

# Improving Coffee Roast Yield Consistency with Self-Tuned Fuzzy-PID Controller

Mohamad Taib Miskon<sup>1</sup>, Mohd Hezri Fazalul Rahiman<sup>1\*</sup>, Mohd Nasir Taib<sup>1</sup>

<sup>1</sup> School of Electrical Engineering, College of Engineering,  
Universiti Teknologi MARA, 40450 Shah Alam, Selangor, MALAYSIA

\*Corresponding Author: [hezrif@uitm.edu.my](mailto:hezrif@uitm.edu.my)

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## Abstract

Precise temperature control is essential in industrial processes like coffee roasting, where consistent quality is crucial. While traditional Proportional-Integral-Derivative (PID) controllers are widely used for temperature regulation due to their simplicity, they often struggle with dynamic process changes, leading to variability in product quality. This research investigates the Self-Tuning Fuzzy PID (STFPID) controller, which uses fuzzy logic to dynamically adjust its parameters, improving performance. The study aims to compare the effectiveness of conventional PID controllers and STFPID controllers in maintaining consistent roasting conditions and product quality. Experiments were conducted with both controllers to regulate the temperature during coffee roasting, focusing on indicators such as weight loss percentage, Agron values (indicating roast level), and peak wavelength (reflecting color properties). Time-temperature profiles for multiple batches were analyzed to assess consistency and stability. Results show that the STFPID controller significantly outperforms the PID controller, achieving a 76.5% improvement in weight loss consistency, a 71.2% reduction in Agron value variability, and a 24.4% enhancement in peak wavelength consistency. These findings demonstrate the STFPID controller's superior ability to adapt to process variations, maintaining uniform conditions and enhancing overall product quality in coffee roasting applications. The significance of this study lies in its potential to enhance the consistency and quality of coffee roasting, providing valuable insights for industrial applications and contributing to the advancement of process control technologies in this field.

## 1. Introduction

### 1.1 Research Background

The precision of temperature control is vital during the coffee roasting process, as it determines the flavor and aroma of the coffee [1–2]. This happens through a series of chemical reactions within the beans that produce volatile components contributing to aroma and taste. These reactions are influenced by both temperature and the length of roasting [3]. Longer roasting times can result in a more bitter taste as more volatile components are lost. A quicker temperature increase can make the coffee structure more porous and brittle, which in turn makes extraction easier during brewing. Roast masters often depend on the consistency of temperature profiles to replicate the desired final taste. The dynamics of roasting vary with different coffee beans and roasting machines. Presently, roasting still relies heavily on the expertise of the roast master to time specific reactions for the desired aroma and flavour [4]. That's why roasting is often considered an art form, and replicating the final roasted

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product is challenging due to the complexity of the process. Coffee roasting involves several stages, beginning with the drying stage where moisture is evaporated from the beans at around 100°C. Following that is the Maillard reaction stage, where beans change from yellow to brown between 100°C to 200°C. The caramelization stage occurs when temperatures exceed 200°C, darkening the beans and enhancing bitterness over time [5]. The precision of temperature control throughout these stages affects the flavor and batch consistency.

Maintaining the consistency of batch-roasted coffee is challenging due to various factors such as bean variety, operating conditions like temperature and humidity fluctuations, and the performance of the roasting equipment [6]. Even if the variety of beans is fixed, ensuring that they are of the same origin, size, and moisture content, the time-temperature profile applied during the roasting process must still be precisely controlled [4]. Temperature fluctuations can cause deviations in the roasting profile, affecting the colour and weight loss of the roasted beans. Controlling temperature is challenging because of the nonlinear nature of the roasting process especially at high temperatures. Additionally, endothermic and exothermic reactions occur at different temperature levels, causing the beans to change dynamically. These changes include size expansion and colour transition from green to yellow, then to brown, and eventually black. The first and second cracks, where heat pressure is released from the internal structure of the coffee beans, can trigger temperature disturbances that will further complicate the process. Furthermore, the nature of roasting method itself, especially in hot air coffee roasting, involves rapid agitation of the coffee beans while delivering heat to the roasting chamber via forced convection [7–8]. This can create chaotic conditions inside the chamber, making it challenging to maintain a uniform roasting environment.

The authors' previous research primarily focused on the development and performance comparison of PID and STFPID controllers in maintaining desired temperature profiles during roasting. The controllers demonstrated their ability to regulate temperature effectively, which is crucial for achieving consistent roast quality [9]. In this work, utilizing the same setup and controllers, the intention and focus shift to assessing the consistency in roast colour and uniformity in weight loss, which are critical indicators of roast quality. By examining these quality parameters, we seek to understand how the controller performance translates into tangible improvements in the final roasted product, providing valuable insights for industrial coffee roasting applications.

## 1.2 Literature Review

There are many quality parameters that can be used to determine roasted coffee yield, with color and percentage weight loss being among the most popular choices [10–12]. Quantitative assessment using the Agtron scale provides specific values that differentiate various roast levels and is reliable for determining roast levels. This scale can be associated with sensory attributes [10]. According to Muhari et al. [13], weight losses of 11%, 15%, and 22% in the roasting process are categorized as light, medium, and dark roasts, respectively. Batch weight loss, typically ranging from 14% to 20% of the initial weight, is another critical metric reflecting the degree of moisture and volatile compound loss during roasting [14–15]. Consistent weight loss is indicative of a stable and uniform roasting process. Variations in weight loss can signal disparities in heat application or bean moisture content, potentially leading to uneven roasting and undesirable flavour characteristics [16]. Therefore, consistency in weight loss is essential for producing high-quality coffee that meets consumer expectations and facilitates better inventory management and yield production across batches.

Traditional PID controllers, while being popular used in temperature regulation for processes such as coffee roasting and other related process, exhibit a significant deficiency in their ability to reject disturbances and their lack of robustness especially if not properly tuned [17–19]. The primary concern is that these controllers are often calibrated for a specific set of conditions, assuming a linear system with predictable dynamics. However, in practical applications, the presence of sudden environmental changes, variable material properties, or system perturbations can introduce disturbances that the PID controller may not effectively compensate for [17]. This limitation mainly come from the design process of PID controllers itself, which do not account for complex, dynamic changes outside of their configured parameters. The lack of robustness in PID controllers further manifests in their inability to maintain optimal performance over a range of operating conditions [18]. Linear control strategy such as conventional PID struggles with non-linear system behaviour, can lead to overcompensation or insufficient response, resulting in temperature overshoots or undershoots — both undesirable outcomes [19]. This condition also happens in coffee roasting process where the heat transfer and bean characteristics can change dramatically that can lead to inconsistent roast quality. To achieve the precise flavour profiles desired in coffee roasting, a control system must swiftly and accurately adjust to these disturbances. The limitations of PID controllers in this regard necessitate the exploration of more advanced control strategies that offer better disturbance rejection and robustness to ensure a consistent and high-quality roasting process.

There are many tuning rules for PID controller. One of them is the Approximate M-constrained Integral Gain Optimization (AMIGO) tuning rule that seek to maximize integral gain and minimize the integrated error to improve robustness to PID design [20]. The rule can easily be used as it utilized the model parameter such as gain,

time constant and dead time as part of the tuning equation. Advantages of using AMIGO tuning rule is that it helps to increase robustness [21], resistance to measurement noise [22], improved transient response performance as well as optimal energy consumption [23]. The use of the AMIGO tuning rule for PID controllers is particularly beneficial in scenarios where robustness, moderate tuning gain, and successful practical applications are desired. The method's versatility, applicability to various industrial processes, and implementation in automation systems further support its suitability for a wide range of control applications. Thus, the PID tuned using AMIGO tuning rules is believed to be the best candidate as a benchmark controller for this work.

Changes in system parameters and loading conditions always make the retuning of PID is compulsory to avoid performance degradation and instability of the system [24–25]. Thus, self-tuning PID controllers have been implemented to achieve better control. To implement this, various studies have explored the use of different PID controller parameter self-tuning algorithms, such as Backpropagation (BP-PID), Particle Swarm Optimization (PSO-PID), and Fuzzy-PID, to optimize the performance of traditional PID algorithms for temperature control [26]. The integration of Fuzzy Logic Controller (FLC) with (PID) controllers for self-tuning of gains has gained attention due to its ability to adaptively adjust the PID parameters based on system behaviours. The self-tuning capability is achieved through fuzzy rules that modify the proportional and integral gains of the PID controller, enhancing its adaptability to varying system dynamics [27]. The integration of FLC with PID controllers has been shown to improve system performance, particularly in applications such as automatic voltage regulation, hydraulic crane control, and DC motor speed control [28–30]. Furthermore, the FLC's ability to tune PID gains has been demonstrated to enhance the robustness and adaptability of PID controllers in various systems, including industrial hydraulic actuators, thermal systems, and robot manipulators [31–33].

While there has been significant progress in the application of advanced control systems, such as self-tuning Fuzzy-PID controllers, in process control and temperature-related applications, gaps remain in the comparative analysis between traditional PID and self-tuning Fuzzy-PID controllers. These gaps are particularly evident in attempts to produce consistent yield outputs in roasted coffee, with a focus on achieving consistent time-temperature profiles that directly contribute to quality consistency in terms of roast level and weight loss.

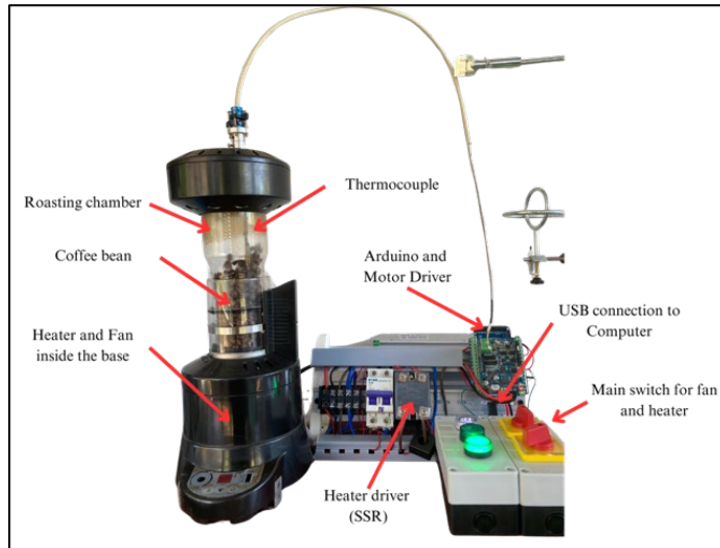
This study aims to address these gaps by providing a detailed comparison of the performance of PID and self-tuning Fuzzy-PID controllers in maintaining consistent coffee roast quality. It will explore their effectiveness in achieving stable colour and weight loss across different batches, offering valuable insights into the field. The research investigates the effectiveness of self-tuning Fuzzy-PID controllers, which combine the robustness of traditional PID control with the adaptive capabilities of fuzzy logic. By comparing these advanced controllers with conventional PID controllers, this study seeks to determine their relative performance in ensuring consistent coffee roast quality across various batches.

## 2. Methodology

### 2.1 Real-Time Temperature Controller for Coffee Roasting Process

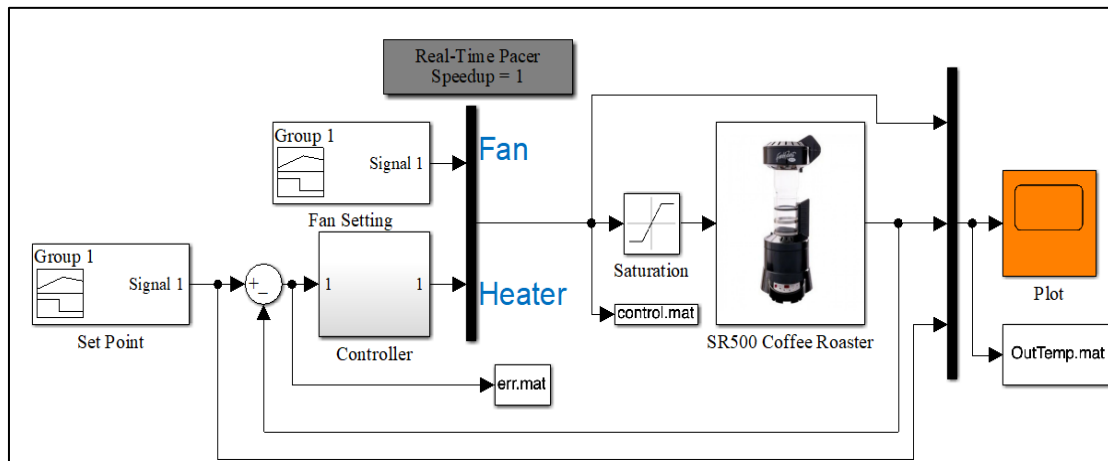
The experimental work began by sorting the Arabica coffee beans to remove defects, stones, and other foreign materials. The sorted beans were then weighed to 120 grams per batch to maintain consistency across all roasting sessions, using a coffee scale (TIMEMORE Basic 2.0 Electronic Espresso Scale with Timer) that has an accuracy of up to 0.1g. The roasting process was carried out using a hot-air coffee roaster with a fixed airflow, with the heater input to the roasting chamber being the manipulated variable for the controller. The desired temperature profile typically ranges from an initial 100–120°C during the drying phase, increases to 150–165°C during the Maillard reaction phase, and further rises to 180–195°C at the first crack stage. Finally, it reaches around 205–220°C at the second crack stage before the cooling phase begins. The final desired temperature was set at 220°C and the total roast duration was fixed at 900 seconds. After roasting, the beans were cooled and weighed again to measure weight loss. Next, the coffee was ground using a TIMEMORE C2 hand grinder and the physical appearance was inspected, focusing on the brownness of the ground beans and the presence of any roasting defects. This process was repeated six times using the PID controller and another six times using the self-tuning Fuzzy-PID (STFPID) controller. Conducting six roast sessions for each controller type (PID and STFPID) ensures a higher level of statistical reliability and robustness in our comparative analysis. This approach allows for a more thorough evaluation by capturing a broader range of potential variability in the roasting process.

The coffee roasting plant used in this study is depicted in Fig. 1. The primary components include the roasting chamber, where the coffee is placed and heated, and the fan and heating element located in the roaster's base. The temperature sensor used in this work is a K-Type thermocouple, which is inserted into the roasting chamber to measure the temperature of the coffee bean pile. The system is controlled by an Arduino board that communicates with MATLAB/SIMULINK software to drive the heater and fan. The heating process for this setup is based on forced convection, utilizing a heater and a blower fan to circulate hot air through the roasting chamber. The flow of hot air is kept constant, and the heating process is regulated by a PID controller and a self-tuning Fuzzy-PID (STFPID) controller, which will be elaborated on in the following section.



**Fig. 1** Hot-air coffee roasting plant utilizing SR500 coffee roaster

Fig. 2 illustrates the PID controller setup used for real-time implementation in this work. The setup consists of several key components: a set point block, a PID controller block, and a mux block that receives the fan setting and heater input computed by the PID controller block. The system also includes a saturation block, which handles and filters out values outside the range of 0 to 100%, as these are impractical and invalid for the coffee roaster. The SR500 coffee roaster block accepts inputs for the fan and heater and outputs the temperature of the pile of beans inside the roasting chamber in response to these inputs. Additionally, a plot block is used to display the temperature response and the inputs given to the roaster. The 'outTemp.mat' file records all events during the roasting process, providing a comprehensive log of the system's behaviour.



**Fig. 2** MATLAB/SIMULINK block for real-time PID controller

The PID block was set based on Equation (1) which includes proportional gain ( $K_p$ ), integral time ( $T_i$ ), and derivative time ( $T_d$ ). Additionally, a derivative filter, denoted by  $D$ , is incorporated in the derivative term as specified in Equation (2) filter out high frequency noise [34]:

$$U(s) = K_p \left( E(s) + \frac{1}{T_i} \cdot \frac{E(s)}{s} + T_d \cdot D \cdot E(s) \right) \tag{1}$$

$$D = \frac{sT_d}{(T_d/N)s + 1} \tag{2}$$

$K_p$ ,  $T_i$  and  $T_d$  are determined using the AMIGO tuning rules, as specified in Equation (4) through Equation (6) [34]. The AMIGO rules are based on a First Order Plus Dead Time (FOPDT) model, represented in Equation (3) with the parameters  $K = 1.94$ ,  $\tau = 58.94$  and  $\theta = 4.82$ .

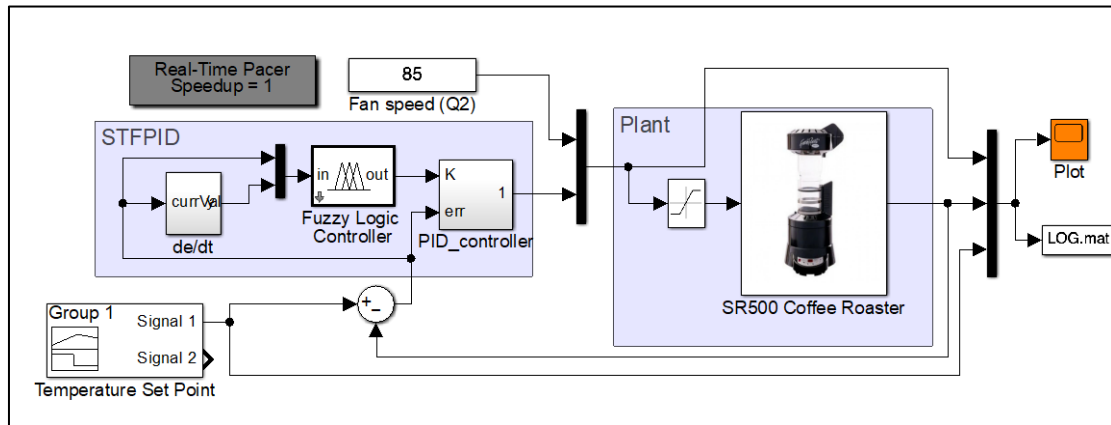
$$G(s) = \frac{K}{\tau \cdot s + 1} e^{-\theta} \quad (3)$$

$$K_p = \frac{1}{K} \left( 0.2 + 0.45 \frac{\tau}{\theta} \right) \quad (4)$$

$$T_i = \frac{0.4\theta + 0.8\tau}{\theta + 0.1\tau} \theta \quad (5)$$

$$T_d = \frac{0.5\theta\tau}{0.3\theta + \tau} \quad (6)$$

Fig. 3 depicts the self-tuned Fuzzy-PID controller setup used for real-time temperature control in this work, implemented with MATLAB/SIMULINK software. This setup enhances the PID controller configuration shown in Fig. 2 by incorporating a self-tuning mechanism for the PID controller gains using a Fuzzy Logic controller. In this configuration, the Fuzzy Logic controller takes the error and the derivative of the error as inputs, which represent how much the temperature deviates from the desired setpoint. The output from the Fuzzy Logic controller block provides the PID controller gains ( $K$ ) which are fed to the PID block to dynamically update the controller's response according to the current state of the error. The PID controller then produces an updated output signal in the form of heater level (ranging from 0% to 100%) to drive the SR500 heating element. The temperature response within the roasting chamber is continuously measured and transmitted back to the computer and MATLAB/SIMULINK blocks for logging and as feedback.

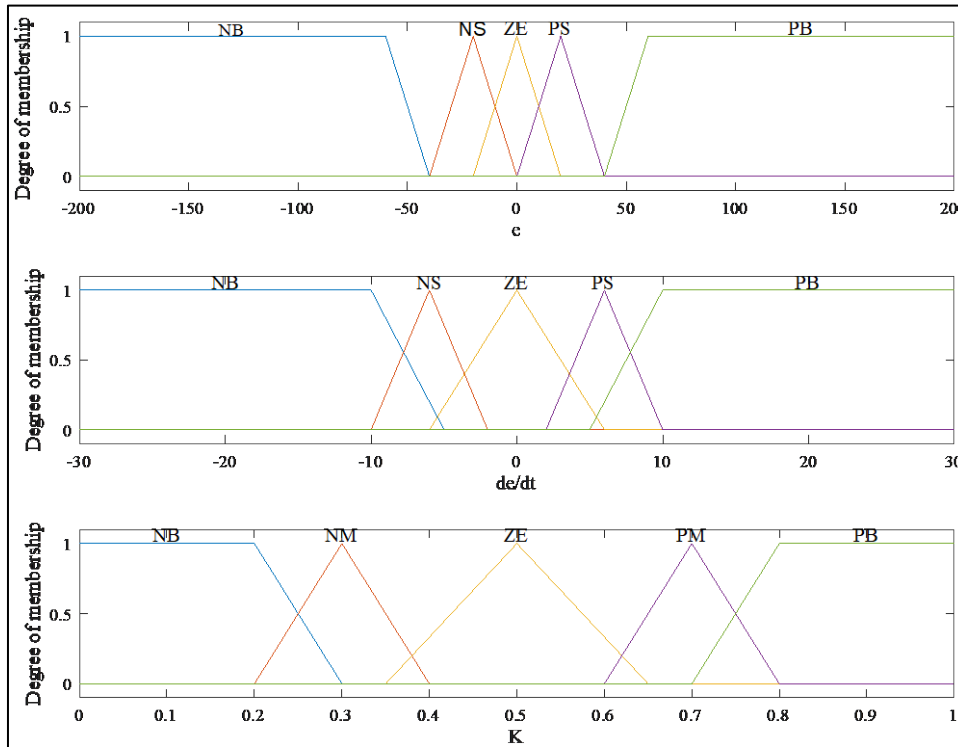


**Fig. 3** MATLAB/SIMULINK block for real-time self-tuned Fuzzy-PID controller

Fig. 4 depicts the detailed setup of the fuzzy membership functions used in the Fuzzy Logic Controller block for this study. The inputs to the controller include the error and the derivative of the error, while the outputs consist of gain multipliers for  $K_p$ ,  $K_i$  and  $K_d$  of the PID controller. The top plot represents the error, the middle plot shows the derivative of the error, and the bottom plot displays the output gain. Each plot uses five membership functions: Negative Big (NB), Negative Small (NS), Zero (Z), Positive Small (PS), and Positive Big (PB). The error range is set between  $-200^\circ\text{C}$  and  $200^\circ\text{C}$ , accommodating the high-temperature applications in this work, which can reach up to  $200^\circ\text{C}$  or more. The range for the derivative of the error is set from  $-30$  to  $30$ , and the gain ranges from  $0$  to  $1$ . These membership functions form the basis for the fuzzy rule set, which consists of 25 rules. These rules are used to determine the updated gain output based on the current input state. The following indicates some of the rules to specify how to adjust the PID gains in response to various combinations of error and derivative of error values:

*IF error is NB and derivative of error is NB, THEN K is NB*  
*IF error is NB and derivative of error is NS, THEN K is NM*  
*IF error is NB and derivative of error is ZE, THEN K is NM*

*IF error is NB and derivative of error is PS, THEN K is NM*  
*IF error is NB and derivative of error is PB, THEN K is ZE*



**Fig. 4** Fuzzy membership function for input (error and derivative of error) and output gain (K)

The complete set of rules can be organized in a table format, as shown in Table 1. This table outlines the relationship between the error (e), the derivative of the error (de/dt), and the corresponding control action for the PID gains.

**Table 1** Fuzzy rule set table for the control action based on the error (e) and derivative of error (de/dt)

Error de/dt	NB	NS	ZE	PS	PB
NB	NB	NM	NM	NM	ZE
NS	NM	NM	ZE	ZE	PM
ZE	NM	ZE	ZE	ZE	PM
PS	ZE	ZE	ZE	PM	PB
PB	ZE	PM	PM	PB	PB

Next, in the PID block, the K values from the Fuzzy Logic Controller output was used to update the PID gains  $K_p$ ,  $K_i$  and  $K_d$  according to Equation (7) through Equation (9), respectively [35].

$$Kp' = K(Kp_{max} - Kp_{min}) + Kp_{min} \tag{7}$$

$$Ki' = K(Ki_{max} - Ki_{min}) + Ki_{min} \tag{8}$$

$$Kd' = K(Kd_{max} - Kd_{min}) + Kd_{min} \tag{9}$$

Based on the relationship, if the observed behavior indicates that the temperature deviates by 50°C, which falls under the Positive Small (PS) region, and the rate of change in temperature (based on previous data) is observed at 20°C, falling under the Positive Big (PB) category, then the control action is calculated in PB category. In this work, the maximum and minimum values for the PID gains are set as follows:  $Kp_{max} = 2$ ,  $Kp_{min} = 0$ ;  $Ki_{max} = 0.1$  and  $Ki_{min} = 0.0$ ;  $Kd_{max} = 6$  and  $Kd_{min} = 0$ .

## 2.2 Yield Consistency Measurement

Consistency of roasting outcomes across batches was evaluated through both qualitative and quantitative assessments. The qualitative evaluation focused on visual inspection of the roasted coffee beans, considering factors such as surface oil presence, colour development, roast uniformity, and the absence of defects like tipping and burn marks. These visual criteria were applied consistently to both whole and ground coffee samples. Quantitatively, the coffee colour measurement was performed using the Sensegood Instruments spectrophotometer, as illustrated in Fig. 5. The setup includes several key components: the spectrophotometer display, a sensor head, a rotating platform to ensure uniform measurement, and a computer for logging the data. This spectrophotometer is designed to measure the Agtron Coffee Number, a standard for evaluating the roast level of coffee based on its colour. In addition to the Agtron Number, the device settings also support measurements in other colorimetric systems, including XYZ and Yxy (which are color space representations used in various applications), and the CIE (Commission Internationale de l'Éclairage) and Hunter Lab color spaces, both of which are widely used in color science for specifying and comparing colors. The spectrophotometer also generates a spectral power plot, which displays the intensity of light across different wavelengths, providing a detailed profile of the coffee's color characteristics. In this work, the Agtron measurement was used to measure roasted coffee yield consistency where the high values indicate lighter roast while a darker roast will produce lower Agtron number. A tight consistency range was used in this study where the acceptable Agtron variable was set within 2 Agtron units that will indicate a uniform roast consistency across different batches.

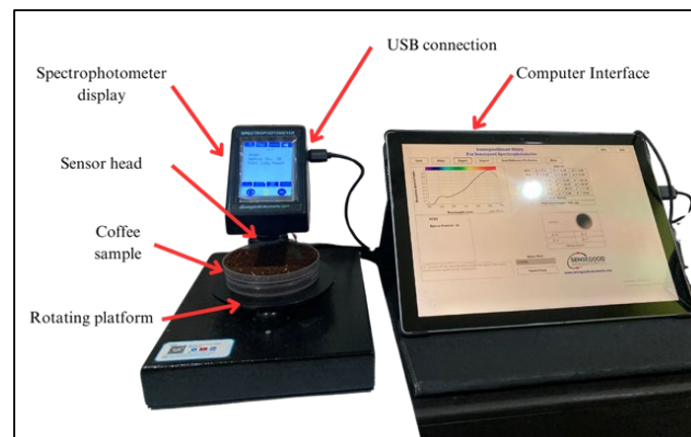


Fig. 5 Spectrophotometer setup that include computer to record measurement data

Post-roast weight also correlates to the roast yield consistency. A darker roast typically result in higher weight loss and likewise lighter roast contributed to lower weight loss. The loss primary caused by the internal moisture evaporation that happen during the roast session due to heat application. The consistent roast loss percentage across different batches indicate uniformity in the roasting process which contributed to consistent flavour. Besides maintaining similar roast loss percentage for each batch roasting can also help inventory and cost management in commercial coffee roasting operation. The roast loss percentage can be calculated using Equation (10) [36] where  $W_g$  represent the weight of the unroasted green bean and  $W_r$  represent the weight of the roasted bean. The weighing process was carried out using a coffee scale with a 0.1g resolution (TIMEMORE Basic 2.0 Electronic Espresso Scale with Timer), where the raw beans were weighed three times before roasting and three times after roasting to ensure accuracy.

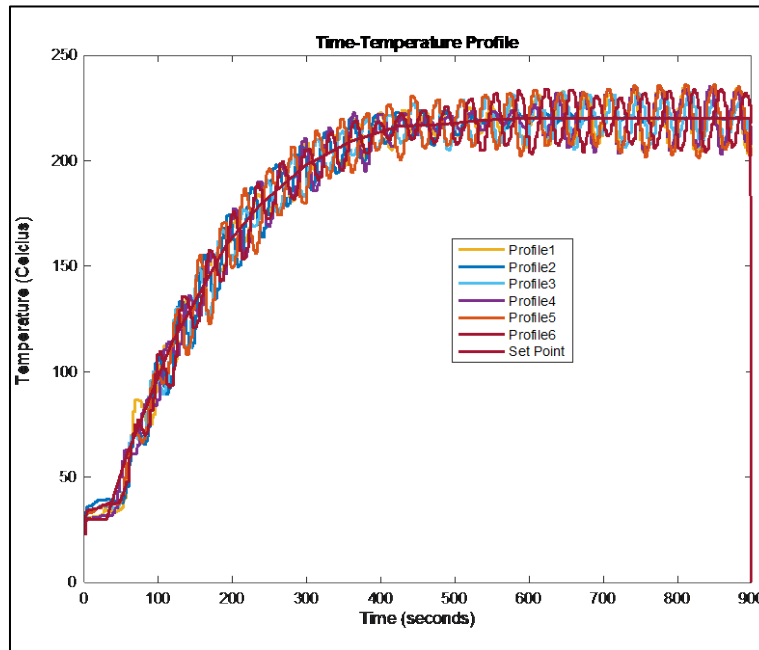
$$\text{Roast Loss \%} = \frac{W_g - W_r}{W_g} \times 100\%. \quad (10)$$

## 3. Results and Discussion

### 3.1 Time-Temperature Curve for PID Controller

Fig. 6 illustrates the time-temperature profiles for six different batches (Profiles 1 to 6) processed using the PID controller, alongside a setpoint temperature curve. The six profiles are represented by distinct coloured lines

(yellow, orange, blue, green, red, and maroon) showing the temperature progression over time for each batch. The setpoint temperature is depicted by a thick maroon line, representing the desired temperature profile that the system aims to achieve and maintain. The temperature control process starts from room temperature and gradually increases to reach the final temperature of 220°C. Once the temperature reaches 220°C, it is maintained at this level until the end of the roasting process. The variations in the time-temperature profiles reflect the PID controller's response to maintaining the desired temperature. While the PID controller manages to keep all profiles within a certain range around the setpoint, persistent oscillations are observed beyond 500 seconds. These oscillations indicate the PID controller's ongoing efforts to maintain the temperature close to the setpoint, continuously adjusting to compensate for any deviation.



**Fig. 6** Time-temperature plot for coffee roasting process using PID controller

### 3.2 Time-Temperature Curve for Self-Tuned Fuzzy-PID Controller

Fig. 7 shows the time-temperature profiles for six batches (Profiles 7 to 12) regulated by the STFPID controller, alongside the setpoint temperature curve. The profiles exhibit minimal oscillations and remain closely aligned with the setpoint. The zoomed-in window highlights a narrow temperature range of 218°C to 222°C, underscoring the controller's ability to maintain tighter thermal control with smaller oscillation amplitudes than the standard PID controller. The close alignment of the profiles indicates a uniform and repeatable thermal response across batches, reflecting the STFPID's enhanced process stability and control performance. This improved thermal consistency is particularly relevant, as it directly influences the yield consistency, which will be discussed in the following section.

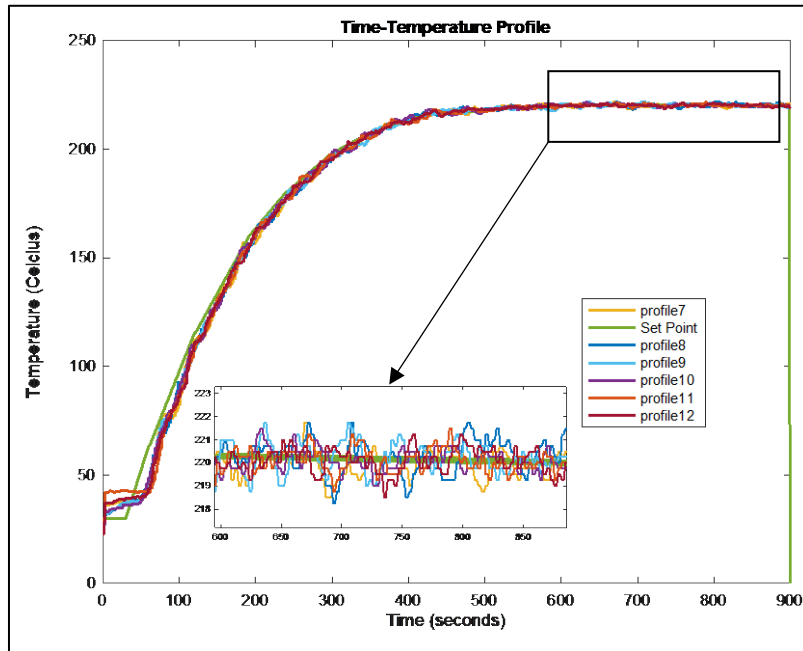


Fig. 7 Time-temperature plot for coffee roasting process using STFPID controller

### 3.3 Colour Consistency Comparison

Fig. 8 showcases a series of coffee batches processed using the PID controller. The top row displays the whole roasted coffee beans from each batch, with each cup representing a different roasting outcome. Visual evaluation was based on observable traits such as the presence of surface oil, degree of roasting (indicated by bean colour), and uniformity. Notably, Profiles 2 and 4 exhibit visible oil on the surface and appear darker, indicating a potentially overdeveloped roast. Profile 6, by contrast, appears lighter than the others, suggesting underdevelopment. Further investigation using a spectrophotometer was carried out, and the spectral power distribution across the batches is depicted in Fig. 9. Based on the figure, the peak wavelengths range from 652 nm to 664 nm. Batch 6 (Profile 6) exhibits a distinct peak at 652 nm, which is notably shorter than those of the other batches, suggesting a lighter roast level. Overall, the profiles have a mean peak wavelength of 658.83 nm with a standard deviation of 5.56 nm. These variations correspond to small differences in colour intensity due to the roasting differences. Table 2 further compares these peak wavelength values with their corresponding Agtron values measured using the spectrophotometer. The Agtron values range from 37 to 46, reflecting more variability in roast levels, with a mean of 41 and a standard deviation of 2.92. This broader range suggests that the PID controller may not provide as consistent control over the roasting process, leading to more significant differences in roast level across batches.



Fig. 8 Coffee samples roasted using PID controller

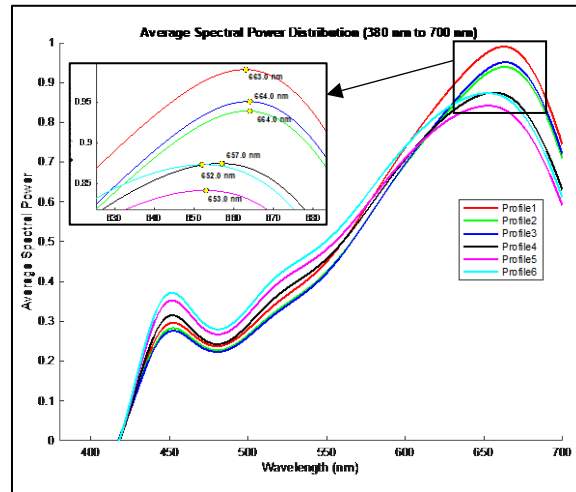


Fig. 9 Average Spectral power distribution across the batches roasted using PID controller

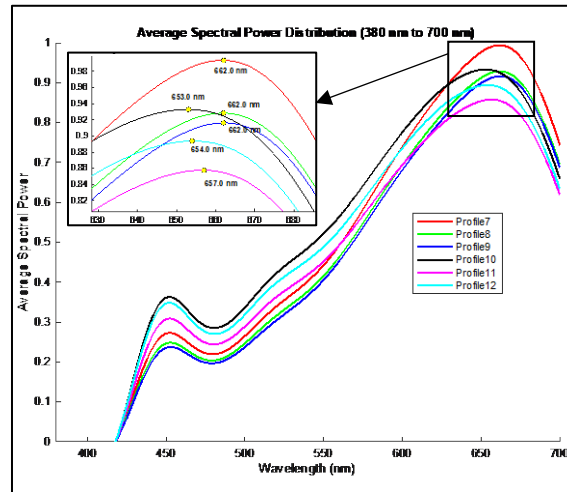
Table 2 Agtron and Peak Wavelength measurement across different batches roasted using PID controller

Batch No	Agtron	Peak Wavelength (nm)
1	41	663
2	37	664
3	40	664
4	42	657
5	40	653
6	46	652

Fig. 10 shows batches roasted using the STFPID controller. Applying the same visual criteria, all batches exhibit a uniform brown colour with no visible surface oil, tipping, or burn marks, indicating stable and consistent roasting. The ground coffee also shows minimal variation in colour, reinforcing the effectiveness of the STFPID controller in producing uniform roast outcomes. Further analysis using a spectrophotometer was conducted, and the results are shown in Fig. 11. The plot reveals that the peak wavelengths are clustered within a narrow range of 653 to 662 nm, with a mean of 658.33 nm and a standard deviation of 4.23 nm. This small variation in peak wavelengths suggests that the STFPID controller maintains stable colour characteristics, which aligns with the consistent Agtron values. Table 3 provides an overview of the correlation between the Agtron values and the peak wavelengths. The Agtron values and peak wavelengths are closely aligned, showing minimal variation with a mean of 41.5 and a standard deviation of 0.84. This indicates that the STFPID controller is effective in consistently maintaining both the roast level and spectral characteristics. The standard deviation of Agtron values for the STFPID controller is 0.84, compared to 2.92 for the PID controller, indicating a 71.2% improvement in consistency with the STFPID controller. Similarly, the standard deviation of peak wavelengths is 4.23nm for the STFPID controller, compared to 5.56nm for the PID controller, reflecting a 24.4% improvement in consistency with the STFPID controller.



Fig. 10 Coffee samples roasted using STFPID controller



**Fig. 11** Average spectral power distribution across the batches roasted using STFPID controller

**Table 3** Agtron and peak wavelength measurement across different batches roasted using STFPID controller

Batch No	Agtron	Peak Wavelength (nm)
7	42	662
8	42	662
9	42	662
10	42	653
11	40	657
12	41	654

### 3.4 Weight Loss Percentage

Table 4 presents a comparative analysis of weight loss percentages across twelve batches processed using different temperature controllers. These coffee batches are roasted by the conventional PID controller and the Self-Tuning Fuzzy PID (STFPID) controller. Batches processed with the PID controller exhibit greater variability in weight loss percentages. The batches processed with the PID controller show weight loss percentages ranging from 13.4% to 26.9%, with a mean value of 22.0%. The range of weight loss percentages is 13.5%, indicating significant variability in the outcomes. The standard deviation is 4.21%, reflecting a high level of dispersion around the mean. This suggests that the PID controller may struggle to maintain consistent process conditions, resulting in varied weight loss across different batches.

**Table 4** Comparative analysis of weight loss percentages across twelve batches processed using different temperature controllers

Temperature Controller	Batch number	Weight loss percentage (%)	Mean (%)	Standard deviation (%)
PID	1	13.4	22.0	4.21
	2	24.7		
	3	22.4		
	4	22.9		
	5	21.7		
	6	26.9		
STFPID	7	14.2	15.9	0.99
	8	16.2		
	9	15.7		
	10	16.5		
	11	17.4		
	12	15.4		

The batches controlled by the STFPID show weight loss percentages ranging from 14.2% to 17.4%, with a mean value of 15.9%. The range is 3.2%, demonstrating much less variability compared to the PID-controlled batches. The standard deviation is 0.99%, indicating that the STFPID controller maintains a high level of consistency with minimal dispersion around the mean. This indicates that the STFPID controller significantly reduces the variability in weight loss, leading to a 76.5% improvement in maintaining consistent weight loss during the process.

#### 4. Conclusion

The research aimed to evaluate and compare the effectiveness proposed STFPID controller in improving roasting consistency over traditional PID controller. The STFPID controller achieves a 71.2% improvement in the consistency of Agtron values, supported by the peak wavelength measurements consistency improvement by 24.4%. In terms of weight loss during the process, the STFPID controller reduces variability by 76.5%, providing more predictable outcomes and demonstrating superior process stability. These improvements highlight the STFPID controller's capability to adapt dynamically to process variations, maintaining optimal conditions for consistent and high-quality results. In conclusion, the findings underscore the STFPID controller's effectiveness in providing enhanced control and uniformity in roasting processes by offering a more precision and consistent time-temperature profile batch after batch.

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#### Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

#### Author Contribution

The authors confirm contribution to the paper as follows: **study conception and design:** Mohamad Taib Miskon, Mohd Hezri Fazalul Rahiman; **data collection:** Mohamad Taib Miskon; **analysis and interpretation of results:** Mohamad Taib Miskon, Mohd Hezri Fazalul Rahiman, Mohd Nasir Taib; **draft manuscript preparation:** Mohamad Taib Miskon, Mohd Hezri Fazalul Rahiman, Mohd Nasir Taib. All authors reviewed the results and approved the final version of the manuscript.

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