Design and Development of A Semi-Autoclave for Packaged Food based on Arduino R4 WiFi and Internet of Things (IoT)

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Abstract. Sterilization is a crucial stage in maintaining the safety and quality of packaged food, yet access to efficient and affordable equipment remains a barrier for micro and small enterprises (MSEs). This study reports the design and development of a compact, low-cost semi-autoclave for packaged food based on an Arduino R4 WiFi microcontroller and the Internet of Things (IoT). A type K thermocouple (via a MAX6675 module) and a pressure transducer transmitter, both mounted on the vessel lid, monitor the process, while a 12V solenoid valve provides closed-loop automatic venting and a manual safety valve acts as a safeguard. Process data are shown on an I2C LCD and transmitted to the Blynk application in real time. Sensor performance was validated against a manual pressure gauge and a digital thermometer by the comparison method. The mean reading error was about 2.3% (maximum 5.0%) for pressure and 0.9% (maximum 2.0%) for temperature. The chamber reached the target conditions of 121°C and 15 psi in about 15 min, and the solenoid responded consistently to automatic thresholds and manual commands, with an IoT transmission delay of 533–1003 ms. The prototype demonstrates the feasibility of affordable IoT-based monitoring and control of the sterilization process for MSEs, microbiological validation of sterility was not performed and is identified as future work.

1 Introduction

Thermal sterilization is a crucial stage in the food industry for ensuring the safety and shelf stability of packaged food. For low-acid shelf-stable products, processing at about 121°C and 15 psi is the established benchmark, and suboptimal processing can lead to microbial contamination that endangers consumers and damages producers [1]. Achieving and

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documenting these conditions reliably is therefore essential to product quality. For micro and small enterprises (MSEs), however, this requirement is difficult to meet in practice. Commercial retorts and industrial autoclaves are capital-intensive, bulky, and depend on trained operators and external validation infrastructure, whereas the affordable equipment that MSEs can access generally lacks instrumentation to monitor, control, and record the process [2]. The specific, practical gap addressed in this work is therefore the absence of a compact and affordable unit that can simultaneously (i) reach and control the temperature–pressure conditions associated with sterilization, (ii) measure and display both parameters, and (iii) support remote monitoring and digital documentation without specialised infrastructure.

The Internet of Things (IoT) offers a route to close this gap. Reviews report rapid adoption of IoT for real-time monitoring across food processing [3,4], and low-cost Arduino-based devices have been demonstrated for measuring food-related parameters [5]. IoT-enabled packaging and biosensors monitor quality and safety [6], IoT frameworks have been proposed for food-quality assessment [7], and low-cost sensor systems have been applied to food-quality monitoring [8]. At the equipment level, PLC/IoT systems have automated specific food processes [9], and low-cost IoT monitoring-and-control architectures have been validated in related agri-food applications [10]. Nevertheless, these works typically target a single parameter or a single function (monitoring, packaging, or control) and are not integrated into an affordable, instrumented sterilization unit dimensioned for MSEs.

Against this background, the contribution of this work is stated explicitly to distinguish what is genuinely new from what is combined from established techniques. The individual building blocks (temperature sensing, pressure sensing, solenoid valve control, and IoT data transfer) are well known. What is new in this work is: (i) the integration of these functions into a single compact, low-cost semi-autoclave dimensioned specifically for MSEs (8L), in which the thermocouple and pressure transducer are mounted intrinsically on the vessel lid so as to sense the chamber directly; (ii) a closed-loop venting scheme in which a 12V solenoid opens the steam valve only when both the temperature (121°C) and pressure (15 psi) set-points are satisfied, backed by an independent manual safety valve; and (iii) the use of the on-board WiFi of the Arduino R4 to provide simultaneous local (LCD) and remote (Blynk) monitoring, notification, and digital documentation without any additional gateway hardware. To the best of the authors' knowledge, an affordable semi-autoclave combining these specific features for micro and small food enterprises has not been reported previously. The objectives are therefore to design and build such a device, to validate the accuracy of its temperature and pressure monitoring, and to evaluate its control behaviour, IoT performance, and heating effect on packaged food.

2 Research method

The device was developed using the Borg and Gall research-and-development method, simplified into four stages: literature study and preliminary design, hardware and software design, testing and validation, and evaluation and documentation.

2.1 Hardware design and hardware

The pressure vessel that serves as the heating chamber has a diameter of 24 cm and a height of 16 cm, giving a capacity of about 8 litres, while the control electronics are housed in a separate protective box measuring 17 cm × 10 cm. The three-dimensional design is showed in Figure 1. The thermocouple, the pressure transducer, and the steam valve are mounted intrinsically on the vessel lid so that they sense the chamber directly, whereas the microcontroller, relay, LCD, and power supply are placed in the electronics box.

The control centre is an Arduino R4 WiFi. The type K thermocouple is interfaced through a MAX6675 module over the SPI bus (data, chip-select, and clock lines); the I2C LCD is connected to the SDA and SCL pins (A4 and A5); the pressure transducer transmitter provides an analog output read on pin A0; and the 12V solenoid valve is driven through a relay module from a digital output pin. A 12V power supply unit (PSU) energises the system. The pressure transducer has a measuring range of 0–175 psi and the type K thermocouple a range of −200 to +1200 °C, both comfortably covering the sterilization window of the device. The circuit schematic and PCB layout were prepared in Proteus and fabricated into a printed circuit board. Figure 2 shows the schematic and the pin assignment summarised above.

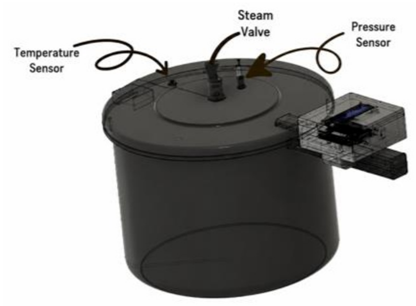

Fig. 1. Design of the semi-autoclave and the sensor positions on the lid.

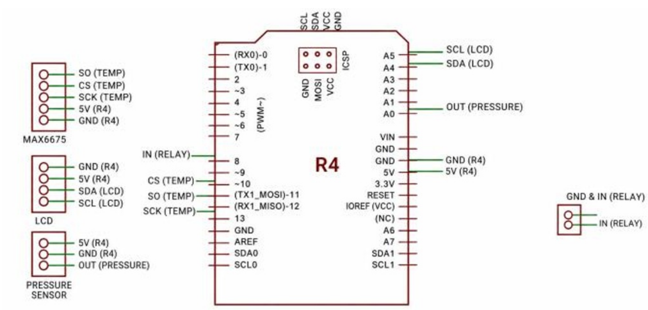

Fig. 2. Circuit schematic and pin assignment of the Arduino R4 WiFi-based semi-autoclave.

2.2 Software and control logic

The firmware, developed in the Arduino IDE, continuously reads the thermocouple and the pressure transducer, displays the values on the I2C LCD, and uploads them to the Blynk application over WiFi. The steam valve follows a dual-threshold control rule: the solenoid is energised (valve open) only when the chamber temperature is at least 121°C and the pressure is at least 15 psi simultaneously, and is de-energised (valve closed) once the readings fall below these set-points. In addition, the user can open or close the valve manually from the Blynk dashboard, and Blynk issues a notification when the set-points are exceeded or when the device goes offline. Blynk was selected because it runs on both smartphones and desktops and supports real-time data exchange and logging.

2.3 Testing and validation procedure

Sensor accuracy was assessed by the comparison method, in which the sensor and a reference instrument measuring the same quantity were read simultaneously. For pressure, a manual

Bourdon-type pressure gauge served as the reference; the chamber pressure was raised stepwise from 0 to 15 psi and held for about one minute at each set-point before recording. For temperature, a digital cooking thermometer served as the reference, with simultaneous readings taken from the thermometer and the sensor LCD. The reading difference and the absolute error percentage were computed with Eqs (1) and (2).

$$\text{Difference } (\Delta) = \text{reference value} - \text{sensor reading} \qquad (1)$$

$$\text{Error } (\%) = (\text{Difference} / \text{reference value}) \times 100\% \qquad (2)$$

It should be stated transparently that the reference instruments were used as supplied; their accuracy class and calibration certification were not independently verified, and each condition was recorded in a single run. Formal repeatability over multiple trials and a complete measurement-uncertainty budget were beyond the present scope and are recommended for subsequent validation. In addition to sensor accuracy, the dynamic control behaviour, the IoT transmission delay, and the heating effect on several packaged foods were evaluated, as reported below.

3 Results and discussion

3.1 Product development result

The prototype was successfully assembled by integrating all hardware and software subsystems. Figure 3 shows the device components: (1) pressure transducer transmitter, (2) safety valve, (3) type K thermocouple, (4) steam valve, (5) 12V solenoid valve, (6) LCD, (7) Arduino R4 WiFi, and (8) power supply unit. In operation, the system measures the temperature and pressure inside the vessel, displays them on the LCD and the Blynk application, and actuates the steam valve through the solenoid according to the control rule of Section 2.2.

3.2 Power supply test

The power-supply test using a multimeter obtained an input voltage of 12.8 V and an output voltage of 12.7 V. This result indicates that the step-down circuit operates stably and meets the component requirements.

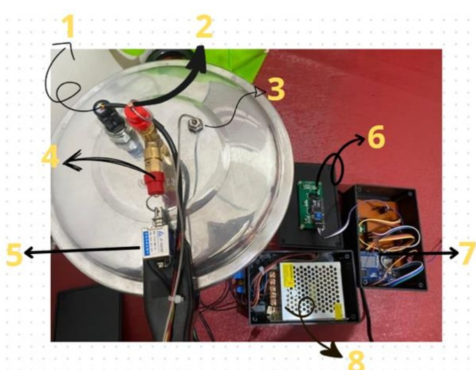

Fig. 3. Components of the semi-autoclave.

3.3 Pressure transducer sensor test

The pressure transducer was tested by raising the pressure stepwise to 15 psi against a manual gauge (Table 1).

Across the measurement points (excluding the 0-psi point, where the error is undefined), the mean absolute difference was about 0.30 psi and the mean error about 2.3%, with a maximum of 5.0% at 2 psi. The readings are accurate and stable over the operating range and are adequate for the device, although the single-run nature of the test should be kept in mind when interpreting these figures.

Table 1. Pressure transducer sensor test results.

Time (min)	Manual gauge (psi)	Transducer (psi)	Difference (psi)	Error (%)
0	0	1.2	1.2	-
2	2	2.1	0.1	5.0
5	4	3.9	0.1	2.5
6.5	6	6.1	0.1	1.6
8	8	7.8	0.2	2.5
10	10	10.0	0.0	0.0
14	12	12.2	0.2	1.6
16	14	13.9	0.1	0.7
17.5	15	15.7	0.7	4.6

3.4 Type K thermocouple sensor test

The type K thermocouple was tested by comparing its temperature readings with a digital cooking thermometer. The test results are presented in Table 2.

The mean absolute difference was about 0.45 °C and the mean error about 0.9%, with a maximum of 2.0%; all values lie within ±0.8 °C of the reference. The thermocouple therefore tracks temperature accurately over the tested range. As above, repeated trials would be needed to characterise repeatability formally.

Table 2. Type K thermocouple sensor test results.

Time (min)	Manual thermometer (°C)	Thermocouple type K (°C)	Difference (°C)	Error (%)
0	33.2	32.7	0.5	1.5
1	34.6	34.7	-0.1	0.2
1.5	39.9	40.7	-0.8	2.0
2.5	48.3	47.5	0.8	1.6
4	66.1	65.7	0.4	0.6
6	86.1	86.7	-0.6	0.7
10	94.3	94.1	0.2	0.2
11	97.4	97.2	0.2	0.2

3.5 Control behaviour and solenoid actuation

The dynamic behaviour was evaluated from a complete heating run. The chamber temperature rose from about 34 °C to 115 °C within 10 min and reached 121 °C at approximately 15 min, while the pressure reached 15 psi at about 18 min. Because the venting rule requires both set-points to be satisfied simultaneously and the pressure lagged the temperature, the chamber temperature overshot to about 130 °C before the 15 psi pressure threshold was met and the solenoid opened the steam valve. After actuation, the chamber decompressed rapidly: temperature fell from about 130 °C to 88 °C and pressure from 15.4 to 10.9 psi within 30 s, returning to about 52 °C and 2.1 psi after roughly 1.5 min, at which point the valve closed automatically. The solenoid responded consistently to both the automatic thresholds and manual commands issued through Blynk. The observed temperature overshoot of about 9 °C above the 121 °C set-point indicates that the simple dual-threshold logic could be refined — for example with proportional control or earlier staged venting — to track the target more tightly; this is noted as future work.

3.6 IoT transmission performance

The IoT performance was assessed by measuring the delay between data appearing on the LCD and on the Blynk dashboard (Table 3). The delay ranged from 533 to 1003 ms with a mean of about 781 ms, indicating near-real-time transmission. The variation reflects the connection speed and the communication process of each interface. Reliability over prolonged operation, behavior under unstable Wi-Fi, and the data-loss rate were not quantified in this study and should be assessed in future work.

Table 3. IoT data transmission delay test results.

Time (min)	Temperature (°C)	Pressure (psi)	Delay (ms)
0	32.4	1.6	902
2	43.2	1.9	978
3	56.1	2.1	697
4	71.9	2.4	944
6	83.7	3.1	679
10	115.5	9.3	533
12	118.0	9.3	608
14	120.0	10.3	1,003
15	123.0	11.5	684

3.7 Packaged food heating test

The test was conducted on six types of packaged food to measure the internal food temperature after resting for 3 minutes following heating at about 121°C and 15 psi. The results are presented in Table 4.

All samples showed an internal temperature rise, but the core temperatures after the 3-min rest (54.3–73.7°C) remained well below the 121 °C chamber set-point, indicating that heat penetration to the product core and the holding time still require optimisation. Importantly, these measurements characterise heat transfer only; they do not by themselves establish microbial sterility. Microbial-reduction assays and process-lethality (F0) determination were not performed in this study and are required to validate sterilization efficacy. This is identified as essential future work and constrains the strength of the present claims accordingly.

Table 4. Packaged food heating test results.

Food type	Process temperature (°C)	Food temperature after 3 min (°C)
Canned liquid milk	122	56.8
Canned sardines	124	59.6
Canned corned beef	128	54.3
Corned beef (polypropylene)	121	73.7
Chili sauce (polypropylene)	121	55.9
Chicken meat (polypropylene)	121	54.6

3.8 Comparison, safety, and limitations

Whereas earlier IoT-based studies addressed single aspects such as real-time monitoring [4], smart packaging [6], or low-cost food-quality sensing [8], the present work integrates simultaneous temperature and pressure monitoring with automatic, IoT-controlled steam-valve actuation in one affordable semi-autoclave dimensioned for MSEs. This integration, rather than any single component, constitutes the contribution of the study.

Because the device operates with pressurised steam, several safety provisions were incorporated. An independent manual safety valve can be pulled to release steam if the system loses power or the automatic valve fails; the closed-loop solenoid vents the chamber automatically once both set-points are reached; and the Blynk notification alerts the user when the set-points are exceeded or when the device goes offline. Identified failure modes include solenoid or relay failure (mitigated by the manual safety valve), loss of WiFi (mitigated by the local LCD, with a local buzzer or light indicator recommended), and sensor drift (mitigated by periodic calibration). A formal risk assessment, for example a failure mode and effects analysis (FMEA), together with characterisation of the over-pressure relief, is recommended before field deployment.

The main limitations of the study are the relatively small chamber capacity (8 litres), the use of a manual external heater (a stove), the single-run nature of the sensor validation without repeated trials or a formal uncertainty budget, the temperature overshoot arising from the simple dual-threshold control, and, most importantly, the absence of microbiological verification of sterility. These limitations frame the scope within which the present results should be interpreted.

4 Conclusion

A compact, low-cost semi-autoclave for packaged food based on the Arduino R4 WiFi and the Internet of Things was successfully designed and built. On a prototype scale, the device monitored temperature and pressure with mean errors of about 2.3% and 0.9% respectively, displayed and transmitted data to an LCD and the Blynk application in real time with a sub-second delay, and automatically actuated the steam valve at the programmed set-points, supported by an independent manual safety valve. These results demonstrate the feasibility of affordable IoT-based monitoring and control of the sterilization process for micro and small enterprises.

However, the study validated the system only at prototype scale and did not include microbiological verification of sterility, repeated-trial repeatability, or long-term IoT reliability; the heating tests also showed that the product core temperature and holding time need optimisation. These issues, together with refinement of the control logic to reduce temperature overshoot and the addition of a local buzzer or indicator and historical data logging (for example Google Sheets or a local server), are the priorities for further work. Within these limits, the prototype provides a practical and affordable basis for IoT-assisted thermal processing in small-scale food production.

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