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Development and Research of a Smart IoT-Enabled Bread Making Machine with Real-Time Browser Interface

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Abstract: *This development proposes an IoT-based application for automatic bread making, providing new opportunities for convenience and customisation of the process. The use of IoT technologies allows connectivity with other smart devices in the home while improving efficiency and control over baking. The developed system includes local control, which provides speed and security through physical connectivity to the home network and eliminates dependence on an Internet connection. The IoT functionality of the machine provides monitoring of basic parameters such as temperature and time for fermentation and baking. The application of a PID regulator significantly improves temperature control, reducing deviations from 15°C with relay control to 4°C after refinement. This leads to more precise baking and improved quality of the final product. The traditional buttons and small displays of commercially available bread machines have been replaced by an intuitive HMI interface and web monitoring via ESP8266, which facilitates machine management. Research has shown that controlling the temperature below 220°C reduces the formation of acrylamide in the bread crust, with the machine set to operate at 162°C. Research in this area has been expanded, and programs have been implemented to prepare bread with alternative flours rich in nutrients. Future development opportunities include the application of AI and predictive models to optimise fermentation and baking processes, as well as integration with smart AI enabled systems such as Alexa+ and Google Home.*

Keywords: *AI enabled; cloud and local control; human-machine interface (HMI); remote operation; sensor integration.*

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1. Introduction

The Internet of Things (IoT) is a technology used to transform traditional appliances into smart ones, with self-sustaining communication and management. With the advancement of IoT technologies, everyday appliances such as refrigerators, washing machines, rice cookers, and bread makers are connected to the Internet, remotely controlled, and monitored by smart devices. This integration brings substantial enhancements in the efficiency and comfort of routine work, leading to the improvement of resource control and user experience (Puzhevich, 2019). IoT technology has been successfully implemented, mainly in the home automation sector. IoT facilitates communication between appliances and devices, which ultimately turns classic houses into smart, efficient, and warm homes. It is realised through real-time monitoring and self-control systems (Patel, Sharma, & Randhawa, 2025).

One of the important features of automated systems is the proportional-integral-derivative (PID) control, which provides stability and precision in industrial processes (Thorat, 2025). PID controllers are widely used in industrial automation, due to their reliability and ability to provide sufficient accuracy in controlling process parameters such as temperature, pressure, and flow. The use of PID control in IoT-based systems makes them efficient and reliable, as well as sufficiently robust to be used in modern automation.

Online monitoring of production processes in the bakery industry has encountered numerous challenges (Melesse & Orrù, 2025). Maintaining stable quality levels of production processes, maximising resource utilisation, and meeting safety standards, involves the installation of advanced control and monitoring systems. The bakery industry has been led by Industry 4.0 technology to embrace digital transformation, including the implementation of solutions such as wireless sensor networks and artificial intelligence-based automation software, that offer real-time monitoring and optimisation of the bread and bakery production process.

ESP8266 is a low-cost Wi-Fi module that offers seamless connectivity and remote control via web interfaces (Alam, 2024). With the help of PID temperature control, the automatic control system can provide stable conditions for maintaining technological quantities in production processes, thereby increasing the quality and uniformity of the final product. In addition, a properly designed human-machine interface (HMI), offered through a touch screen or browser interface, increases human interaction and control over technological processes (Aparna, 2025).

HMI is being integrated into modern coffee machines and toasters, such as the Revolution InstaGLO (Revolution Cooking, Woburn, MA, USA). Using an IoT system, the device can be controlled and monitored over the Internet. Touchscreen IoT toasters offer several advantages, including precise time and temperature control, personalised toasting profiles, real-time monitoring through smart connectivity, and ensuring consistent and quality results. They also offer user convenience in terms of pre-programmed options, voice integration, and compatibility with home automation systems. Disadvantages include an elevated cost of the device compared to traditional toasters, potential software or connectivity issues, and reliance on constant updates for full functionality.

There have been limited developments in the application of IoT and HMI for devices that require a more complex technological process, compared to toasters (Srinivas, Swami Das, & Malathi Latha, 2021). Automatic bread machines are significantly more complex than toasters, as they include multiple stages such as kneading, fermentation processes and baking, which require precise process control and coordination. They rely on sophisticated IoT systems and multiple sensors to monitor parameters such as temperature and humidity, ensuring consistent quality. Automation and customisation of processes further increase the complexity of the human-machine interface (HMI). In comparison, toasters have a significantly simpler operating principle, focused solely on heating, which makes them easier to control and with fewer requirements for sensors and control systems.

Plant additives in bread making in an automatic bread machine can significantly improve the quality and nutritional value of the product. They affect the texture, taste, colour, and shelf life of the bread (Akanbi & Folorunso, 2022; Naumenko et al., 2017). Plant additives enrich the bread with fibre, vitamins, and minerals, making it healthier.

One example of a plant additive is pigweed (Amaranthus), which can increase the protein and fibre content. Amaranthus gives a slightly greenish tint to the bread crumb and can make the crust darker. It improves the nutritional value of the bread by adding essential amino acids and minerals (Sushil & Suneeta, 2018; Mesta-Corral et al., 2024).

Another example is purslane (Portulaca oleracea), which adds antioxidants and omega-3 fatty acids to bread. Purslane gives bread a darker crust and a denser crumb structure. It also improves the taste and increases the shelf life of bread (Khakimova et al., 2024). Pigweed and purslane additives can affect fermentation processes by slowing them down. This is due to the high content of antioxidants, fibre, and proteins that interact with yeast and change their metabolism (Shanshan & El Bushuty, 2020; Sadeghzadeh-Benam et al., 2022).

Pigweed and purslane vegetable additives demonstrate significant potential to improve the quality and nutritional value of bread made in an automatic machine. They not only add important nutrients but also affect the texture, taste, and shelf life of bread, although they can slow down fermentation processes.

Powered by generative AI, Alexa+, and Google Home, there are AI assistants that are smarter, more interactive, and more capable. To ensure effective integration, the devices controlled by these assistants must be thoroughly analysed and subject to precise operational control. The more common automatic bread machines do not provide such capabilities at the current level of development in science and technology. A detailed study of the operation of these machines and refinement of their control and communication systems is essential. This will establish a foundation for the precise and effective integration of bread machines with intelligent user management systems. This approach includes refining bread recipes and using healthy and safe raw materials for its preparation. The technological process embedded in the machine should be adapted to accommodate the characteristics of the raw materials that are used. This would also lead to the improvement of nutritional value, healthiness, and organoleptic characteristics, acceptable to the consumer of the final product.

Considering the limitations and shortcomings of existing technical solutions, the goal of this development is to propose an IoT application for automatic bread making through efficient and reliable automation of related processes.

2. Related Works

A comparative analysis of six automatic bread machines distributed in the commercial network was conducted. Table 1 lists the models of the machines compared. Automatic bread machines from different manufacturers are marked with “BM” (Bread Maker). All machines, except BM4 and BM5, have an electrical power of 650 W. BM4 has a power of 600 W, and BM5 is rated at 580 W. Most of the models, except BM5, can produce bread with a maximum mass of 1 kg. BM5 has a capacity of 0.9 kg. The machines are produced by different manufacturers such as Medion, Sanyo, Kenwood, Morphy Richards, Cookworks, and Breville.

Table 1. Models of the bread machines compared

Designation	Model	Electric power, W	Wmax,kg	Manufacturer
BM1	MD-18636	650	1	Medion, Essen, Germany
BM2	SBM-20	650	1	Sanyo Electric Co., Ltd., Osaka, Japan
BM3	BM-250	650	1	Kenwood, Tokyo, Japan
BM4	48280-00	600	1	Morphy Richards, Swinton, UK
BM5	EHS20AP-P	580	0.9	Cookworks, St. Asaph, Wales
BM6	BBM100	650	1	Breville Group Ltd., Alexandria, Australia
Wmax – maximum bread weight				

Figure 1 illustrates the bread machines being compared in general. The visual comparison of the models gives a general overview of their appearance and design. The presented models show different functions and capabilities based on different technological approaches for preparing bread, yoghurt, and jam.

Figure 1. Automatic bread machines compared – general view. (a) BM1; (b) BM2; (c) BM3; (d) BM4; (e) BM5; (f) BM6. [sources: manufacturers]

Figure 2 illustrates temperature profiles in automatic bread machines during baking. Data are from Hamlet, Jayaratne, & Morrison (2006), Elfnor (2015), and Slices of Blue Sky (2025).

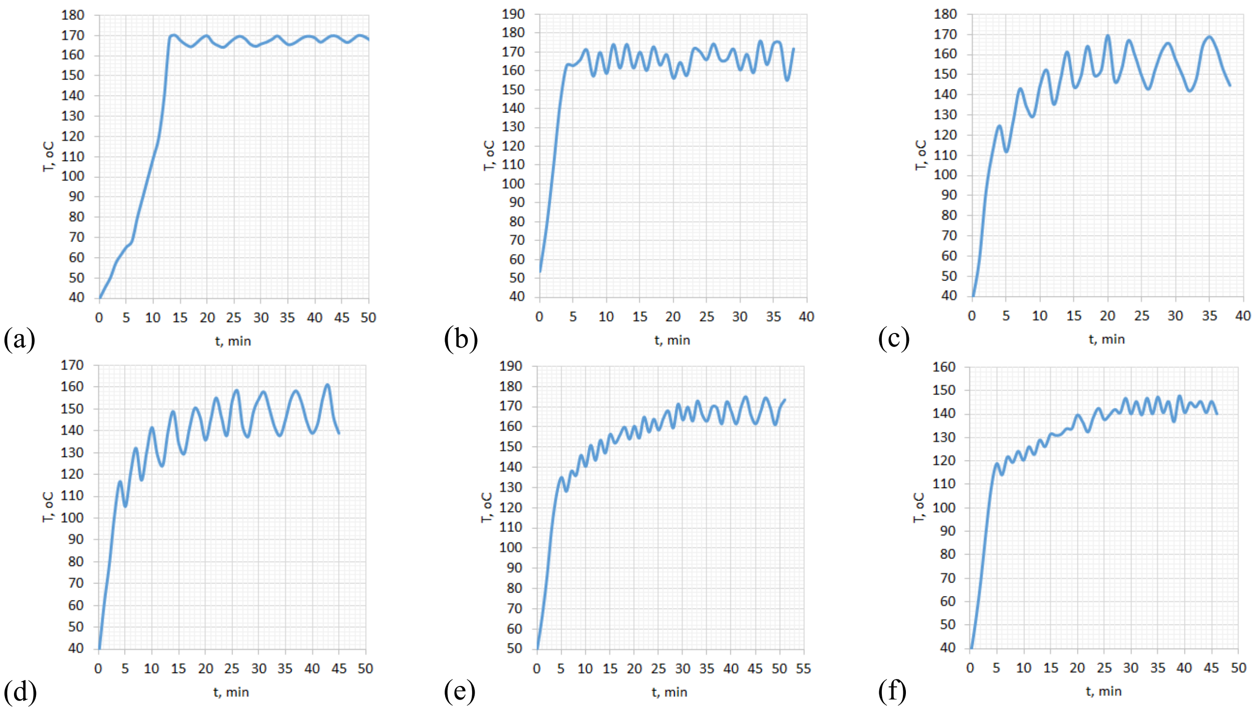

Figure 2. Temperature variation in automatic bread machines. (a) BM1; (b) BM2; (c) BM3; (d) BM4; (e) BM5; (f) BM6

Measurements were made by recording the temperature from the generally accepted position of the temperature sensor attached to the metal tank, behind the main heater. From the graphs presented, it can be summarised that the temperature control in these machines is not precise. The temperature curves exhibit significant variation and fluctuation across models, potentially compromising the consistency of the baking outcome. Uneven temperature changes lead to problems such as underbaked bread or excessive crust browning. Temperature control is by a two-position regulation method. In the baking stage, it varies within significantly wide limits, reaching a deviation from its set value of ±15°C. The graphs show that the Medion (BM1) and Breville (BM6) models have more precise baking temperature control compared to other bread machine models.

Research by Hesketh, Slater, & Flynn (2001) demonstrates that automatic bread machines have limitations in terms of precise control of key parameters such as temperature, humidity, and fermentation time. Measurements on the examined bread machine models show temperature fluctuations in the range of ±12–15°C.

According to Hamlet, Jayaratne, & Morrison (2006), temperature fluctuations are a major factor in the unevenness in porosity and volume of the final product, which is observed mostly in automatic bread machines. It was found that with prolonged baking above 220°C, the concentration of acrylamide in the crust of bread is increased by 78%, which significantly exceeds the safe limits established in industrial production. Further analysis revealed that by reducing sugar content of more than 2.5% in the dough, the formation of acrylamide increases proportionally, reaching the maximum concentrations of 95 µg/kg in specific recipes. In dough mixes containing tomatoes and onions, acrylamide levels are increased by 60% compared to standard recipes, highlighting the need to control the ingredients that were used and the temperature regimes.

In automatic bread makers, the possibilities for process control are significantly limited: temperature deviations can reach ±15°C, the fermentation time is often fixed according to the device programs and, in many cases, does not correspond to the optimal parameters for dough development. Research by Ioannidis (2015) demonstrates that through integrated control of bread makers using the Arduino platform, significant improvements in the process of control can be achieved. Through adaptive control of temperature and baking time, an improvement in the texture and consistency of bread is established, which brings its characteristics closer to those achieved in industrial production. In the conducted experiments, significant differences in heat distribution were measured, and in automated models with additional temperature control, the variation in baking is reduced by 27% compared to standard models. Further research revealed that in models with improved thermal control, moisture loss during baking was reduced by 15%, which contributed to greater softness and a slower hardening process of the bread. In addition, the use of PID controllers for dynamic control of the thermal process allows for precise regulation of the internal temperature of the breadmaker, ensuring a homogeneous structure. According to observations conducted within the framework of the study, bread prepared in an environment with optimised humidity control showed 22% less shrinkage in volume after baking and cooling.

Elfnor's (2015) study focused on the importance of monitoring and controlling temperature and humidity during baking, using microcontrollers, which enable a significant reduction in temperature variations and improve homogeneity. The research demonstrated that, by applying PID algorithms to dynamically adjust the thermal profile, the average temperature variations were reduced by up to 35%, resulting in more uniform baking.

According to Alam (2020), the automatic bread maker has significant advantages, such as increased efficiency, convenience, and safety, and is particularly suitable for busy restaurants where time is a factor. The addition of a “handwheel” for portability and a safety box increases convenience and safety, and the design optimisation using SolidWorks 2014 saves material and space consumption. In addition, customer feedback through quality function deployment (QFD) ensures that the machine meets the user’s requirements. The identified limitations include potential maintenance issues, dependence on a continuous power supply, and restricted ergonomic flexibility that limits functional adaptability. These limitations aside, the machine is a useful development in automated bread-making technology.

Analysis by Slices of Blue Sky (2025) highlights the role of dynamic temperature control in reducing the difference between the core and the surface. The results show that by constantly monitoring the core temperature and precisely controlling the heaters, the difference in the degree of baking between the core and the surface is reduced by 24%. Additional analysis in the study confirms that by optimising the temperature in the range of 180–200°C, the moisture loss in the final product is reduced by 12%, which contributes to improving the softness of the crumb and delaying the staling process. The analysis shows that the use of humidity sensors in a closed baking environment can reduce the difference in the moisture level between the outer crust and the bread core from 8% to 3%, which leads to improved texture and homogeneity.

Zlatev (2021) systematises methods for assessing bread quality based on spectral analysis and automated measurement techniques. Studies using spectral analysis confirm that the variation in the texture of bread produced in industrial conditions is up to 3%, while in automatic bakeries it reaches 18%. The data from the analyses show that industrial production methods provide an average of 15% higher elasticity of bread and a 12% longer shelf life, compared to products produced by an automatic machine. Spectral analysis shows that industrially produced products retain an average moisture of 38% after 72 hours of storage, while in bread from automatic bakeries this indicator decreases to 28%, which leads to its faster hardening. Additionally, the analysis of crumb porosity found that industrial processes achieve air chamber uniformity in the range of 0.5-1.2 mm, while in automatic bread machines this range is significantly wider (0.4-2.5 mm), resulting in uneven bread crumb texture. These differences highlight the need for further developments in the control of temperature parameters in automatic bread machines, including the integration of advanced algorithms for adaptive humidity and temperature control, to approach the results achieved by industrial technical means.

According to Lee, Kim, & Kim (2023), the use of AI in bread making is beneficial, offering enhanced quality control, precise monitoring, and process phase optimisation, resulting in uniform loaf volume. The Baking Process Prediction Model (BPPM) is effective in predicting changes in the environment in real time. The disadvantages are increased levels of baking losses, increased baking time, and dependence on the accuracy of the temperature sensor. The constant training of the model and large data sets are an obstacle to the wider application of this development. Despite these limitations, AI-based bread baking technology has the potential to improve the efficiency and consistency of bread making.

The reviewed literature highlights the need to devise novel methodologies for improving the operational parameters of automatic bread-making machines. By improving temperature control and implementing more precise algorithms for regulating humidity and baking time, good quality characteristics of the final product can be achieved. The development of hybrid baking systems that combine the advantages of industrial technologies with the convenience of automatic bread makers represents an opportunity to improve the quality and safety of the prepared bread.

The core objectives of the current study include: (1) the development and investigation of an IoT-based automatic bread maker with web monitoring capabilities using Arduino and ESP8266, (2) the implementation of PID-based temperature control, and (3) the design of an effective human–machine interface (HMI) operable via both touchscreen and web browser.

3. Materials, Methods, and Tools

The section discusses the methods used for bread making, including the selection of appropriate raw materials and the improvement of technological processes. The selection of hardware devices, such as sensors, electric motors, and controllers, which provide precise control of the technological processes in the bread machine, is described. The used software tools are also presented, along with the algorithms that provide control and monitoring of various parameters such as temperature, switching on and off the electric motor, and fermentation time, in order to achieve maximum quality and efficiency in bread making.

3.1. Methods and Materials for Bread Production

The bread-making process in the automatic machine followed the standardised methodology outlined in AS02/2011, the Bulgarian Approved Standard for "White Bread" (accessed on 21 February 2025). Based on this methodology, the formulation was adapted, the temperatures of the fermentation processes and the bread baking were determined.

The raw materials are: flour, wheat, white, Sofia Mel type 500 (GoodMills Bulgaria Ltd., Sofia, Bulgaria); drinking water, according to Bulgarian Regulation No. 9/2001 on the quality of water intended for drinking and domestic purposes of the Ministry of Health, Ministry of Regional Development and Public Works, and Ministry of Environment and Water, (published, Bulgarian State Gazette, issue 30, 2001); Baker's yeast (Saccharomyces cerevisiae), bread yeast, vital dry Picantina instant yeast for bread and fine pastries (Kendi Ltd., Bankya, Bulgaria); iodised cooking salt (Khimsnab-Orbel Ltd., Lom, Bulgaria), according to the Bulgarian Regulation on the requirements for the composition and characteristics of salt for food purposes (adopted by Bulgarian Council of Ministers Decree No. 23 of 2001; promulgated, State Gazette, issue 11 of February 6, 2001); pigweed (Amaranthus spp.) and purslane (Portulaca oleracea), crushed whole stalk (Bulgarian Bio Product Ltd., Simitli, Bulgaria), distributed in the commercial network.

Based on preliminary formulation trials with 0%, 5%, 10%, and 15% inclusion levels of pigweed and purslane in bread, and using the methodology described by Kolev, Taneva, & Zlatev (2023), the optimal inclusion levels were established as 3.49% for pigweed and 7.13% for purslane.

3.2. Selection of Hardware Devices

For communication and control of an automatic bread machine, the following hardware components have been selected: IoT module NodeMCU ESP 8266; single-board microcomputer Mega 2560; programmable display; an automatic bread machine model MD-18636 (Medion, Essen, Germany) was selected, with a total electrical power, according to the manufacturer's data of 650 W and a maximum mass of bread of 1 kg. The full descriptions of technical means used in this study are presented in Appendix A.

The bread making machine was selected because it is repairable and allows modifications to its control. Also, the temperature of the heater is regulated by a two-position (relay) control, in which significant deviations (up to 20%) from the desired set temperature are observed.

The housing in which the developed control system is placed was made on an Ender-3 Neo 3D printer (Creality 3D Technology Co., Ltd., Shenzhen, China). The following software products were used: AUTODESK TinkerCAD online application (Autodesk Inc., San Francisco, CA, USA) and UltiMaker Cura ver. 5.3.1 (Ultimaker B.V., Utrecht, The Netherlands).

3.3. Software Tools and Description of the Algorithms

The software for the MEGA 2560 and NodeMCU ESP8266 single-board microcomputers was developed using Arduino IDE, ver. 2.3.4 (Arduino LLC, Boston, MA, USA).

The graphical interface of the display was developed in the Nextion Editor v.1.65.1 program (ITEAD Intelligent Systems Co. Ltd., Shenzhen, PR China).

A PID algorithm was developed according to the methodology proposed by Hägglund & Guzman (2024). The PID algorithm was implemented in the following steps: the control error, proportional, integral, and differential parts of the regulator were calculated. Functions for limiting the action of the integral and differential parts were calculated. The control effect was determined.

Determination of the control error e(t),

$$e(t) = Setpoint - Input(t) \tag{1}$$

where Setpoint is the set temperature; Input(t) is the measured temperature value from the sensor at a given time.

Determining the proportional part of the controller P(t),

$$P(t) = K_p \times e(t) \tag{2}$$

where Kp is the coefficient of proportionality.

Determined by the integral part of the regulator I(t) with Anti-Windup,

$$I(t) = I(t-1) + K_i \times e(t) \tag{3}$$

with restrictions:

$$I(t) = \min(\max(I(t), outMin), outMax) \tag{4}$$

where Ki is the integration coefficient; outMin and outMax the minimum and maximum value that the output of the single-board computer can perform.

Determination of the differential part of the regulator D(t) with Low-Pass Filtering.

The differential of the input DInput(t) is calculated.

$$DInput(t) = \mathrm{Input(t)} - \mathrm{Input(t-1)} \tag{5}$$

The filtered differential part of the controller input DInputfiltered(t) has the form:

$$DInput_{filtered}(t) = \alpha \times DInput(t) + (1-\alpha)DInput_{previous} \tag{6}$$

where α is the filter coefficient; $DInput_{previous}$ is the previous value of the differential part of the regulator *DInput*.

The differential part of the regulator D(t) is determined by:

$$D(t) = -K_d \times DInput_{filtered}(t) \tag{7}$$

where Kd is the differentiation coefficient.

The control output *Output(t)* is determined by:

$$Output(t) = \mathrm{P(t) + I(t) + D(t)} \tag{8}$$

with restrictions:

$$Output(t) = \min(\max(\mathrm{Output(t), outMin}), \mathrm{outMax}) \tag{9}$$

where *outMin* and *outMax* the minimum and maximum value that the output of the single-board computer can perform.

A *Soft Stop* has been implemented, which is executed under the following condition:

$$if\ Input(t) \geq Setpoint, Output(t) = 0 \tag{10}$$

The discretisation and execution time of the PID calculations are performed every Ts, ms, using discrete time intervals (approximately 1 or 2 s).

The settings of the PID controller coefficients are determined according to the methodology proposed by Eriksson (2008). This methodology is presented in Figure 3, through an L-a approximation of the transient characteristic of the object.

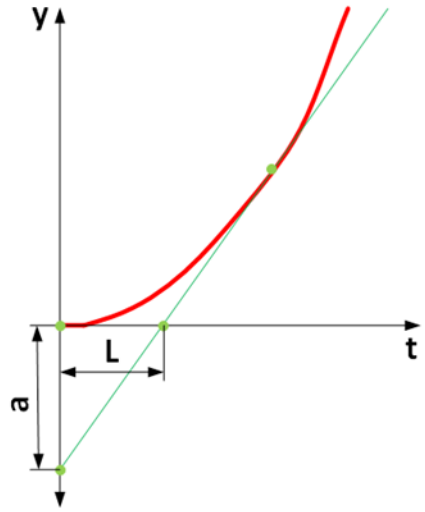

Figure 3. Method for determination of PID coefficients by step response of the plant

According to the specified methodology, the parameters of the PID controller are calculated as:

$$K_p = \frac{1.2}{a};\ T_i = 2L;\ K_i = \frac{K_p}{T_i};\ K_d = \frac{L}{2};\ \alpha = \frac{T_s}{\frac{L}{a} + T_s} \tag{11}$$

where:
- *L* and *a* represent the time and temperature values derived from the *L–a* approximation;
-*Kp* is the proportional gain;
- *Ti* is the integral time;
- *Ki* is the integral gain;
- *Kd* is the derivative gain;
- α is the filter coefficient for the derivative term;
- *Ts* is the sampling interval for each temperature measurement.

After uploading the parameters to the physical controller, an additional fine-tuning was performed using the procedure outlined in 2019, in the "PID Tuning" section ("Build a PID Controller", 2019). The NodeMCU ESP8266 module communicated with a wireless router (model WF2409E, Netis Systems Co., Ltd., Shenzhen, China), and the communication stability was evaluated by varying the distance between the router and the single-board computer. Table 2 presents the technical specifications of the network-enabled hardware components. These characteristics were taken into account and used in the calculations.

Table 2. Characteristics of network devices

Device Characteristic	WF2409E	NodeMCU ESP8266
WiFi Transmission Power, dBm	20	19,5
WiFi Reception Power, dBm	not provided	-91
WiFi standard	IEEE 802.11n/b/g, 2.4 GHz	IEEE 802.11g, 2.4 GHz
Antenna gain, dBi	3 antennas x 5	2
Frequency, GHz	2.4-2.4835	2.4-2.484

The communication parameters between the single-board computer and the router were determined according to the methodology presented by Todorov, Stoykova, & Zlatev (2023).

The NodeMCU ESP8266 test programs for operation in a Wi-Fi network, provided by Shamshiri (2019), were used.

The signal loss SL was determined by:

$$SL = 10.n.\log_{10} d\ , dB \tag{12}$$

where *d* is the distance between the router and the single-board computer, m; *n* is the signal loss rate that characterises the propagation medium.

The received signal strength indicator *RSSI* is determined by:

$$RSSI = P_t - SL, dBm \tag{13}$$

where P_t is the power of the transmitted signal, W; *SL* is the signal loss between the transmitter and the receiver, dBm.

The signal-to-noise ratio (*SNR*) is defined by:

$$SNR = SS - NL, dB \tag{14}$$

where *SS* is Signal Strength, dBm; *NL* is Noise Level, dBm.

Network throughout (*NTO*) is calculated by:

$$NTO = B \times \log_2(1 + SNR), Mbs \tag{15}$$

where *B* is the bandwidth (for the network devices used it is 30–40 MHz); *SNR* is the signal-to-noise ratio.

3.4. Technological Characteristics of Bread

The heat losses of bread TL,% are calculated using the following formula:

$$TL = \frac{W_d - W_b}{W_d} \times 100, \% \tag{16}$$

where W_d is the mass of the dough; W_b is the mass of the bread.

The organoleptic evaluation of the bread was carried out in accordance with the method of organoleptic analysis of foods, described in BNS EN ISO 13299:2016 (Sensory analysis. Methodology. General guidance for establishing a sensory profile), according to this standard, the bread is evaluated by appearance, volume, colour of the crust and crumb, chewiness, porosity, taste, and aroma. Nine trained assessors, including academic staff and students from the Department of Food Technologies, Faculty of Food Technology – Yambol, participated in the sensory analysis. They have prior training in performing this type of analysis of food products.

The requirements of the code of ethics of the university community (https://trakia-uni.bg/wp-content/uploads/2024/04/EtichenKodeks.pdf, accessed on 28 February 2025) were met. The informed consent was obtained from all participants in the consumer evaluation of the bread. A 5-point Likert scale was used to evaluate the bread (1-completely does not correspond to the indicator; 5-completely corresponds to the indicator) (Guerra, Gidel, & Vezzetti, 2016).

The colour digital images of the bread were obtained with a video sensor of a mobile phone model E32S (Motorola, Inc., Schaumburg, Illinois, USA). The characteristics of the video sensor are: focal length of 26 mm, maximum resolution of 16 MP, pixel size of 1 μm, and aperture size of F2.2 (OmniVision Technologies Inc., Santa Clara, California, USA).

The homogeneous illumination of the captured scene was provided by a light source, which consists of a dome-shaped part, in which white LEDs with cold white light (6400K) were installed, model VT-3528-60 (V-TAC Europe Ltd., Plovdiv, Bulgaria).

The colour adjustment was made with a colour scale with 24 colour fields Danes Picta Colour chart BST11 (Danes-Picta, Praha, Czech Republic).

Colour digital images were obtained in the RGB colour model and converted to the Lab colour model, according to CIE Lab 1976. Functions for converting colour components were used at observer 2° and illuminance D65.

The colour difference *ΔE* for bread was calculated by the following formula:

$$\Delta E = \sqrt{(L_c - L_a)^2 + (a_c - a_a)^2 + (b_c - b_a)^2} \tag{17}$$

Lc, ac, bc – lightness and chromaticity components of the control sample
La, aa, ba – corresponding components of the sample containing the additive

4. Results and Discussion

This section presents the main stages of the development of an improved automatic bread machine. The hardware architecture and integration of the components are described, as well as the definition of recipes and technological operations with appropriate times for bread preparation. The configuration of the PID controller and the processed software-based data are addressed, both contributing to precise control over the technological workflow. The developed HMI and web interfaces are also presented, which allow easy interaction with the user, both locally and remotely. The results of the experimental evaluation of the machine's efficiency are presented.

4.1. System Hardware Architecture and Implementation

Figure 4 shows the control system of the automatic bread machine. The entire circuit is powered by a 5V DC, 2A source. The temperature measurement in the bakery is implemented with a MAX6675 module and a K-type thermocouple connected to it. The module is connected to the MEGA 2560 single-board microcomputer via an SPI interface, implemented in software via the digital D4, D5, and D6 pins. The sound signaling is provided by a "Buzzer" module connected to digital output D7. The heater is controlled via digital output D9, and the electric motor via digital output D8. Both devices are controlled via SSR, with 10 kΩ resistors connected in parallel to their inputs. The communication with the HMI display is established through a serial channel using pins Tx2 and Rx2. Furthermore, the communication with the NodeMCU ESP8266 single-board computer, providing a web interface, is via serial pins Tx3 and Rx3.

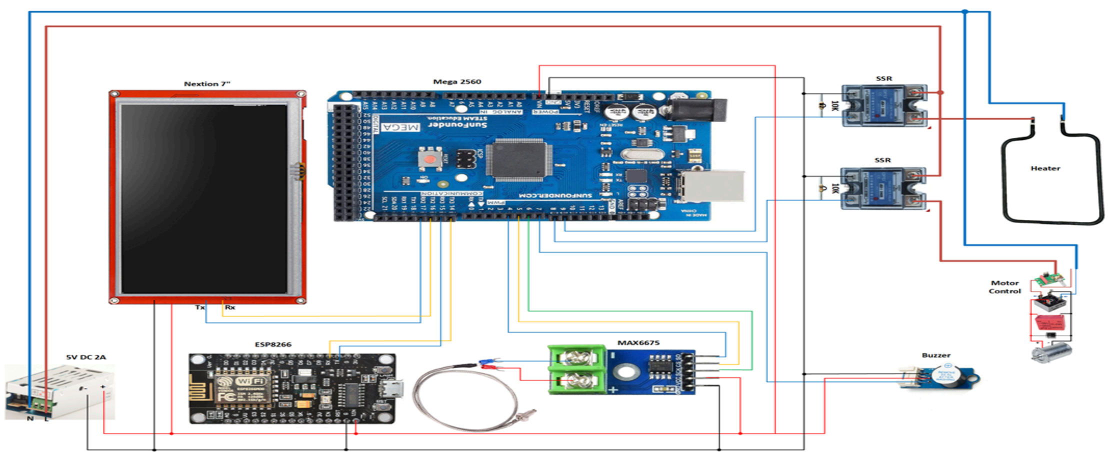

Figure 4. Control system for automatic bread machine – electrical schematic

Figure 5 shows a basic rectifier circuit for controlling a DC motor. The circuit is powered by 220V AC, 50 Hz. The power regulator is connected to the input of the rectifier. In order to achieve complete rectification of the voltage, a capacitor is connected to the output of the rectifier. Since the motor is an inductive load, a flyback diode is connected to the output to protect the circuit.

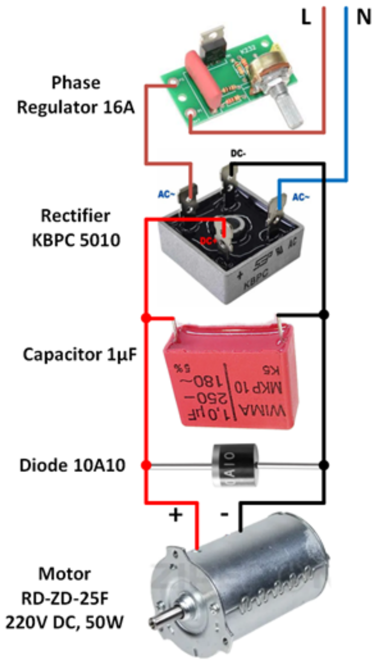

Figure 5. Rectifying schematic for DC motor control

Figure 6 shows the automatic bread machine before and after the introduction of the improved control system. The machine with the original control has a backlit display. The menus are controlled by physical buttons. The control is achieved using a relay-based regulation principle. In the present development, a completely new control system has been created, with a graphical HMI, implemented with a touch-screen. The software-implemented PID regulator improves the temperature regulation process. Three programs have been implemented for basic, sourdough bread and purslane bread. A DEMO program is provided to demonstrate the capabilities of the machine.

Figure 6. Automatic bread making machine. (a) before modification [source: manufacturer]; (b) after modification [source: own picture]

4.2. Recipes and Times for Performing Technological Operations in an Automatic Bread Machine

Based on preliminary baking under conditions similar to those for making bread in an automatic machine, according to the methodology presented in AS02/2011, the composition and times for performing the technological operations for making bread have been determined.

Table 3 shows the quantities of raw materials required for making different types of bread in an automatic machine. The recipes are based on 500 g of wheat flour. Three variants are presented: basic bread, bread with pigweed, and bread with purslane. The main raw materials are white wheat flour, drinking water, dry baker's yeast, and table salt. The primary differentiating factor among the breads is the inclusion level of functional additives: absent in the Basic formulation, 17 grams in Pigweed bread, and 36 grams in Purslane bread. These quantities of additives affect the composition of the dough but retain the same requirements for hydration and fermentation.

Table 3. Quantity of raw materials for making bread

Type of bread	**Basic**	**Pigweed**	**Purslane**
Flour, g	500	483	464
Drinking water, ml	270	270	270
Baker's dry yeast, g	7	7	7
Table salt, g	8	8	8
Additive, g	0	17	36

Table 4 lists the times, temperatures, and motor status required to make each type of bread in an automatic machine. The process is divided into different stages, which include mixing, kneading, resting, proofing, rounding, final fermentation, baking, and keeping warm. Most of the stages take place at the same temperature of 37°C, while the baking stage is at 162°C. The main difference between the breads is in the time for proofing and final fermentation. Sourdough bread has a slightly longer time for proofing (30 minutes compared to 25 minutes for the other two types of bread) and final fermentation (40 minutes compared to 35 minutes for the other two types of bread), which is necessary due to the influence of individual elements of the sourdough composition on the dough structure. Despite these differences, the total processing time is relatively close, with 157.15 minutes for the pigweed bread and 147.15 minutes each for the basic and purslane breads.

Table 4. Times and temperatures for bread preparation in automatic bread machine

Type of bread			**Basic**	**Pigweed**	**Purslane**
Procedure	Temperature, ºC	Motor	time, minutes		
Start	-	-	0.05	0.05	0.05
Mix	37	On	5	5	5
Knead	37	On	10	10	10
Rest	37	Off	5	5	5
Knead	37	On	20	20	20
Rise	37	Off	25	30	25
Roll	37	On	0.05	0.05	0.05
Proof	37	Off	35	40	35
Bake	162	Off	47	47	47
End	-	-	0.05	0.05	0.05
Keep Warm	35	Off	60	60	60
Total time, minutes			147.15	157.15	147.15

4.3. PID Tuning, Software, and Data Processing

Figure 7 shows the results of the L-a approximation of the temperature curve of the bread machine process. The process has a small delay. A clearly expressed inflection point is observed. Data L=62 s, a=32ºC were used to determine the parameters of the PID controller.

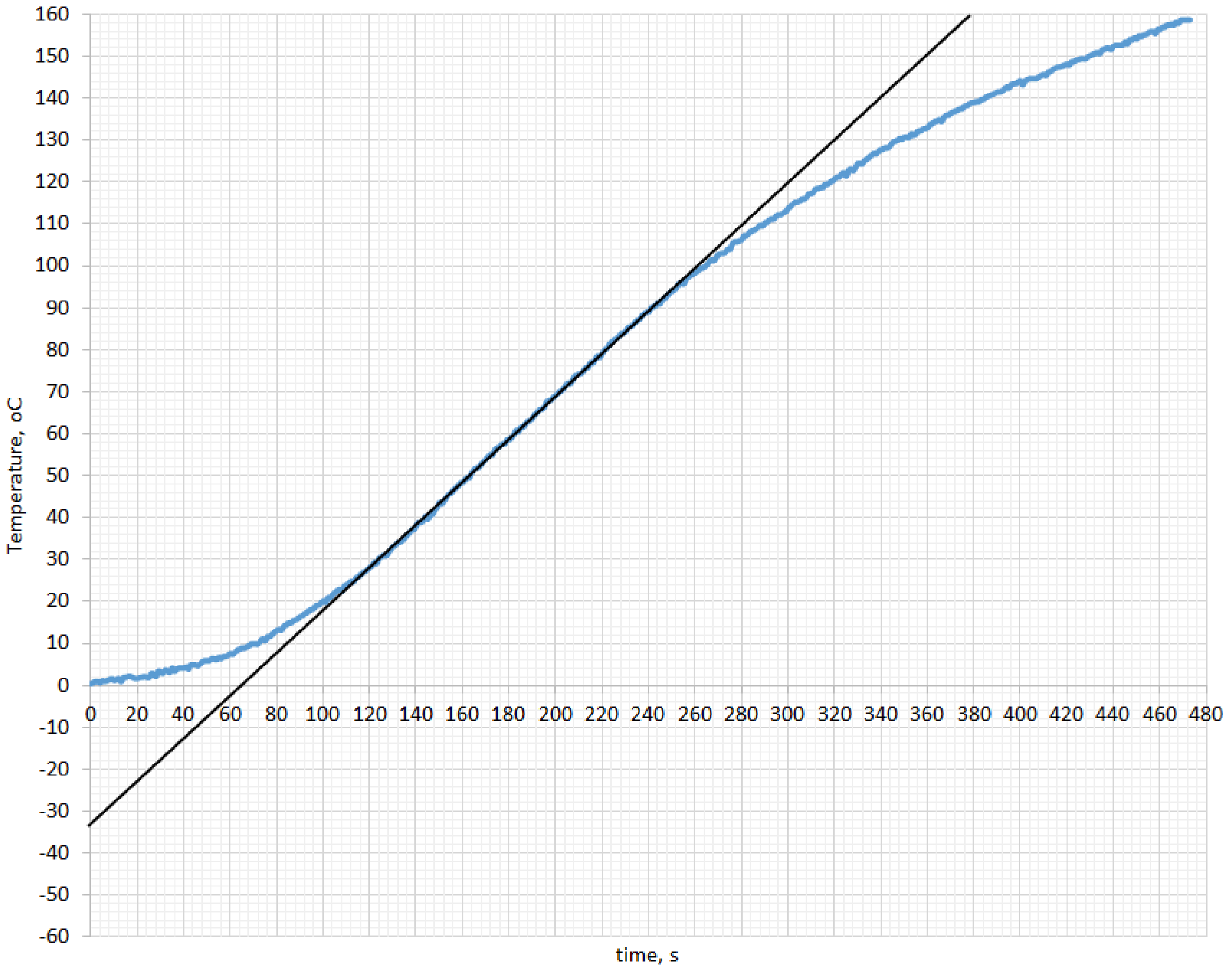

Figure 7. L-a approximation of temperature curve of the bread machine

Based on the mathematical dependencies presented in the previous sections, the settings of the PID controller parameters have been determined. Table 5 shows the calculated settings of the controller and those obtained after fine-tuning. Kp is increased 193 times, Ki is increased about 18 times, Kd is reduced 15 times, and α is reduced 4 times.

Table 5. PID settings

PID parameter	Calculated	Set
K_p	0.04	7
T_i	120	47
K_i	0.0083	0.15
K_d	30	2
α	0.35	0.1

An algorithm and program for controlling an automatic bread machine have been created. A complete listing of the program is presented in Appendix A. It consists of four main functions. The first is related to the initialisation of the devices connected to the main single-board microcomputer MEGA 2560. The second function implements the PID algorithm. The third function implements the bread-making program. The fourth function serves to process the commands received from the HMI display.

In the first part, the measuring, control, communication, and visualisation devices and mechanisms are initialised.

In table 6, the algorithm of the subroutine implementing the PID law is presented. The PID algorithm regulates the temperature by continuous reading from the MAX6675 module. The proportional, integral, and differential parts are calculated with an anti-windup mechanism applied to the integral part and low-pass filtering for the differential part. The control effect is sent to the heating element via PWM, ensuring stable temperature regulation.

Table 6. PID algorithm function

Stage	Description
Read temperature	Read temperature from the MAX6675 module.
Calculate error	Calculate the error between the setpoint and actual temperature.
Compute PID output	Compute the PID output using proportional, integral, and derivative terms with filtering.
Anti-winup	Implement an anti-windup mechanism for the integral term.
Filter of K_d term	Ensure smooth derivative term calculation using a low-pass filter.
Control output	Apply output constraints and send the result to control the heater (PWM on pin 9).

Table 7 presents the bread-making function. The bread-making process follows sequential steps, starting with a start signal and an update of the HMI display. The mixing and kneading phases involve controlling the motor, while maintaining the temperature. The resting and maturing phases enable the dough to ferment with controlled heat. During baking, the temperature is raised to 162°C, followed by an end signal and a one-hour-keep-warm function at 35°C.

Table 7. Bread making function

Stage	Description
Start Signal	Activate sound for 3 seconds.
Mixing	Run motor intermittently and regulate temperature (Setpoint at 37 °C).
Kneading Start	Run motor continuously, regulate temperature (37 °C).
Resting	Keep dough at 37 °C without motor action.
Kneading Continue	Resume kneading while regulating temperature (37°C).
Rising	Maintain dough at 37°C for fermentation.
Rolling	Briefly rotate motor to shape the dough.
Proofing	Continue fermentation at 37 °C.
Baking	Heat oven to 162 °C and maintain temperature.
End Signal	Activate sound for 3 seconds.
Keep Warm	Maintain bread at 35 °C for an hour.

Table 8 presents the function for processing the commands that the single-board microcomputer receives from the HMI display. The various technological processes for preparing bread are triggered by specific commands. The control system is capable of executing production sequences for standard bread, yeast-fermented bread, and purslane-enriched bread. Each stage of the technological process follows a predefined sequence of temperature control and motor operation for kneading, resting, fermentation, and baking. A demonstration (DEMO) mode has also been created, in which the elements of the technological process are presented by rotating the electric motor and turning on the heater for a few seconds.

Table 8. Command processing function

Command	Description	Defined time Stages (Mix, Knead, Rest, etc.)
basic	Standard bread process.	5, 10, 5, 20, 25, 35, 47 minutes
pigweed	Adjusted times for pigweed bread.	5, 10, 5, 20, 30, 40, 47 minutes
purslane	Different kneading and resting durations.	5, 0.05, 5, 20, 25, 35, 47 minutes
DEMO	Shortened demo mode for testing.	0.06 min per stage.

4.4. Algorithm and Program for a Web Interface

An algorithm and a program for a web interface that visualises the operation of the bread machine have been created. A complete listing of the program implemented for the NodeMCU ESP8266 is presented in Appendix B. Table 9 presents the initial initialisation and setup stage. The ESP8266 module connects to a specified WiFi network using the SSID and password credentials. A serial communication is initialised for debugging, and the ESP8266WebServer is created to handle the HTTP requests. Once connected, the system displays the assigned IP address and registers the primary endpoint for serving the web page. The server is then started, allowing clients to connect.

Table 9. Initialisation and Setup

Component	Description
WiFi Connection	Connects to the specified WiFi network using SSID and password.
Serial Communication	Initialises Serial at 115200 baud for debugging and monitoring.
Web Server	Creates an instance of ESP8266WebServer on port 80 to handle HTTP requests.
IP Address	Displays the assigned IP address after successful WiFi connection.
Server Setup	Registers the root endpoint and starts the web server to accept client connections.

Table 10 presents the stages of creating and processing a web page. A dynamic HTML page is generated, showing the current state of the bread-making process. The web page includes a list of predefined process stages, with the active stage marked in yellow. A JavaScript script refreshes the page every two seconds. When a client requests the page to load, the server responds with dynamically generated content.

Table 10. Web Page Handling

Component	Description
HTML Page	Generates a dynamic webpage displaying the bread-making stages.
Highlighted Word	Updates the active bread-making stage by applying a yellow background colour.
JavaScript Refresh	Uses JavaScript to reload the page every 2 seconds for real-time updates.
List of Stages	Displays the predefined bread-making stages in an unordered list.
Server Response	Sends the dynamically generated HTML content to connected clients.

Table 11 presents the serial communication and command processing stages. The system continuously listens for serial input, which is expected to be a command describing one of the predefined stages of the technological process. Upon receiving a valid string, the program updates the variable “highlightedWord”, ensuring that the corresponding stage is visually highlighted on the web page. This mechanism allows for seamless synchronisation between the bread-making process and the web-based system for its monitoring.

Table 11. Serial Communication and Word Processing

Component	Description
Serial Input	Reads a word from the Serial monitor representing the current process stage.
Trimming	Trims any whitespace from the received input to ensure accurate matching.
Word Matching	Compares the received word with the predefined bread-making stages.
Highlight Update	Updates the “highlightedWord” variable, if a match is found.
Debugging Output	Prints the received word to the Serial monitor for verification.

4.5. Developed HMI and Web Interface

Figure 8 shows screens from the HMI bread machine. After connecting the machine to the power supply, a "main" menu is displayed, from which the remaining screens are accessible. The three buttons for main, bread with yeast, and bread with purslane, activate the screens for preparing the corresponding type of bread. The three screens for preparing a specific type of bread are relatively identical. They have a button for returning to the main menu, and below it, the stages of the machine's operation are visualised if the "Start" button is pressed. The "Information" button from the main menu opens a screen on which the recipes of the three types of bread are displayed. Also, from this screen, the "DEMO program" button opens a screen for the demonstration program. The "START Demo Program" button runs a program that demonstrates the individual stages of the machine's operation for a few seconds.

Figure 8. Screens of HMI. (a) Main screen; (b) Basic bread screen; (c) Pigweed bread screen; (d) Purslane bread screen; (e) Information screen; (f) Demo program

Figure 9 shows screens from the web interface of the bread machine. The screens are from a personal computer and a mobile phone. At the top is the title, indicating that the elements of the technological process for preparing bread are being monitored. When executing the control program, MEGA 2560 sends a string via a serial channel to the NodeMCU ESP8266, which corresponds to the given technological operation. After conversion, the text with the name of the operation is coloured yellow for visual feedback to the user. The procedure is repeated until the end of the execution of the bread preparation program.

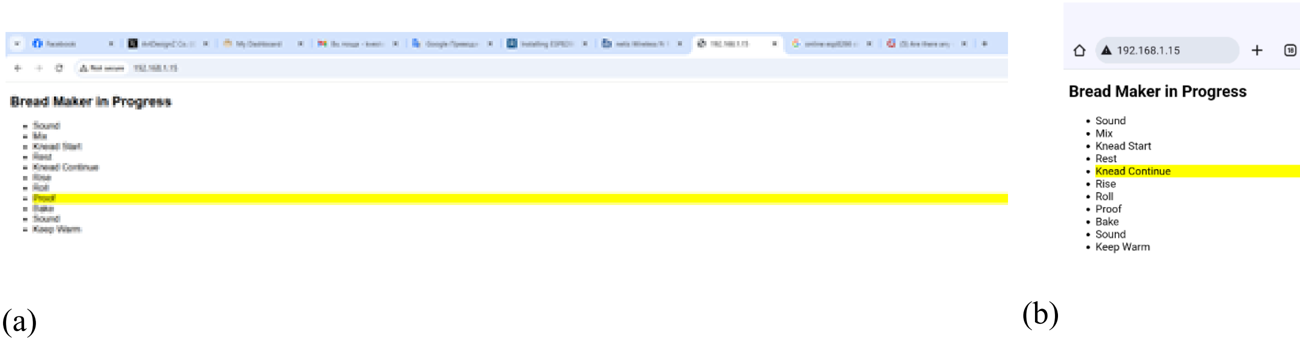

Figure 9. Web interface screens
(a) Web browser on personal computer; (b) Web browser on mobile phone

4.6. Experimental Evaluation and Performance Analysis

Table 12 presents measurement data related to signal strength estimation, including distance (d), real, calculated, and simulated RSSI (received signal strength indicator), signal loss (SL), signal-to-noise ratio (SNR), and network throughput (NTO). The distance values range from 5±2 m to 16±3 m, with real RSSI values ranging between -58±5 dBm and -74±8 dBm. The calculated RSSI values show a wider variation, from -51±5 dBm to -35±4 dBm, while the simulated RSSI remains more constant, between -71±1 dBm and -59±6 dBm. The signal loss (SL) values range from 42±4 dB to 69±5 dB, while the SNR ranges from 26±5 dB to 44±8 dB. The network throughput (NTO) remains relatively stable, between 42±3 Mbps and 50±3 Mbps, indicating minimal impact of RSSI fluctuations on throughput. The measurement methodology involves the use of specialised signal measurement tools and simulation of RSSI values. Analysis of the results shows that the real and simulated RSSI values have some differences, which may be due to specific conditions and sources of error during the measurement. Despite these variations, the network throughput remains relatively stable, indicating that the impact of RSSI and NTO fluctuations is minimal.

Table 12. Measured and calculated data for WiFi signal, according to the distance between NodeMCU ESP8266 and Wi-Fi router

d, m	**16±3**	**15±3**	**10±2**	**8±4**	**5±2**
real RSSI, dBm	-72±5	-74±8	-68±8	-70±6	-58±5
calculated RSSI, dBm	-48±6	-51±5	-35±4	-28±16	-24±4
simulated RSSI, dBm	-67±4	-71±1	-66±4	-69±2	-59±6
SL, dB	66±6	69±5	57±4	45±16	42±4
SNR, dB	42±5	44±8	40±8	40±6	26±5
NTO, Mbps	48±2	49±3	47±4	50±3	42±3

Figure 10 shows the working process of the automatic bread machine. At the beginning, the raw materials are mixed, with the electric motor operating cyclically for 300 seconds. This is followed by kneading, during which the motor operates continuously for 600 seconds. Then the dough rests for 300 seconds, during which it relaxes, and kneading continues for 1200 seconds with less load on the motor. During the following stages, the motor is switched off. To round the dough, the motor is switched on for 3 seconds and then switched off. During each stage, visual signals are displayed on the machine display to the user, informing them of the current status and progress in the execution of the bread-making program. The temperature regulation begins with an overshoot, with a peak of up to 50°C observed, which disappears in about 500 seconds. Then the regulator maintains relatively constant temperature values with maximum deviations of 2°C. This continues throughout all processes until the bread is baked. In the second task (baking), the temperature is maintained at 162°C, but with slightly larger deviations of up to 4°C.

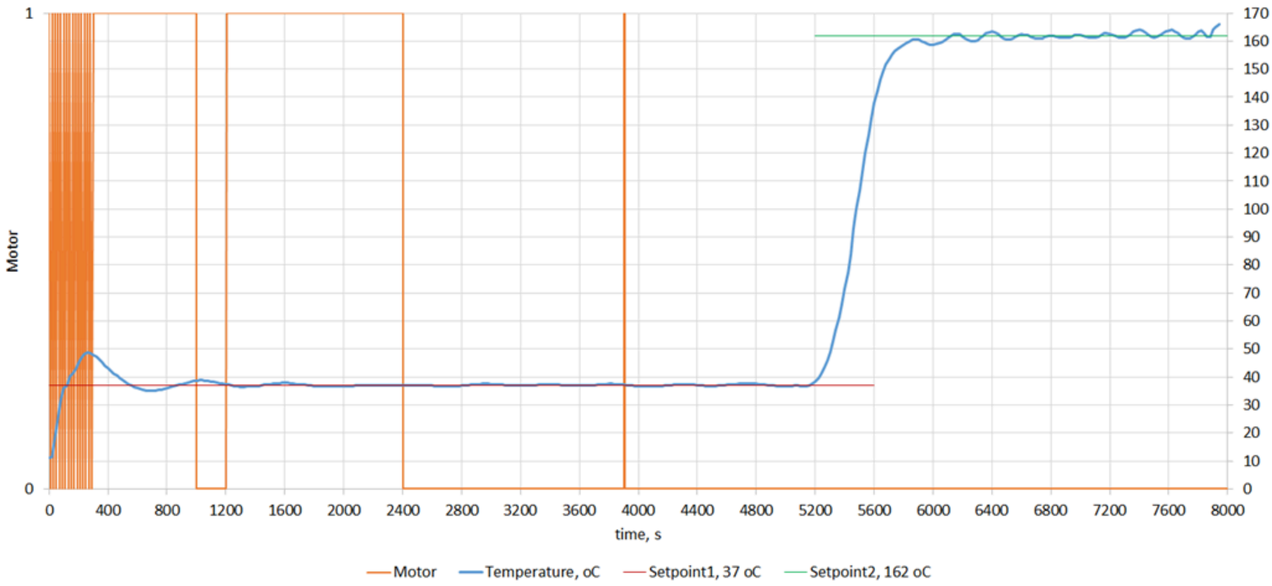

Figure 10. Temperature and motor control of the automatic bread making machine

Figure 11 shows the resulting bread, prepared in an automatic machine. The control sample, which does not contain additives, has a golden brown crust and a light, even crumb texture.

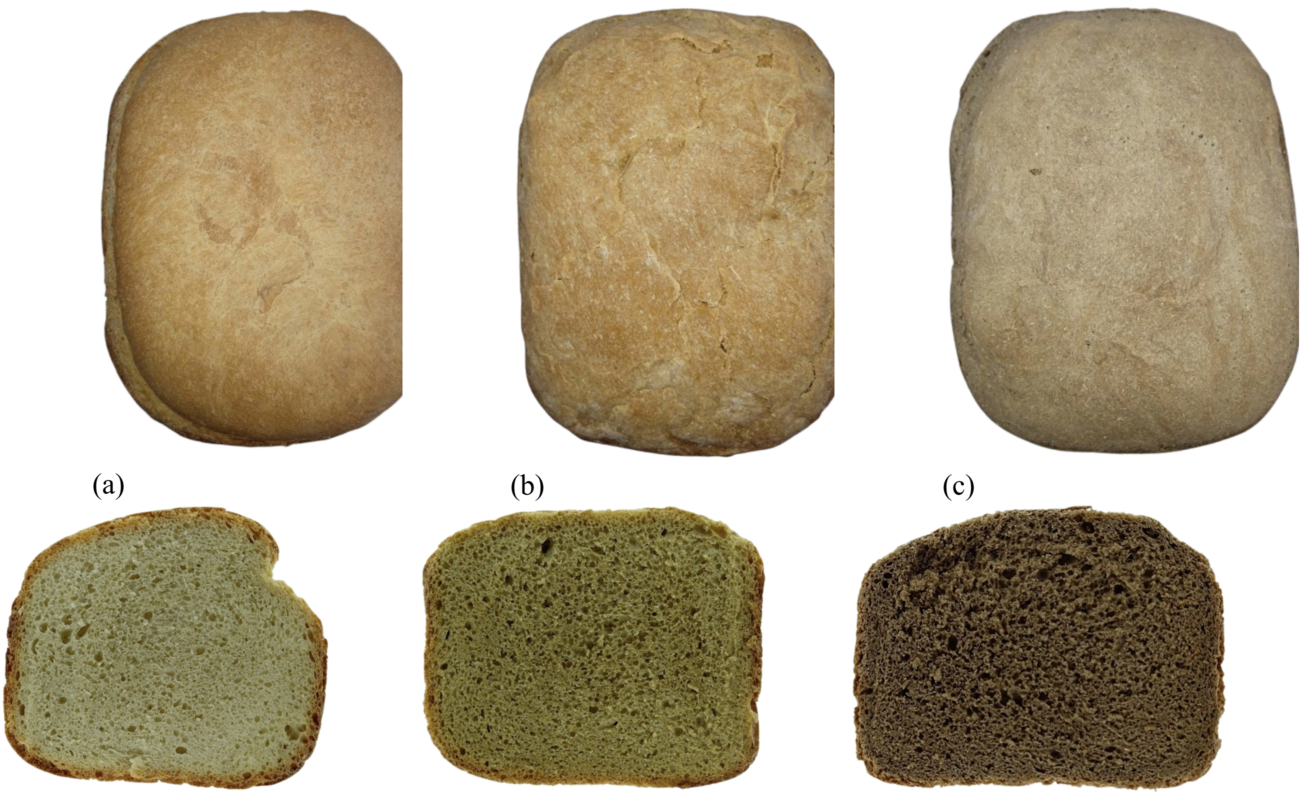

Figure 11. Crumb and crust of the obtained bread
(a) Basic bread; (b) Pigweed bread; (c) Purslane bread

The sample with 3.69% pigweed flour shows a darker crust colour compared to the control sample. The crumb core is more compact, displaying a slight greenish-yellow hue. Visually, this sample has a firmer crust and lower crumb porosity. The sample with 7.13% purslane flour has the darkest crust and a visibly darker and denser crumb structure, compared to the other two samples, which are significantly more compact and dark brown. The addition of pigweed and purslane leads to significant changes in the colour, texture, and flavour characteristics of the bread. The pigweed gives a darker colour and a denser consistency, while the purslane adds the darkest crust and the most compact centre. Vegetable additives significantly affect the visual and organoleptic properties of bread, with each type of additive imparting specific characteristics to the final product.

Table 13 shows data on heat losses when preparing different types of bread, in an automatic machine. In all cases, the losses are below 14%. The smallest losses are for purslane bread, and the largest, compared to the others, are for basic bread.

Table 13. Thermal losses of bread prepared in automatic bread machine

Parameter Type of bread	**Dough, g**	**Bread, g**	**TL, %**
Basic	785.25	689.04±3.03	12.25±0.39%
Pigweed	785.25	706.27±5.59	10.06±0.71%
Purslane	785.25	710.35±2.2	9.54±0.28%

Table 14 shows the results of the organoleptic analysis of the resulting bread. The results of the organoleptic analysis show that the addition of pigweed and purslane has a different impact on the quality of the product. The control sample has the highest scores in all characteristics, while the addition of pigweed leads to a slight decrease in the values of appearance, structure, and chewiness, but a significant decrease in taste (due to the residual bitter taste). Purslane leads to a significant decrease in appearance and structure, but has a smaller impact on aroma and chewiness. The overall score is also lower for both additives, compared to the control sample, with purslane having a stronger impact.

Table 14. Organoleptic evaluation of bread with the additions of pigweed and purslane

Type of bread, Characteristic	**Basic**	**Pigweed**	**Purslane**
Appearance	4.94±0.04	4.66±0.15	2.78±0.53
Structure	4.99±0.01	4.60±0.10	2.70±0.55
Chewness	4.88±0.05	4.60±0.08	4.19±0.21
Flavour	4.91±0.05	4.73±0.13	4.66±0.12
Taste	4.94±0.06	3.71±0.85	4.57±0.08
Overall assessment	4.91±0.09	4.43±0.20	3.77±0.18

Figure 12 shows the values of the Lab colour components for the crust, and the crumb of bread prepared in an automatic machine. For the crust of the bread, the data for basic is located in a certain range of the graph. The data for pigweed overlaps significantly with basic, but also has distinct points. The data for purslane is located in a different range, which does not overlap significantly with basic and pigweed. This makes them clearly distinguishable. For the crumb of the bread, the data for basic is located in a certain range of the graph. The data for pigweed partially overlaps with basic, but also has points that are outside this range. The data for purslane is located in a different range, which overlaps minimally with the other two groups, which makes them clearly distinguishable. The data for basic and pigweed show a significant overlap, while the data for purslane are clearly distinguishable from the others. This shows that the additions of pigweed and purslane have different effects on the colour components of the bread, which is evident from the graphs.

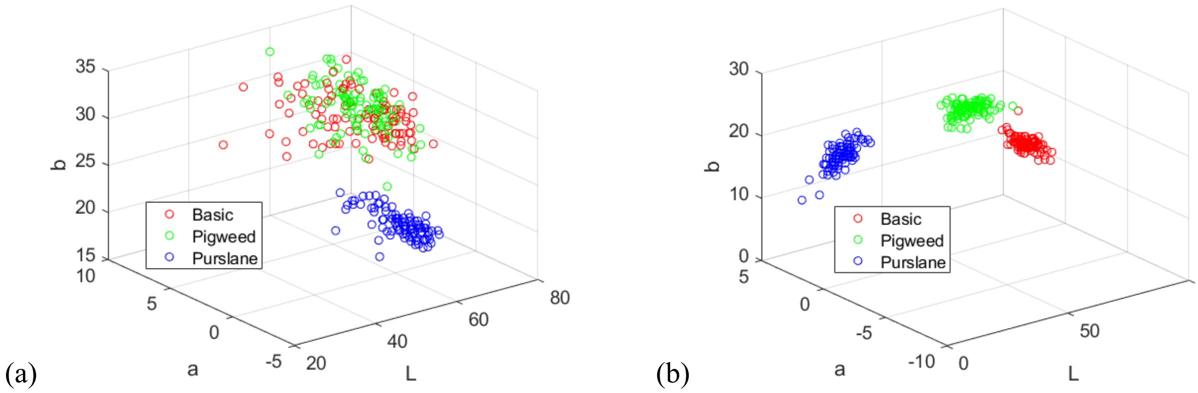

Figure 12. Lab colour components of bread: (a) crust; (b) crumb

Figure 13 shows the colour difference in ΔE for the crust and the crumb of a bread made in an automatic machine. Pigweed has a colour difference with the control sample (basic) of approximately 10 for the crumb and about 20 for the crust. These differences are significant and indicate that the addition of pigweed visibly affects the colour of bread. Purslane shows the largest colour difference with basic, with the crumb having a ΔE of about 15 and the crust close to 30. This indicates that the addition of purslane has a significant effect on the colour of bread. The figure illustrates that the addition of pigweed and purslane lead to significant colour differences compared to the basic bread, with purslane having clearly distinguishable colour differences, for both the crumb and the crust of the bread.

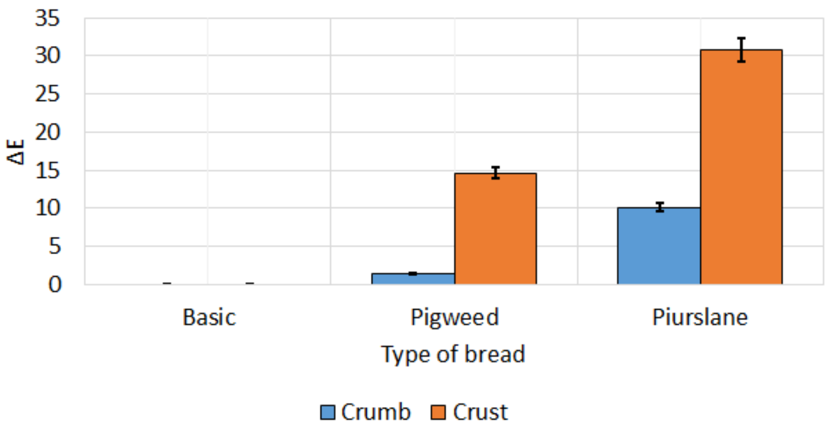

Figure 13. Colour difference for bread prepared in an automatic machine

5. Discussion

The developed IoT-based bread machine is in the field of home automation. The technology of smart automatic bread machines creates new potential for convenience, optimisation, and personalisation in everyday life. IoT-based technologies allow the device to be connected to other smart devices in the house, which makes the bread-making process more convenient and efficient. The local control of the device, physically connected to the home network and not requiring Internet, provides a faster and more secure response when controlling the bread-making process. In the event of a loss of Internet connection, the machine may be able to continue to function without interruption. The cloud control offers additional features, such as remote access from anywhere in the world with Internet access, updating the machine's software, and integration with other smart devices. The user's needs and desires for convenience and security must be balanced against local and cloud control. Also important is the ability to analyse data—the IoT device can track parameters such as temperature, humidity, and fermentation tim, and provide the user with recommendations on how to refine the bread recipe.

The results obtained improve the existing solutions for commercial automatic bread machines. The relay (two-position) control is replaced by an accurate PID. Temperature deviations from the set point of 15°C are reduced to about 4°C. In addition, the buttons and the user interface with a small screen are replaced by a sufficiently large HMI, through which the bread machine is controlled graphically and textually. A web interface is provided.

The research of Hamlet, Jayaratne, & Morrison (2006) is supplemented, according to which, with prolonged baking above 220°C, the acrylamide concentration in the bread crust increases by 78%, which significantly exceeds the safe limits established in the industrial production. In the present work, the baking temperature is set to 162°C. Using a precise PID controller eliminates the need to complicate the bread machine control software, for example, with adaptive control, as recommended by Ioannidis (2015).

The results of Elfnor (2015) are supplemented, according to which the use of a PID algorithm significantly reduces deviations from the set temperature in the bakery. This has also been proven for bread with the addition of rye flour and purslane. The research of Zlatev (2021) is further improved. The author proposes a control system for an automatic bread machine with only one program for basic white bread. In this work, programs for making bread with less commonly used additives, but with healthy and nutritional potential, are proposed (Mesta-Corral et al., 2024; Sadeghzadeh-Benam et al., 2022).

In future research, it is necessary to verify the possibility of applying AI and predictive models for the main technological variables related to the preparation of bread in an automatic machine. In this way, the recommendations of Lee, Kim, & Kim (2023) will be implemented and supplemented.

The IoT and AI enabled machine can be used to provide personalised recommendations to the user, based on the collected data. For example, the machine can suggest changes to the bread recipe or the duration of a given process, achieving a sufficiently good final product. Based on the collected data, resources can be managed, optimising energy consumption and the efficient use of available raw materials, reducing waste.

6. Conclusion and Future Work

6.1. Conclusion

This study proposed an IoT-based application for the automatic preparation of bread, achieved through the effective and reliable automation of associated processes. Tasks covering the development and research of an IoT-based automatic bread machine with web monitoring, implemented with Arduino and ESP8266, have been carried out. PID temperature control has been implemented, which improves the fermentation processes and bread baking.

Integrating AI assistants like Alexa+ and Google Home with automatic bread machines requires precise control and detailed study of these devices. Current machine models lack the necessary capabilities, making system refinement essential. Enhancing communication, optimising recipes, and adapting processes to raw materials will improve nutritional value, safety, and consumer appeal.

An intuitive interface for control via a touch screen and a web browser has been designed, replacing the traditional buttons and the small displays.

The structure of the control system of an automatic bread machine, as well as its software, has been improved. The hardware and software components of an automatic machine control system have been studied and designed. The execution times of individual technological operations have been analysed, and the control program has been improved. It has been proven that the modernised hardware and software devices increase the productivity of the automatic bread machine, and the achieved results are in accordance with the regulatory documents of the Republic of Bulgaria.

It has been proven that the use of a PID controller reduces the temperature deviation from the set point by up to 4°C, which eliminates the shortcomings of the relay control used in automatic bread machines. A PID algorithm with anti-windup functions for the integral component, and a filter for the differential component of the controller, have been adapted.

The fermentation and baking time parameters have been analysed and improved, and a lower temperature (162°C) has been applied in order to reduce the amount of acrylamide formed in the bread crust.

Organoleptic analysis results indicate that the inclusion of pigweed and purslane differentially affects the sensory attributes of the bread. While pigweed leads to a significant decrease in the taste characteristics, due to the residual bitter taste, purslane causes a stronger deterioration of the appearance and structure of the bread. However, the chewiness and aroma remain relatively good.

The analysis of the colour components shows that the addition of pigweed and purslane leads to significant differences in the colour of the bread, compared to the control sample. Purslane leads to the largest changes in colours, which is due to its specific chemical composition. The calculated ΔE values prove that these additives have a significant impact on the final visual appearance of the product.

The inclusion of IoT and AI-enabled technologies in the proposed smart bread-making machine supports real-time data capture and analysis for optimum control of the process of baking and fermentation. The system supports precise temperature profile control for optimum quality of bread and real-time optimisation of fermentation time for optimum volume and texture. The IoT system personalises the user experience by auto-suggesting recipe modifications based on ambient conditions (e.g., adjusting water levels in arid climates). Time is also conserved through automatic adjustment of baking time and temperature depending upon the type of dough.

6.2. Future Research and Development Directions

Future enhancements to the automatic bread maker may involve developing an advanced web interface featuring enhanced visual analytics for process monitoring, alongside functionality for user-specific recommendations.

Support for integration with smart AI-enabled home systems, such as Alexa+ and Google Home, will allow control via voice commands and additional interaction with other smart devices in the house. The ability to adapt AI-based bread-making software will allow the machine to learn and self-adjust in terms of making adjustments to temperature, humidity, bread fermentation, and baking times.

Supplementary Materials: The following supporting video information can be viewed at: https://www.youtube.com/watch?v=0HRbdZRMh9o (accessed on 23 February 2025).

Acknowledgements

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Appendix A

Technical specifications of technical means used in this study

Model	Type of the device	Manufacturer	City, Country of origin
NodeMCU ESP 8266	Single-board microcomputer	Espressif Systems (Shanghai) Co., Ltd.	Shanghai, PR China
Mega 2560	Single-board microcomputer	Sunfounder Inc., PR China	https://www.sunfounder.com (accessed on 10 February 2025)
Nextion Intelligent 7" NX8048P070_011	Touch screen display	ITEAD Intelligent Systems Co. Ltd.	Shenzhen, China
Vemark VGX-4825DA	Solid state relay	Vikiwat Ltd.	Plovdiv, Bulgaria
HM-550, based on integrated circuit Max6675	Thermocouple amplifier	Chipskey Technology Co., Ltd.	Shenzhen, PR China
YL-44	Piezo buzzer	RUI XIAO Enterprise Co., Ltd.	Yangjiang, PR China
220V AC to 5V DC, 2A	Power supply	Penghan New energy Co., Ltd.	Zhejiang, PR China
KBPC3510	Rectifier block	Lingshine Electric CO., Ltd.	Zhejiang, PR China
1 µF, 250V DC MKP10	Capacitor	WIMA GmbH & Co. KG	Mannheim, Germany
MD-18636	Automatic bread machine	Medion	Essen, Germany
RD-ZD-25F, 220V DC, 50 W	Bread maker electric motor	Ruian Donglai Commutator Co., Ltd.	Rui'an City, Zhejiang Province, PR China

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