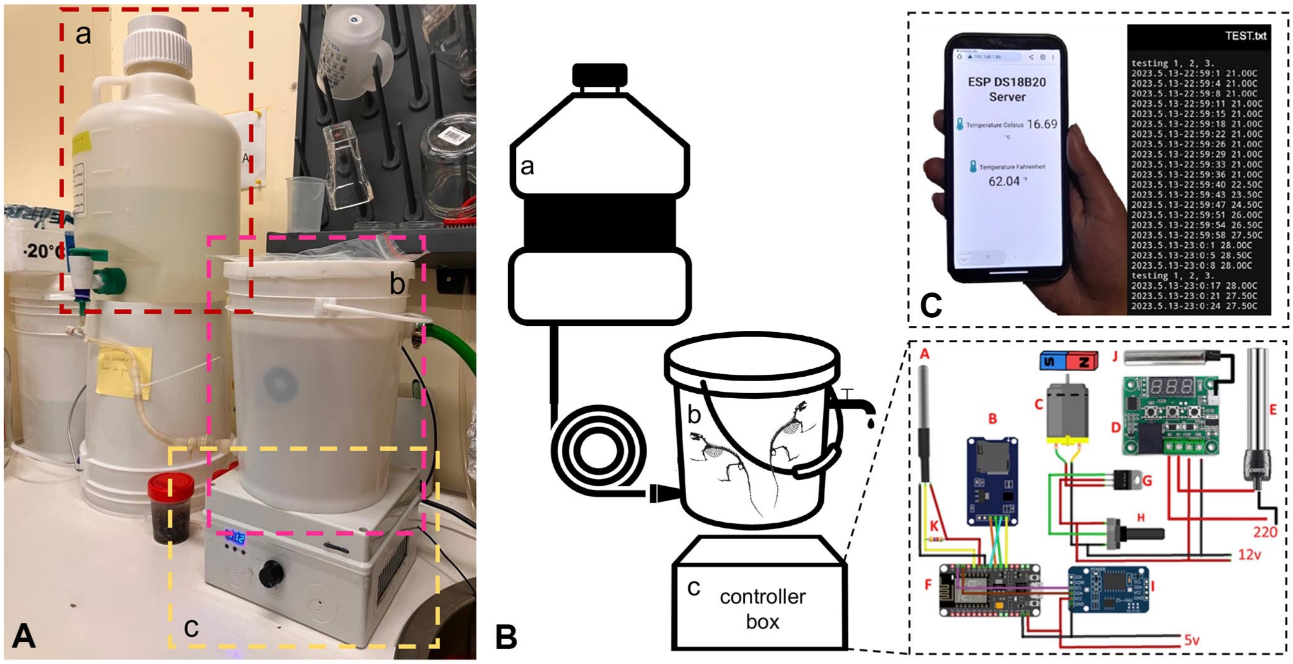

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Fig. 1. The maceration control system consists of several key components: (a) a 10-liter distilled water container, (b) a 10-liter maceration container, and (c) a control box. The diagram of the control box includes (letters in red): A) DS18B20 thermocouple, B) SD card reader module, C) 12V motor with neodymium magnet, D) W1209 relay thermostat, E) submersible aquarium heater, F) ESP8266 NodeMCU V3 CH340 development board, G) IRFZ44N MOSFET, H) 10k variable resistor, I) RTC3231 module, and J) B3950 NTC thermistor. The temperature of the bone maceration system can be monitored through a mobile phone interface, and the data is stored on an SD card in .txt format, expressed as date, time, and temperature.

Table I. Components used in the low-cost bone maceration control system

Component	Description
12V 2A Charger	Power supply providing 12V and 2A for electrical devices.
10k Potentiometer	Adjustable resistor of 10 kilo-ohms used to control voltage or current.
MOSFET IRFZ44N	Field-effect transistor used for switching and controlling high currents.
5V 2A Cell Phone Charger	Power supply providing 5V and 2A for charging mobile devices.
Generic ESP8266 NodeMCU V3	Development board based on the ESP-12E chip, compatible with Arduino IDE, for WiFi connectivity.
PG-7 Cable Gland (3.5 mm - 6 mm)	Accessory used to secure and seal cables at entry points of electronic equipment.
12V Computer Fans FAN-8025 (2 units)	12V fans used for cooling and air circulation and the magnetic stirrer.
HC-50 50W Aquarium Heater	50W stainless steel heater for maintaining water temperature in aquariums, brand “Sobo.”
IP55 Junction Box	Waterproof junction box measuring 187 mm x 187 mm x 105 mm for housing electrical components, brand SAIME SG.
10-Liter Bucket with Hermetic Lid	10-liter container with a hermetic seal lid for maceration, brand HADDAD.
Micro SD Card Module	Module with SPI interface for data storage on Micro SD cards, compatible with Arduino.
DS18B20 1-Wire Temperature Sensor	Waterproof digital temperature sensor made of stainless steel with a 1-meter cable.
W1209 Digital Thermostat with Relay	12V temperature controller with a relay and waterproof NTC stainless steel sensor.
I2C RTC DS3231 Module	Real-time clock module with Atmel24C32 EEPROM memory and CR2023 3V lithium battery.

device included a DS18B20 digital temperature sensor, a DS3231 clock module, a magnetic stirrer, and an aquarium heater controlled by a W1209 digital thermostat with a relay. A phone charger (5V) was used to power the development board and its modules, and a 12V charger was used for the relay thermostat, as well as for the fan and magnetic stirrer motors.

Circuit. The temperature control of the maceration system was achieved using a HC-50 50W Steel aquarium heater (Sobo), controlled by a digital thermostat with a relay (mod. W1209; 12V) featuring an NTC temperature sensor. The thermostat was set to maintain a constant temperature of 35°C in the experimental group. The DS18B20 temperature sensor was placed inside the maceration bucket to monitor the water temperature in real-time. This sensor sent temperature data to the NodeMCU (ESP8266), which adjusted the heater through the digital thermostat to maintain the desired temperature. The W1209 thermostat activated or deactivated the relay as needed to regulate the power supplied to the aquarium heater. The NodeMCU served as the system's brain, providing WiFi connectivity and processing power to control all components. This microcontroller was programmed using the Arduino IDE environment. Several modules were connected to the NodeMCU to achieve the desired functionalities, such as a microSD card reader module (for storing data collected during the maceration process), a DS18B20 temperature sensor (connected to the NodeMCU to measure water temperature inside the maceration bucket, utilizing the "OneWire" library for communication), and a DS3231 clock module (providing accurate time and date for recording events during the maceration process, connected to the NodeMCU via I2C communication). The NodeMCU recorded the temperature sensor data and the DS3231 clock module data using the programming defined in Arduino IDE. A magnetic stirrer was used to ensure constant agitation of the water inside the maceration bucket in the experimental group. This component was controlled by a simple voltage regulator circuit with a potentiometer, adjusted to 1500 r/min. This constant agitation ensured uniform temperature distribution and greater efficiency in the maceration process. These connections and configurations ensured that the bone maceration system operated efficiently, precisely controlling critical variables such as temperature and agitation, and allowing for remote monitoring and adjustment through the IoT connectivity provided by the NodeMCU.

Code. To create and implement the code, Arduino IDE 1.8.19 was installed (https://www.arduino.cc). Initially, the esp8266 library was installed from the page: https://github.com/esp8266/arduino. The link https://arduino.esp8266.com/stable/package_esp8266com_index.json was copied and pasted into the Arduino IDE menu: "File > Preferences > Additional Boards Manager URLs". Then, "esp8266" was searched in the "Tools > Board > Boards Manager..." section and the esp8266 library (version 3.1.2) were installed. To connect the RTC clock module and the DS18B20 temperature sensor, the corresponding libraries were installed in the "Sketch > Include Library > Manage Libraries..." menu. "rtclib" was typed in the search field and "RTClib by Adafruit" was installed. Similarly, the "OneWire" library (version 2.3.7) was installed.

Specimens and groups. To validate the device, we conducted maceration tests on C57BL mice. Two groups were contrasted: control (n=5, weight=17 g) subjected to maceration in 4 liters of water at 10 °C without agitation, and experimental (n=5, weight=17 g) exposed to maceration in 4 liters of water at 35 °C, with agitation at 1500 r/min and water flow renewal at a rate of 900 ml/h. The specimens were evaluated based on their degree of maceration, and additionally, they were cleaned, weighed, and photographed.

RESULTS

The total maceration time for the control and experimental group specimens was 730 hours and 60 hours, respectively. In the experimental group, no foul odors, damage, or bone demineralization were detected. The cost of the device was $60. Programming through the Arduino IDE environment was straightforward. The hardware-focused approach in creating the device contributed to accessibility and time savings. The system operated using a conventional power outlet and required a water supply, making it adaptable to various configurations with greater capacity. Under this configuration, we effectively controlled variables such as temperature, agitation, and water flow. We evaluated the effects of two different maceration protocols on rat specimens, organized into two groups: control and experimental. Observations were made at specific time intervals: 0, 15, 24, 39, 48, and 63 hours (Fig. 2). The specimens in the control group were subjected to a constant maceration protocol at 10 °C without agitation. At 15 hours, barely any changes were noticed in the specimens. At 24 hours, there was a slight reduction in tissue, but the specimens remained predominantly intact. At 39 hours, changes were minimal compared to the experimental group, with most soft tissue still present. At 48 hours, slight maceration was noted, but the skeleton was not clearly exposed or disarticulated. At 63 hours, although some decomposition had occurred, the soft tissue largely adhered to the bones, and disarticulation was not complete. The specimens in the experimental group were subjected to a constant maceration protocol at 35°C with constant agitation at 1500 r/min and water renewal at a rate of 900 ml/h. At 15 hours, a clear reduction in soft tissue was observed. At 24 hours, most soft tissue had been removed, exposing a large portion of the skeleton. At 39 hours, the specimens showed almost complete maceration with bones clearly visible and well-defined. At 48 hours, the skeleton was completely disarticulated and clean. By 63 hours, all bones were completely separated and clean, with no visible soft tissue remnants. These findings demonstrate that the maceration protocol used in the experimental group, which included higher temperature and constant agitation, was significantly more efficient for the rapid and complete maceration of bone specimens compared to the control method at a lower temperature and without agitation.

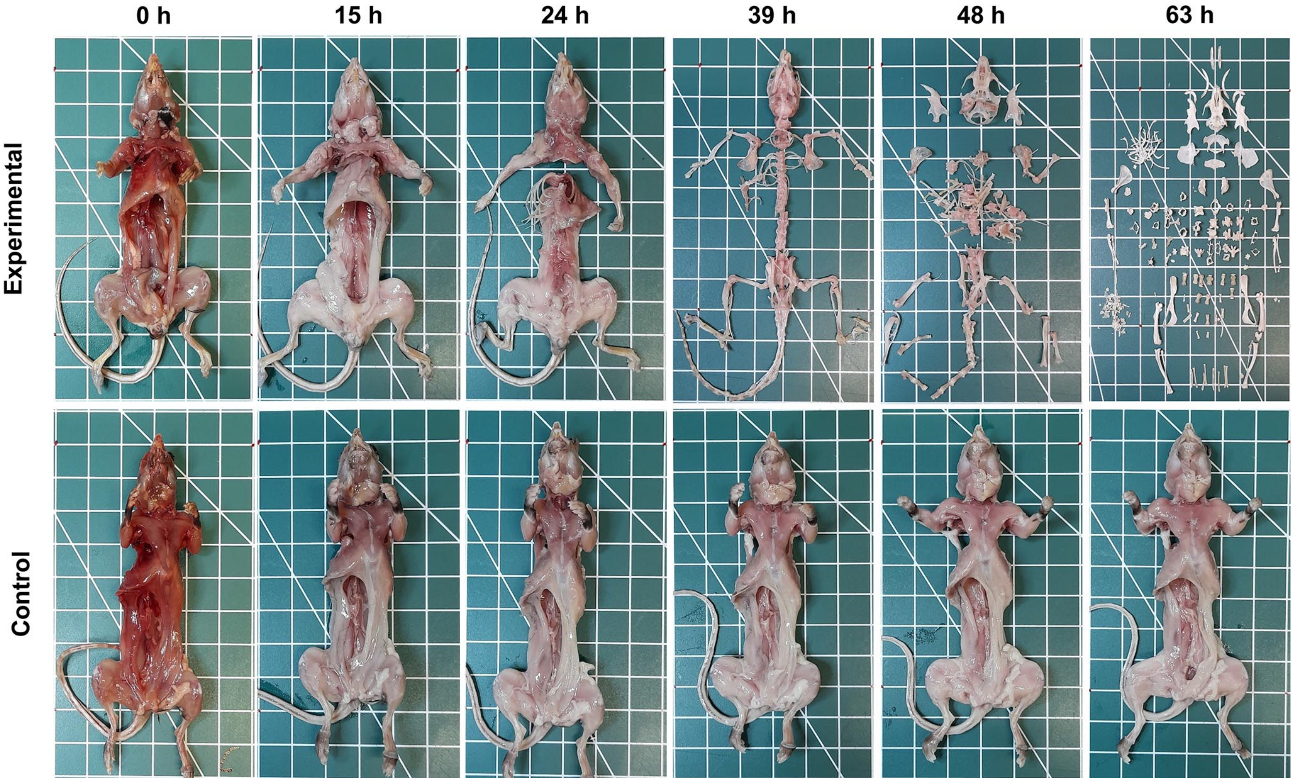

Fig. 2. Comparison of the cadaveric maceration process between the experimental group and the control group at different time intervals. The graph shows the progression of the bone maceration process in the experimental group compared to the control group at various time intervals: 0 h, 15 h, 24 h, 39 h, 48 h, and 63 h. The experimental group utilized a maceration control system based on NodeMCU and Arduino-IDE, featuring precise control of temperature, agitation, and water flow. The control group did not employ these additional controls. The figure illustrates the efficiency of the experimental system in accelerating the maceration process and improving the quality and consistency of the obtained bone specimens.

DISCUSSION

In the present study, a low-cost and accessible bone maceration control system was developed and validated, based on the integration of IoT technology with NodeMCU and Arduino IDE. The main objective was to demonstrate the feasibility and benefits of incorporating this technology into the bone maceration process, achieving precise control of critical variables such as temperature, agitation, and water flow. The results show a significant reduction in maceration time for the experimental group compared to the control group (60 hours versus 730 hours, respectively), without the presence of foul odors or damage to the bones. These findings highlight the efficiency and potential application of this system in anatomical and osteotechnical practices, representing a significant advancement in the automation and optimization of biological processes through the use of emerging technologies.

Comparison of maceration time. In this study, a significant reduction in the time required for bone maceration was observed in the experimental group compared to the control group. Specifically, the maceration time in the experimental group was 60 hours, while in the control group it was 730 hours. This notable decrease in processing time has important implications for efficiency and practicality in anatomical laboratories. The reduction of maceration time to just 60 hours in the experimental group was achieved through the implementation of an IoT-based automated maceration control system, which allowed precise control of critical variables such as temperature, agitation, and water flow. In contrast, the control group, which did not utilize agitation or proper temperature control, required significantly more time to reach a comparable degree of maceration. The implications of this reduction in time are multiple. First, improving the efficiency of the maceration process allows for a greater number of experiments in a shorter period, optimizing the use of laboratory resources. Additionally, the ability to obtain maceration results in just 60 hours facilitates more flexible and rapid scheduling of laboratory activities, enabling researchers to respond more quickly to experimental needs and analysis demands. Furthermore, this reduction in time minimizes exposure to potential contaminants and reduces the need for constant monitoring, freeing up technical staff for other important activities in the laboratory. Simonsen *et al*. (2011) and Savitri *et al*. (2023) state that the decrease in maceration time also implies less generation of foul odors and a reduction in the risks associated with the prolonged handling of decomposing biological samples.

Effectiveness of controlling critical variables. The effectiveness of controlling critical variables such as temperature, agitation, and water flow in the bone maceration process was evaluated in this study by comparing two experimental groups: one subjected to controlled conditions and another under traditional conditions without precise control. The results indicated that precise control of these variables had a significant impact on the quality and consistency of the macerated specimens. Temperature is a fundamental variable in the maceration process, as it directly influences the rate of soft tissue decomposition. In the experimental group, the temperature was consistently maintained at 35°C using a W1209 digital thermostat with a relay, whereas in the control group it was kept at 10°C without additional regulation. The specimens in the experimental group achieved complete maceration in 60 hours, with bones clearly visible and no demineralization, in contrast to the 730 hours required in the control group, where maceration was incomplete with a significant presence of adhered soft tissue. Odukoya *et al*. (2017), reported similar results, comparing the effectiveness of cold and hot water maceration techniques for developing bone specimens from cadavers. Hot water maceration showed changes in bone color and bones were very soft after bleaching but hardened upon drying in the sun. Cold water maceration, although slower, better preserved bone integrity. Agitation, controlled at 1500 r/min in the experimental group using a magnetic stirrer, also proved to be significant in improving the maceration process's efficiency. Constant agitation facilitated a homogeneous temperature distribution and accelerated the removal of soft tissue. In the absence of agitation, as in the control group, the process was considerably slower and less uniform, resulting in specimens with variations in the degree of cleanliness and bone exposure. Water flow, maintained at a rate of 900 ml/h in the experimental group, contributed to the continuous renewal of the maceration medium, removing decomposition products that could inhibit the process. Continuous water renewal during maceration has been described previously. For example, Dekeirsschieter etal. (2009) stated that it not only improved process efficiency but also significantly reduced the generation of foul odors, a common issue in traditional maceration methods. In the control group, the lack of water flow resulted in the accumulation of waste and unpleasant odors, as well as a less efficient maceration process.

Cost and accessibility of the device. The bone maceration control system developed in this study, costing 60 USD, stands out for its cost-effectiveness and accessibility. Compared to commercial systems that cost hundreds or thousands of dollars, it is an attractive option for laboratories with limited budgets. Its low cost allows the implementation of advanced technology without significant investment. The system, which controls critical variables such as temperature, agitation, and water flow using IoT with NodeMCU and Arduino IDE, surpasses many traditional systems that rely on manual adjustments and constant supervision. By utilizing open-source components like NodeMCU, the DS18B20 sensor, and the W1209 thermostat, the design is straightforward and customizable, allowing laboratories of various sizes to adopt the system without requiring advanced technical skills or expensive equipment. NodeMCU, with its Wi-Fi module and powerful processor, is an economical and efficient alternative to other microcontrollers like Arduino. For example, in IoT-based inventory management systems, NodeMCU has proven to be convenient and cost-effective, integrating with sensors and cloud storage without the need for additional components (Mansor *et al*., 2023). The combination of NodeMCU and Arduino IDE has enabled the creation of reconfigurable testbeds for real-time IoT applications, particularly useful in educational settings (Le-Viet *et al*., 2019). In smart home applications, NodeMCU reduces hardware costs by simplifying circuits, making solutions more affordable and scalable (Qiang *et al*., 2018). In educational environments, these devices enable low-cost scientific experiments (Hyun *et al*., 2021). The use of NodeMCU and LoRa technology in microclimate monitoring demonstrates its effectiveness and low cost, ideal for remote areas without constant internet access (Camparim *et al*., 2022).

Performance of electronic components. The bone maceration control system based on NodeMCU and associated modules has been extensively evaluated, highlighting both its strengths and areas for improvement. The NodeMCU, with its ESP-12E chip, provided effective WiFi connectivity and processing power, facilitating programming through Arduino IDE and enabling reliable real-time data transmission. However, using the ESP32 could enhance future performance with greater power and Bluetooth capability. Compared to other maceration methods, such as those evaluated by Keyes *et al.* (2024), the system with NodeMCU demonstrates advanced technological integration. However, similar to the studies by Steadman *et al.* (2006), the DS18B20 temperature sensor was accurate, but the NTC sensors in the W1209 thermostat exhibited durability issues due to water leakage. To address this, it is recommended to improve the sealing or use higher quality sensors. The DS3231 clock module functioned correctly, maintaining reliable timekeeping even without power, which is crucial for precise time tracking. Compared to the work of King & Birch (2015), the integrity of the neodymium magnet in the magnetic stirrer, which maintained agitation at 1500 r/min, could be an area for improvement. It is suggested to use professional laboratory stirrers or centrifugal pumps for greater stability. The aquarium heater, controlled by the W1209 thermostat, maintained the desired 35°C. However, as suggested by studies by Franchi *et al.* (2011) and Frank *et al.* (2015), it is recommended to use glass heaters for safety. These findings underscore the effectiveness of the NodeMCU-based maceration system and highlight the need for improvements to ensure its robustness and performance in forensic and laboratory contexts.

Monitoring and remote control. Remote monitoring and data storage via WiFi provided significant benefits in the developed bone maceration system. The ability to monitor critical variables in real-time, such as temperature, agitation, and water flow, allowed precise and continuous control without constant supervision, enhancing operational efficiency and process consistency (Drakshayani *et al*., 2022). Storing data on an SD card provided a detailed record for subsequent analysis, crucial for evaluating performance and making adjustments to the experimental protocol, thereby improving reproducibility. Remote access facilitated the management of laboratory time and resources, enabling researchers to review progress from any location (Alsayaydeh *et al*., 2023). Future developments could include a mobile application for remote control of system variables, allowing real-time adjustments and programming alarms and notifications for deviations, ensuring immediate responses. Additionally, the application could offer an intuitive interface to customize and save maceration profiles for different samples, increasing the system's adaptability (Ladino-Moreno *et al*., 2023). Integrating artificial intelligence could automatically optimize conditions based on historical and real-time data, reducing the need for manual intervention and enabling an almost autonomous process.

Comparison with existing technologies. The IoT-based bone maceration system is similar in many respects to bioreactors used in microbiology, although each has specific applications and key differences in their configurations and objectives. Both systems aim to optimize biological processes through precise control of critical variables and automation, but significant opportunities exist to improve the efficiency of the bone maceration system by incorporating technologies and techniques commonly used in bioreactors. Microbiology bioreactors are highly sophisticated and designed to control and monitor a wide range of parameters, including temperature, pH, dissolved oxygen, and agitation speed, among others. These systems often incorporate advanced sensors and feedback technologies that allow real-time adjustments to optimize microorganism growth and production (Zhang *et al*., 2010; Rauh *et al*., 2011). Integrating advanced sensors and actuators into the bone maceration system could significantly improve its efficiency. Additional sensors to monitor waste concentration and water quality would allow automatic adjustments to maintain optimal conditions throughout the process. Continuous filtration systems could also improve the quality and consistency of the macerate. In bioreactors, filtration systems are used to remove waste products and keep the medium in optimal conditions (Janssen *et al*., 2005). Similarly, a filtration system in the bone maceration process could remove debris and particles, reducing water turbidity and improving the process's visibility and effectiveness. This would not only keep the medium clean but also prevent the accumulation of unpleasant odors, a common concern in traditional maceration methods. Using high-pressure water jets could be another significant advancement. Bioreactors often use sophisticated agitation systems to ensure the homogeneous mixing of nutrients and microorganisms. In the context of bone maceration, high-pressure water jets could provide more effective agitation, ensuring proper water circulation around the specimens and improving theremoval of soft tissue (Stevens *et al*., 2005). Integrating an advanced interface for remote control and monitoring of the system would also benefit from developments in bioreactor technology. A mobile application or web-based interface allowing users to adjust parameters and monitor the process in real-time, along with receiving alerts and notifications about the system's status, would increase the convenience and effectiveness of the maceration system.

Impact on education and anatomical practices. The implementation of IoT technologies in anatomical education and specimen preparation has the potential to revolutionize these fields, offering significant benefits in terms of efficiency, precision, and accessibility. Modernizing and digitizing traditional anatomical practices through IoT can transform both teaching and research in anatomy. One of the most notable impacts is the improvement in the quality and consistency of prepared specimens. The ability to precisely control critical variables such as temperature, agitation, and water flow ensures that specimens are prepared uniformly and reproducibly, significantly enhancing the learning experience for students (Patra *et al*., 2022). Well-prepared specimens allow for better visualization and understanding of anatomical structures, facilitating more effective teaching. The digitization of anatomical practices through IoT technologies also allows for the automation of processes that are traditionally labor-intensive and time-consuming. The ability to remotely monitor and adjust maceration conditions reduces the need for constant supervision, freeing up time and resources for laboratory staff. This automation increases operational efficiency and enables researchers and educators to focus on more complex and creative activities, such as designing new experiments or improving teaching methods. Real-time data collection and storage are other significant benefits of IoT technology (Grignon & Duparc, 2021). The ability to continuously record process conditions and specimen status provides a valuable database that can be used to analyze and optimize preparation protocols. These data can be shared among different educational and research institutions, promoting collaboration and standardization of anatomical practices. Furthermore, the integration of IoT technologies in specimen preparation can enhance laboratory safety. The ability to remotely monitor critical conditions and receive real-time alerts allows for quick responses to any issues, minimizing risks associated with handling biological materials and using laboratory equipment (Lazarus *et al*., 2024). This is especially relevant in educational settings, where student safety is a priority. From an educational perspective, IoT technology also offers opportunities for developing new teaching tools. The possibility of creating mobile applications or online platforms that provide real-time data access and allow remote control of maceration processes can enrich the learning experience (Bodur *et al*., 2019). Students could interact with these tools to better understand the principles behind specimen preparation and the importance of controlled variables in biological experiments.

Improvements, future applications, and scalability. The bone maceration control system has significant potential for improvements and scalability. Using the ESP32 can enhance processing capacity and add Bluetooth functionality. Improving the sealing of the NTC sensors or replacing them with higher-quality sensors would increase durability. The magnetic stirrer could be replaced with a laboratory-grade model or a centrifugal pump system for greater stability. Glass heaters, instead of stainless-steel ones, would enhance safety. The adaptable design allows its use in preparing small samples and in larger volumes for industrial applications. Scalability can be achieved by increasing the capacity of the containers and adding additional components. Larger capacity tanks with more powerful agitation and heating systems would enable the processing of larger volumes. Complete automation would be achieved by integrating controlled inputs such as bacteria, gases, liquids, solids, nutrients, detergents, and/or bleaches. Specialized bacteria and nutrients would optimize maceration, while gases like oxygen would accelerate decomposition (Molina *et al*., 2019). Abrasive solids could remove resistant tissue remnants. Precise sensors and actuators, connected to the IoT system, would allow specific programming of agitation, temperature, and water flow cycles, ensuring optimal conditions and minimizing manual intervention. An advanced interface, possibly via a mobile application, would facilitate remote management. Artificial intelligence functions could automatically optimize process conditions based on historical and real-time data, maximizing the efficiency and quality of maceration.

System limitations. During the implementation of the bone maceration control system, several limitations were identified. The durability of the waterproof NTC temperature sensor was a primary issue, as water penetrated the epoxy resin seal, causing failures in temperature readings and thermal control. We recommend using higher quality sensors or improving the existing ones by encapsulating them in stainless steel or installing them through a waterproof connection in the container wall. Another limitation was the stability of the magnetic stirrer. The neodymium magnet tended to detach at high speeds, compromising agitation. We suggest using laboratory-grade magnetic stirrers or centrifugal pump systems to enhance the consistency and efficiency of the process. Scalability and adaptability were also limited, as the system was optimized for small volumes. To improve scalability, versions with larger capacity and additional components such as cranes, filtration systems, wastewater treatment mechanisms, and odor control mechanisms could be developed. The user interface and remote-control capabilities require improvements. Although the system allowed for remote monitoring via WiFi and data storage on an SD card, a mobile application could facilitate real-time control with advanced features like alarms and notifications.

CONCLUSIONS

Precise control of temperature, agitation, and water flow allowed for high-quality, consistent macerated specimens, optimizing processing time and reducing complications associated with traditional methods. This underscores the importance of automation and continuous monitoring in anatomical techniques, presenting a significant advancement in the preparation of specimens for morphological and anatomical studies. The developed cadaveric maceration control system is cost-effective and expands technological possibilities in anatomical laboratories, enhancing the accessibility and functionality of traditional maceration methods. While the system has proven effective and reliable, areas for improvement have been identified that could increase its robustness and performance. Implementing these enhancements would optimize the system, making it more efficient and safer for future applications. Remote monitoring and data storage via WiFi improve operational efficiency, precision, and flexibility. The incorporation of a mobile application for remote control promises to enhance these capabilities, offering more sophisticated and personalized control of the maceration process and opening new possibilities for the automation and optimization of anatomical techniques. This innovative approach can transform the preparation of anatomical specimens, making the process faster, cleaner, and more reproducible. The modernization and digitalization of traditional anatomical practices with IoT can significantly improve specimen preparation and anatomical education, benefiting students, researchers, and educators. The scalable bone maceration system based on the NodeMCU development board has improved the performance and adaptability of existing systems, extending its accessibility by reducing cost, complexity, and odors, making it useful for forensic science, private conservation workshops, and educational purposes.

RIVERA, J. & SALINAS, P. Sistema de control de maceración corporal a escala accesible y de bajo costo: Integración de internet de las cosas-NodeMCU con Arduino-IDE. *Int. J. Morphol., 42(5)*:1239-1247, 2024.

RESUMEN: El rápido avance del Internet de las Cosas (IoT) ha transformado nuestras vidas al conectar objetos y crear un entorno inteligente que impulsa la automatización y la recolección masiva de datos. El IoT ha superado desafíos a través del monitoreo remoto, la robótica y los sensores, con tecnologías inalámbricas potentes que abren posibilidades en diversos campos, incluidas la anatomía y las técnicas anatómicas. El objetivo de este estudio fue demostrar la viabilidad y los beneficios de integrar la tecnología IoT en el proceso de maceración cadavérica mediante el desarrollo de un dispositivo de control de maceración automatizado, accesible y de bajo costo, compatible con el entorno de programación Arduino IDE. Usando un sistema NodeMCU de código abierto basado en el chip ESP-12E, que emplea el lenguaje de programación LUA y es compatible con Arduino IDE, incorporamos un módulo lector de tarjetas microSD para el almacenamiento de datos, un sensor de temperatura digital (DS18B20), un módulo de reloj (DS3231), un agitador magnético y un calentador de acuario controlado por un termostato digital con relé (W1209). Para validar el dispositivo, realizamos pruebas de maceración en ratones C57BL, comparando dos grupos: control (n=5; peso=17g) sometido a maceración en 4 litros de agua a 10°C sin agitación; experimental (n=5; peso=17g) expuesto a maceración en 4 litros de agua a 35°C, con agitación a 1500 r/min y renovación del flujo de agua a una velocidad de 900 ml/h. Los especímenes fueron evaluados según su grado de maceración, limpiados, pesados y fotografiados. El tiempo de maceración para los grupos control y experimental fue de 730 horas y 60 horas, respectivamente. En el grupo experimental no se detectaron malos olores, daños ni desmineralización de los huesos. El costo del dispositivo fue de 60 USD y la programación a través del entorno Arduino IDE fue sencilla. El enfoque en el hardware contribuyó a la accesibilidad y al ahorro de tiempo. El sistema operaba con una fuente de alimentación convencional y requería un suministro de agua, lo que lo hace adaptable a diversas configuraciones con mayor capacidad. Bajo esta configuración, controlamos eficazmente las variables (temperatura, agitación y flujo de agua). El sistema de maceración ósea basado en NodeMCU mejoró el rendimiento y la adaptabilidad de los sistemas existentes, y aumentó la accesibilidad al reducir los costos, la complejidad y los malos olores.

PALABRAS CLAVE: Anatomía; Internet de las Cosas; Técnica Anatómica; Maceración; Arduino; Automatización.

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