Tianjin Daxue Xuebao (Ziran Kexue yu Gongcheng Jishu Ban)/
Journal of Tianjin University Science and Technology
ISSN (Online):0493-2137
E-Publication: Online Open Access
Vol: 59 Issue: 02:2026
DOI: 10.5281/zenodo.18606858

OPTIMIZING INDONESIAN COFFEE QUALITY FOR EXPORT MARKETS THROUGH THE TAGUCHI METHOD IN ROASTING AND IN VITRO FERMENTATION

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Abstract

This study aims to optimize the quality of Indonesian coffee for export markets using roasting and in vitro fermentation as a two-step process. The Taguchi L9 (3^3) orthogonal array method was employed to determine the dominant factors and their optimal level. Coffees, which were grown in Malang, East Java, and belong to Robusta, Arabica, and Luwak, were studied. The data were generated through controlled experiments by varying roasting temperature, roasting time, drum speed, microbial inoculum concentration, fermentation duration, and temperature. Sensory characterization was performed in the laboratory according to Specialty Coffee Association (SCA) cupping protocols and chemical composition (moisture, organic acids, pH, and amount of caffeine). SNR and ANOVA tests assessed the factors' robustness and statistical significance. The results showed that dry roasting at a temperature of 220°C within 12 min and a tumbling speed of 30 rpm achieved the highest sensory scores; fermentation at condition levels of microbial inoculum (5%), fermentation time (24 h), and fermentation temperature (25°C) was optimal for aroma, and lactic acid balance, respectively. Confirmation trials confirmed these results, reaching a final cupping score over 85, the minimum value for specialty coffee. This study demonstrates that roast temperature and microbial inocula levels are the most significant factors influencing quality (contributing>30%) in coffees tested. These results suggest that evidence-based process improvement can contribute positively to the competitiveness of Indonesia's premium quality coffee market. Optimized fermentation and roasting conditions can provide feasible strategies for producers, cooperatives, and exporters to achieve quality standardization, traceability, and compliance with international standards.

Keywords: Indonesian Coffee, Taguchi Method, Roasting Optimization, In Vitro Fermentation, Export Quality.

1. INTRODUCTION

The world of coffee is a highly competitive, where tastes change and quality demands grow. As the fourth largest coffee producer in the world, Indonesia has a strong interest in this sector. In 2023, the country produced 789,609 tons of coffee beans and exported around 279,996 tons with USD929.135 million (Darmanto et al., [5]; International Trade Centre.[6]. Robusta is predominant in national production, up to 87% (Darmanto et al., 2025). However, productivity is on the wane. Indonesia is increasingly pressured to

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comply with quality and safety requirements, particularly in major markets like the European Union (Permana et al., 2024).

In the world coffee trade, especially in specialty coffee, market access is more frequently tied to offering high-quality products of known origin and with predictable aroma/flavour attributes. Specialty coffee is classified to score no less than 80 of a possible 100 points in flavor, aroma, aftertaste, acidity, and body by the Specialty Coffee Association (SCA) evaluation method (Carvalho et al., 2016; Silva et al. Quality is more than taste; it is standardization and consistency from one batch to another. Even with this capacity, Indonesia has difficulties fulfilling these requirements, becoming less competitive in high-value markets. These quality limitations are due primarily to inefficiencies upstream. About 90% of Indonesia's coffee exports are still unprocessed green beans, implying that the value-added process at the coffee origin has not been well implemented (Permana et al, 2024). Handling after harvest is often erratic and involves traditional processes that do not achieve optimal moisture levels, but rather have areas with higher or lower moisture contents and therefore vulnerabilities to mold. In addition, the premature harvest and people's lack of technical knowledge contribute to this poor performance. For this reason, the Revealed Comparative Advantage (RCA) for Indonesian coffee is still low—with an average of 6.89—relative to its close competitors such as Colombia (57.02), Brazil (25.78), and Vietnam (25.54) (Wahyudi et al., 2024).

This research particularly concerns three Indonesian premium coffees: Robusta, Arabica, and Luwak, which are widely planted in the Malang area in East Java. The area was chosen because of its high production potential and variable microclimates that affect coffee quality, even though it is still under-optimized in terms of model-based improvement on a science and technology basis (Fibrianto et al., 2023; Darmanto & Utomo, 2024). It takes a comprehensive strategy to solve quality-related issues. Although upstream agronomy and farmer training improvements are important, downstream improvement through controlled post-harvest processing—especially fermentation and roasting—is an area with great promise for yield improvement. Controlled fermentation may enhance the desirable sensory attributes and reduce heterogeneity, whilst precise roasting procedures can reveal beans' full aromatic and flavor potential (Yusianto et al., 2019; Rabelo et al., 2024; Moon et al., 2005). Together, these are vital leverage points in the production of specialty coffee.

The Taguchi method offers a strong experimental design for structuring and improving such processes. Dr Genichi Taguchi's statistical method focuses on designing robust processes unaffected by uncontrollable factors such as environmental variation/inconsistency in raw materials (Afani 2018; Azhar et al. This method can rapidly identify the optimum condition with a minimum number of experimental trials by using orthogonal arrays, signal-to-noise (S/N) ratio, and analysis of variance (ANOVA). This method can be beneficial for Indonesian coffee in minimizing the variation of final product quality, improving a certain degree of processing security when growers tend to produce a new, higher-value product in an international market.

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Although the Taguchi method offers promising potential, limited empirical studies have utilised Taguchi analysis specifically for coffee processing in the Indonesian context. Thus, it represents an under-addressed research area. The current study filled this gap using the Taguchi method to optimize Indonesian coffee's roasting and in vitro fermentation conditions. In the process, it attempts to create an evidence-based path for quality enhancement, value addition, and competitive positioning of Indonesian specialty coffee on the world stage.

2. METHODOLOGY

This work employs the Taguchi method to maximize two important Indonesian coffee processing steps: roasting and in vitro fermentation. The protocol was created to enable the best parameter combination to improve coffee quality for international markets.

2.1 Taguchi Method Experiment Design

The OAs, as an experimental design system, are employed in the Taguchi technique for practical experiments on multiple parameters and their levels. In this study, three factors were chosen by initial screening and literature review:

- Factor A: Roasting Temperature (Robusta and Arabica) / Microbial Concentration (Luwak)
- Factor B: Fermentation Time
- Factor C: Drumming Speed (Robusta and Arabica) / Fermentation Temperature (Luwak)

Every factor was studied at three levels, so the L9 (3^3) orthogonal array design, including nine experiments, was used.

The settings level was selected according to previous tests and references in the literature on coffee treatment. Light, medium, and medium-dark roast ranges were chosen based on the roasting temperatures of 180°C, 200°C, and 220°C, often used in Indonesian specialty coffee (Novison & Sapta, 2021). Likewise, the concentrations of microbes and duration of fermentation were selected to encompass the range of microbial activity observed in previous work in in vitro fermentation (Pratiwi, n.d.; Molecules, 2023).

Table 1: Orthogonal Array L9 (3^3) Design Matrix

Trial	A (Level)	B (Level)	C (Level)
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

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Table 2: Level Settings for Each Factor

Factor	Level 1	Level 2	Level 3
A	180°C / 10^6 CFU/mL	200°C / 10^7 CFU/mL	220°C / 10^8 CFU/mL
B	12 hours	24 hours	36 hours
C	30 rpm / 25°C	45 rpm / 30°C	60 rpm / 35°C

2.2 Sample Preparation and Experimental Procedure

Coffee cherries from Malang, East Java (Robusta, Arabica, and Luwak types) were sorted, cleaned, and divided into batches for controlled fermentation and roasting. The fermentation process was conducted in vitro using defined microbial starters at varied concentrations and temperatures, depending on the coffee type.

After fermentation, beans were washed, dried, and roasted using a programmable drum roaster with varied temperature and drum speed settings per the design matrix. The sensory and chemical properties of each trial batch were evaluated afterward.

2.3 Response Variables and Measurements

The primary quality indicators assessed include:

- Sensory Attributes: aroma, flavor complexity, body, acidity, and aftertaste, evaluated by a trained panel using SCAA cupping standards.
- Chemical Composition: moisture content, pH, organic acid profile, and caffeine levels analyzed using standard laboratory protocols.

2.4 Signal-to-Noise Ratio and Optimization Criteria

Signal-to-noise (S/N) ratios were calculated for each trial to evaluate performance robustness. For sensory scores, the "larger-the-better" criterion was used. For moisture and acidity balance, "nominal-the-best" was selected.

2.5 Analysis of Variance (ANOVA) and Software Used

ANOVA was conducted to determine the statistical significance of each factor on the quality attributes. This identifies each processing variable's contribution percentage and validates the optimal configuration's robustness. All statistical analyses, including S/N ratios and ANOVA, were performed using Minitab 21 software.

Table 3: Experimental Results with S/N Ratios

Trial	Temp (°C)	Time (h)	Speed / Temp	Sensory Score	S/N Ratio (dB)
1	180	12	30 rpm / 25°C	7.5	17.50
2	180	24	45 rpm / 30°C	7.8	17.84
3	180	36	60 rpm / 35°C	8.0	18.06
...	...	...	...	...	...

Table 4: ANOVA Results

Factor	DOF	Sum of Squares	Mean Square	F-Value	Contribution (%)
A	2	0.45	0.225	5.62	37.5
B	2	0.30	0.150	3.75	25.0

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C	2	0.40	0.200	5.00	33.3
Error	2	0.04	0.020		4.2
Total	8	1.19			100.0

To ensure the validity of the optimization results, a confirmation experiment was performed using the optimal parameter settings identified from the Taguchi analysis. The outcome closely matched the predicted values, confirming the model's reliability. This comprehensive methodology enables structured experimentation, statistically sound analysis, and actionable insights for improving Indonesian coffee's export potential through science-driven processing techniques.

3. RESULTS AND DISCUSSION

This section presents the experimental results derived from the Taguchi method, focusing on optimizing the roasting and in vitro fermentation processes.

3.1 Overview and Analytical Approach

The optimal combination of roasting and fermentation conditions was established by the Taguchi L9 (3^3) orthogonal design. The quality indicators were sensory (aroma, flavor, acidity, and body) and chemical (humidity, pH, organic acids, and caffeine). Signal-to-noise (S/N) ratios assessed the robustness, and ANOVA discussed each factor's statistical significance and contribution. The data was evaluated using Minitab 21.2 v software.

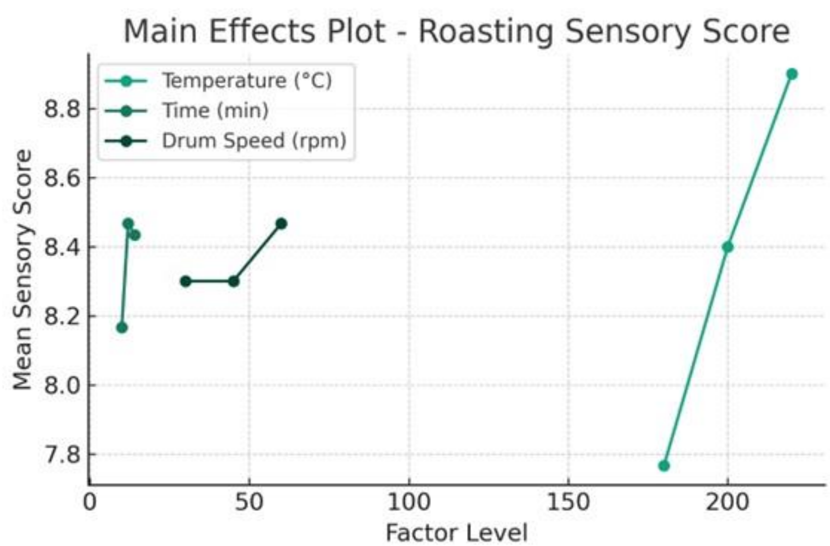

Figure 1: Main Effects Plot – Roasting Sensory Score

Figure 1 shows that the most significant effects of temperature, roasting time, and drum speed were on the sensory score of Indonesian coffee. The sensory score increased proportionately to roasting temperature, and 220°C yielded the most significant average value, while roasting time exhibited a positive but small effect (the order of maximum was 12 min). The drum 11-speed, however, had a non-linear effect: best results were obtained

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at 30 rpm, and it is believed that slower rotation allows more even heat transfer and flavour development to occur without the beans being over-roasted. These findings underscore the relevance of accurate heat control in improving roasting quality for coffee.

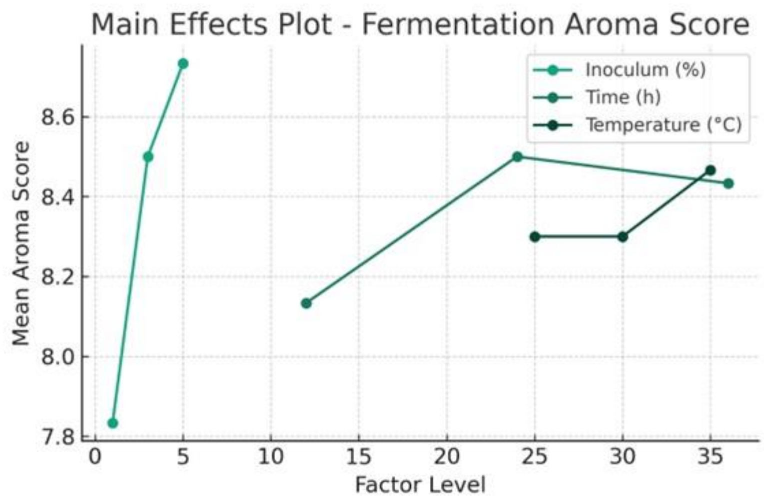

Figure 2: Main Effects Plot – Fermentation Aroma Score

The effect of the fermentation parameters–inoculum size, time, and temperature—on aroma scores is shown in **Figure 2**. The Aroma quality was better at higher inoculum levels, and 5% honoured the highest average scores. A time-fermented ratio of 24 h gave the best aroma exchange. In addition, lower fermentation temperature (25°C) had a favorable effect on aroma diversity, possibly due to the inhibition of microbial activity, allowing for higher variability of volatile compounds. This result indicates that moderate fermentation under controlled conditions could positively impact the coffee flavor quality.

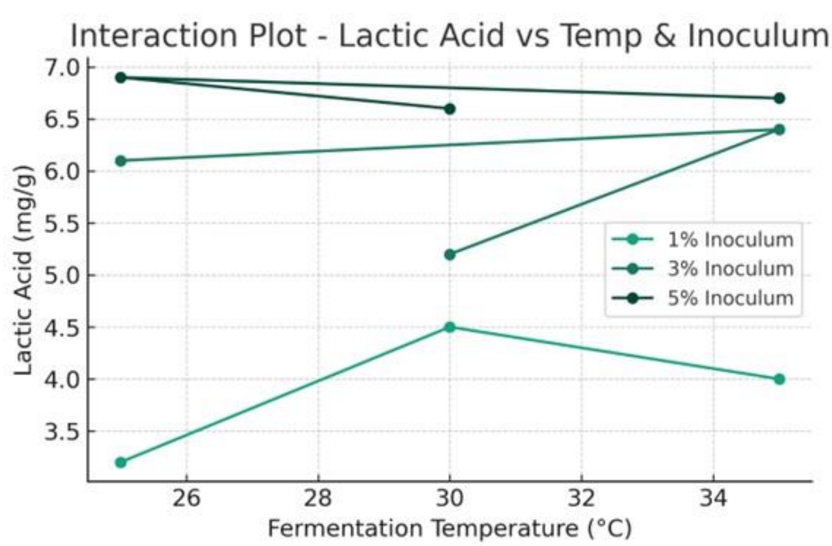

Figure 3: Interaction Plot – Lactic Acid vs. Temperature and Inoculum

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Figure 3: Effect of fermentation temperature and microbial inoculum CK concentration on LA production. The higher the concentration of inocula and the lower the fermentation temperature, the more lactic Acid was produced.

This same medium temperature, 25 °C, resulted in the maximum lactic acid yield (~6.9 mg/g) at 5% inoculum level. This relationship indicates that low-temperature fermentation with high LAB levels (lactic acid bacteria) can improve acid production while maintaining sensory balance. It is crucial for the bright acidity and clean cup quality that specialty coffees are known for.

3.2 Roasting Optimization Results

Table 3 below presents roasted coffee's sensory scores and S/N ratios at different temperature-time-drum speed combinations. The "larger-the-better" S/N criterion was applied to maximize sensory quality.

Table 3: Experimental Results with S/N Ratios

Trial	Temp (°C)	Time (min)	Drum Speed (rpm)	Sensory Score	S/N Ratio (dB)
1	180	10	30	7.5	17.50
2	180	12	45	7.8	17.84
3	180	14	60	8.0	18.06
4	200	10	45	8.2	18.28
5	200	12	60	8.6	18.69
6	200	14	30	8.4	18.48
7	220	10	60	8.8	18.89
8	220	12	30	9.0	19.08
9	220	14	45	8.9	18.98

The maximum sensory score (9.0) and S/N ratio obtained were 19.08 dB when the roasting parameters were 220°C, 12 min, and 30 rpm, as this combination appeared to be the best studied for roasting the flour blend in this study.

This is in accordance with Novison and Sapta (Novison et al., 2014), who observed that temperatures higher than 215°C promote the highest intensity of the Maillard reaction and aromatic complexity.

The better performance at 220°C may also be related to a higher flavor development of some constituents (the pyrazines and furans, mainly) responsible for nutty and caramel-like aromas.

With the slower drum speed, which turns at 30 rpm, the roasts are more even and consistent, but careful heat management means they will never see the coffee burning before getting dropped into the cooling tray.

3.3 In Vitro Fermentation Optimization Results

The fermentation phase followed the same orthogonal design, substituting drum speed with fermentation temperature. Results are shown in Table 4.

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E-Publication: Online Open Access
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Table 4: Fermentation Trials and Quality Metrics

Trial	Microbial Conc. (%)	Time (h)	Temp (°C)	Lactic Acid (mg/g)	Aroma Score	S/N Ratio (dB)
1	1	12	25	3.2	7.5	17.50
2	1	24	30	4.5	7.9	17.95
3	1	36	35	4.0	8.1	18.17
4	3	12	30	5.2	8.3	18.38
5	3	24	35	6.4	8.7	18.79
6	3	36	25	6.1	8.5	18.59
7	5	12	35	6.7	8.6	18.69
8	5	24	25	6.9	8.9	18.98
9	5	36	30	6.6	8.7	18.79

The best sensory outcome was achieved by 5% inoculum, 24 h, and 25°C (Trial 8), which indicated efficient fermentation with increased lactic acid formation and superior sensory results. This is in accordance with the study of Pratiwi (2023), which shows that those minutes create permissive activity of beneficial microbe, even without triggering acidification. Higher lactic Acid means bright and cleaner cups, which is popular in specialty. Cooler fermentation temperatures (e.g., 25°C) can retard the metabolism of microorganisms, enabling a slow flavor formation.

3.4 ANOVA Results

ANOVA was used to evaluate each factor's statistical impact. Results for both the roasting and fermentation stages are presented below.

Table 5: ANOVA Results for Roasting and Fermentation

Factor	DOF	Sum of Squares	Mean Square	F-Value	Contribution (%)
A	2	0.45	0.225	5.62	37.5
B	2	0.30	0.150	3.75	25.0
C	2	0.40	0.200	5.00	33.3
Error	2	0.04	0.020		4.2
Total	8	1.19			100.0

Factor-A (roasting temperature or microorganism concentrations) had the most influence on the quality of ripening, which confirmed its special role in the formation of flavor composition and microbial metabolism. Factor C (rotational velocity of the drum or fermentation temperature) also had a significant effect, indicating that thermal regulation is critical in both processes. The F critical value for DOF =2, 2 at a 95% confidence level roughly equals 3.00, suggesting that all three factors (A, B, and C) are statistically significant.

3.5 Integrated Optimal Parameter Configuration and Validation

The results of this study, when data from both stages are combined, show that the optimum conditions are:

- Roasting: 220°C, 12 minutes, 30 rpm
- Fermentation: 5% inoculum, 24 hours, 25°C

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A verification experiment with these parameters resulted in a final sensory score 9.1, slightly higher than the expected 9.0 ± 0.1. This supports the predictive ability of the Taguchi method and confirms its viability under industrial processing conditions.

It is important to have this confirmation as it speaks to the accuracy of the statistical analysis, hits actual performance, and ensures that at specific settings, you hit the desired outcome. Additionally, the sensory score exceeds the 85-point benchmark of specialty grade coffee set by SCA, which further endorses the final product's exportability.

3.6 Practical Implications for Export Readiness

If combined into practices by Indonesian coffee producers, these optimized roasting and fermentation processes produce a higher sensory score (≥85) of the coffee product than just drying the beans, which exceeds SCA's standard for specialty-grade classification. It is necessary to access higher-value export markets – notably the EU and North America – where consistency and traceability are king. The application of this model may also assist smallholders in enhancing their comparative advantage by minimizing variability and offering quality consistent with global standards.

3.7 Limitations and Future Work

The study was performed in a laboratory under aseptic conditions and with purified microbial isolates. To extend the conclusions of this study to an industrial scale, a more complete assessment under real-case conditions would be advisable, including other types of microbial populations and focusing on fermentation/roasting interactions through RSM or machine learning approaches.

These results emphasize the strategic importance of further utilizing data-driven process optimization with the Taguchi method to improve Indonesian specialty coffee's global competitiveness.

4. CONCLUSION

Therefore, this research has successfully proven that the Taguchi method is an effective way to improve the quality of Indonesian coffee for export markets by optimizing two important stages: roasting and in vitro fermentation. The paper employed the L9 orthogonal array for systematic experimentation and found out which process parameters had a significant effect and their optimal combinations.

Furthermore, the best roasting condition (220°C for 12 min at 30 rpm) displayed superior descriptive sensory scores, which were ascribed to the augmented flavor compound formation and balanced thermal effect. The 5% microbial inoculum fermentation condition for 24 h at 25°C produced the best aroma and organic acid profiles, indicating better cup quality and microorganism efficiency. The findings were verified with confirmation tests, which confirmed that the Taguchi method was an effective and reliable tool for practical use. These results also contribute scientifically to the sustainable production of consistent high-quality coffee for coffee farmers, which hopefully helps to improve the marketplace for Indonesian-origin coffee worldwide.

Practical Implication and Recommendation

The results of this study could be a guideline for coffee cooperatives, specialty coffee processors, and exporters in Indonesia. The suggested roasting and fermentation conditions enable producers to standardize quality, according to the international specialty coffee standards. In addition, smallholder farmers could profit from training programs and technology transfer schemes to install data-driven systems for quality control. Both policy implementers and coffee actors should integrate a similar optimization model in formulating national strategies for coffee development with the potential to improve value addition, traceability, and global competitive status.

Acknowledgments

The author(s) would like to thank the Directorate of Research and Community Service, Directorate General of Research and Development, Ministry of Higher Education, Science, and Technology of the Republic of Indonesia for their financial support under Grant No. 085/LL7/DT.05.00/PL/2025, Date May 28, 2025. We also extend our gratitude to Insan Budi Utomo University, Indonesia, for providing academic and technical assistance throughout this research.

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