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Innovating Coffee Production: Integrating Anaerobic Carbonic Maceration Technology to Achieve International Standards

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Abstract

In the coffee industry, product quality is a key factor in competing in the international market. The Teaching Factory (TEFA) at Polije faces challenges in maintaining quality consistency and meeting international standards. This study aims to implement Anaerobic Carbonic Maceration (ACM) technology in the coffee fermentation process at TEFA Polije to enhance the quality of the produced coffee. The methods used include technical training for workers on the operation and maintenance of ACM technology, the application of strict quality protocols, and the optimization of the logistics system from raw material management to product distribution. Data were collected through sensory evaluation and interviews with workers. The results indicate that the implementation of ACM technology significantly improves the coffee's aroma and flavor profile, as well as the consistency of bean texture, aligning with international standards. The evaluation shows that 80% of workers were able to operate the technology correctly, and 75% of the products met premium standards after implementation. The conclusion of this study is that ACM technology is effective in improving the quality of TEFA Polije coffee while also creating opportunities for expansion into the international market.

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INTRODUCTION

The coffee industry in Indonesia continues to experience significant growth, with increasing domestic consumption and expanding exports (Desnky et al., 2018; Lubis et al., 2022). In this context, the Teaching Factory (TEFA) for Coffee Processing at Politeknik Negeri Jember (Polije) operates on a relatively small scale, with an average production capacity of 50 kg per month. TEFA focuses exclusively on producing robusta coffee, which, while limiting product diversification, allows for specialization and expertise development in this niche. The primary supplier for TEFA, located in Panti, Jember, provides a strategic advantage as the region is renowned for producing high-quality robusta coffee in Indonesia.

Despite these advantages, TEFA faces challenges related to production scale, particularly due to limited roasting capacity, which is only 2 and 10 kg per batch. While this capacity may be sufficient for small-scale boutique operations focusing on quality, it becomes a constraint when

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demand increases significantly (Fortuna, 2018; Sinulingga et al., 2023). Thus, efficiency and optimization in the roasting process are critical factors in maximizing output within the available capacity.

Furthermore, TEFA primarily produces and sells ground coffee, allowing for standardized production and operational efficiency. However, this limitation also makes TEFA more vulnerable to shifts in market trends, which increasingly favor diverse coffee products, including whole beans and various extraction methods. Another challenge is TEFA's reliance on a single primary supplier (coffee farmers in Panti, Jember) which presents risks concerning supply stability and consistency in raw material quality. While this dependency facilitates strong relationships and better quality control, diversifying supply sources could enhance supply security and broaden the flavor profile of the products.

As the coffee market grows increasingly competitive, with rising consumer demand for high-quality and sustainable products, TEFA has the potential to capitalize on these trends through quality improvement and effective marketing strategies. Collaborative efforts with local coffee farmers in product development, research on new coffee varieties, and the implementation of sustainable agricultural practices could offer a competitive edge and strengthen TEFA's position in the industry. Given these considerations, this study aims to analyze the factors influencing the efficiency of TEFA's coffee production at Politeknik Negeri Jember, particularly in terms of roasting capacity, supply chain management, and marketing strategies. It seeks to identify potential product diversification and strategies for increasing production capacity to enhance TEFA's competitiveness in the national coffee industry. Furthermore, this research evaluates the impact of implementing sustainability-based production and marketing strategies on TEFA's operational growth and stability. Ultimately, this study aims to provide strategic recommendations for improving TEFA's production efficiency, expanding its market reach, and strengthening its collaboration with local coffee farmers as part of a long-term development strategy. By addressing these objectives, TEFA is expected to optimize its operations, enhance its competitiveness in the coffee industry, and contribute to the empowerment of local farmers while fostering a more sustainable coffee ecosystem. The solutions for addressing the challenges in this community service project are presented in Table 1.

Table 1. Solutions to Challenges in the Community Service Program

No	Solution	Description
1	Implementation of Anaerobic Carbonic Maceration (ACM) Technology	The strategic steps include: 1. Training and Skill Development: Conducting training sessions on ACM principles and practices, including fermentation management and quality monitoring. 2. Investment in Equipment: Acquiring ACM fermentation equipment, such as sealed tanks that regulate pressure and gas composition. 3. Development of Fermentation Protocols: Formulating specific fermentation protocols for Robusta coffee from Panti, Jember
2	Product Innovation	Developing new products by leveraging ACM fermentation: 1. Introduction of Whole Bean Coffee: Expanding the product line by introducing whole bean coffee in addition to ground coffee. 2. Specialty and Limited-Edition Coffee: Utilizing specialty fermentation batches to produce premium coffee with unique flavor profiles. 3. Sustainable Packaging and Branding: Implementing eco-friendly packaging and branding that highlights sustainability.
3	Production Capacity Enhancement	Increasing production capacity through the following strategies: 1. Optimization of Roasting Processes: Assessing and improving roasting efficiency using advanced roasters. 2. Expansion of Production Facilities: Expanding production space to support ACM processes and accommodate higher production volumes. 3. Efficient Supply Chain Management: Enhancing logistics systems to

		ensure raw material availability and smooth product distribution.
4	Diversification and Supply Stability	Reducing risks by expanding supplier networks: 1. Collaboration with Other Local Farmers: Establishing relationships with additional farmers to diversify and explore new coffee varieties. 2. Farmer Capacity-Building Programs: Providing training and technical support to help farmers improve quality and sustainability
5	Marketing Strategy and Market Penetration	Developing a comprehensive marketing approach: 1. Digital Marketing and Social Media: Utilizing digital platforms for product promotion and consumer engagement. 2. Partnerships with Key Stakeholders: Collaborating with cafés, restaurants, and distributors to expand market reach. 3. Participation in Coffee Exhibitions and Competitions: Showcasing products at exhibitions and competitions to build brand reputation.
6	Community Engagement and Sustainability	Strengthening community relations and promoting sustainability: 1. Community Education Programs: Organizing workshops and seminars on coffee and sustainability for both local communities and consumers. 2. Sustainability Initiatives: Implementing sustainable practices, from waste management to the adoption of renewable energy.

METHOD

Anaerobic Carbonic Maceration (ACM) is a fermentation method conducted in an airtight environment with the injection of carbon dioxide gas to control the microbial metabolism process within coffee beans. This technique allows for the development of a more complex flavor profile, enhances balanced acidity levels, and produces richer and more unique aroma characteristics compared to conventional fermentation methods. Carbonic Maceration in coffee processing is a fermentation process aimed at enhancing the taste and aroma quality of coffee (Mangku et al., 2022). The process begins with cherry flotation, where coffee cherries are separated based on their density—floating and sinking cherries—since sinking cherries typically indicate better quality. Next, 25 kg of sinking cherries are weighed and placed into a sealed fermentation tank or barrel. At this stage, CO_2 gas is injected into the tank to create an anaerobic environment, allowing controlled fermentation to occur without oxygen exposure (Du et al., 2023). The fermentation process is monitored to determine when it is complete, based on changes in the coffee beans, including variations in color, texture, and aroma.

Once fermentation is complete, the coffee beans are removed and dried until they reach a moisture content of 12%. Proper drying is crucial to maintaining quality and preventing mold growth, which can damage the coffee beans (Batista et al., 2017). After reaching the desired moisture level, the beans undergo hulling, a process that removes the outer layer of the beans (Franco et al., 2016).

Following hulling, the coffee beans are sorted to remove defective beans, ensuring optimal quality before the roasting stage (Ferreira et al., 2019). High-quality beans are then roasted to develop their distinctive flavor profiles (Illy & Viani, 2005). The final stage is cupping, where the brewed coffee is tested by consumers or expert panels to assess its taste and aroma (Specialty Coffee Association, 2018). This systematic process aims to produce premium-quality coffee that meets international standards while delivering a unique sensory experience to consumers (Leroy et al., 2006; Specialty Coffee Association, 2020).

Below is a flowchart illustrating the Carbonic Maceration method steps:

Figure 1. Steps of the Carbonic Maceration Method

RESULTS AND DISCUSSION

Below is the before-and-after table for each activity in the Community Service program that has been accomplished:

NO	ACTIVITY	BEFORE CONDITION	AFTER CONDITION
1	Technical Training on Anaerobic Carbonic Maceration Technology Operations	Before the training, TEFA Coffee Processing workers had basic knowledge of coffee fermentation but lacked understanding of the more advanced Anaerobic Carbonic Maceration technology. Operational processes were still carried out manually without a deep understanding of the new technology procedures, leading to operational errors and inconsistency in product results.	After the training, 80% of TEFA workers were able to understand and operate the new fermentation technology by following the established standard operating procedures. They were also able to perform maintenance and troubleshooting if issues arose and apply product quality protocols with at least 70% accuracy. As a result, the coffee production process became more consistent and aligned with international quality standards.
2	Implementation of	Before the implementation of the	After the implementation of the standards,

	Coffee Product Quality Standards	standards, TEFA coffee products often experienced fluctuations in quality, including aroma, flavor, and bean texture. The lack of standardized procedures made it difficult for products to meet international market expectations.	80% of TEFA coffee products met international quality standards, including aroma profile, flavor, and texture consistency. Sensory testing showed that the coffee products achieved premium quality in line with global market expectations.
3	Skill Enhancement for Workers through Training and Workshops	Before the training, TEFA workers only had basic skills in coffee fermentation processes and had not mastered quality control techniques and comprehensive workplace safety protocols.	After the training, 80% of the trainees were able to master and practice new techniques in the coffee fermentation process and quality control. They also applied workplace safety and cleanliness protocols effectively, as demonstrated by practical work evaluations, with at least 70% of the workforce reaching the expected competency level.

1. Introduction to the Anaerobic Carbonic Maceration Method

This training started with an introduction to the theory and practice related to the Anaerobic Carbonic Maceration (ACM) method for Robusta coffee. Participants were trained to understand the basic principles of anaerobic fermentation using CO2 gas to create an oxygen-free environment, aiming to influence the coffee's flavor profile. This stage was illustrated with demonstrations and explanations of the necessary equipment, including fermentation tanks and CO2 injection systems.

Figure 2. Training Photo

2. Coffee Cherry Separation and Selection

The first step in this process is the flotation, where coffee cherries are separated based on their density (floating and sinking). The sinking cherries are selected because they have better quality and flavor potential. In this training, participants were taught to manually perform flotation and how to recognize the ideal cherries for the next steps.

3. CO2 Injection and Fermentation Observation

After collecting the sinking cherries, participants weighed and placed them into fermentation tanks with a capacity of 25 kilograms. In this stage, participants learned how to inject CO2 into the fermentation tank with the correct pressure. During fermentation, they were asked to observe and record the fermentation duration and changes in the coffee beans. The

observations revealed that fermentation duration significantly affects the coffee's aroma and flavor.

Figure 3. CO2 Injection Process

4. Fermentation Results and Drying

Once fermentation was complete, the beans were removed from the tank and dried until their moisture content reached 12%. Participants were taught proper drying techniques to avoid mold growth and preserve the quality of the beans. Moisture content was measured using a specialized moisture meter, and participants practiced how to use the device for accurate results.

5. Hulling and Sorting

The next stage is hulling, where the coffee beans are peeled from their outer layers. Participants had the opportunity to use the hulling machine and learned how to operate and maintain it. After hulling, participants manually sorted the beans to separate defective beans from the high-quality ones. This sorting ensures that only high-quality beans are used in the roasting process.

6. Roasting and Flavor Profiling

Participants were also trained in the roasting process using a small-scale roasting machine. This stage is crucial as the roasting duration and temperature determine the final flavor profile of the coffee. Participants tried different roasting profiles and compared the results, finding that roasting at specific temperatures and durations produced the desired flavor and aroma, in line with international standards.

7. Sensory Testing and Consumer Trials

After roasting, the coffee was tested in a cupping session where participants and consumers were invited to assess the quality of the brewed coffee. This sensory testing included evaluating the aroma, taste, aftertaste, and body of the coffee. The results showed that coffee processed using the ACM method had a more complex flavor profile and stronger aroma compared to traditionally processed coffee.

8. Fermentation Duration Evaluation
One important variable in the ACM method is fermentation duration. Through intensive observation and evaluation, it was found that overly long fermentation led to a too-acidic taste that was less favored by consumers. In contrast, shorter fermentation tended to produce a smoother aroma and a more balanced flavor profile.

9. Moisture Content and Coffee Quality
The drying process, which reduces the moisture content to 12%, is crucial in determining the final quality of the coffee. If the moisture content is too high, the coffee is more susceptible to mold contamination, while too low moisture content can damage the bean's texture. Participants successfully applied optimal drying techniques, resulting in coffee with the ideal moisture content for further processing.

10. Processing Results and Coffee Quality
The overall results showed a significant improvement in the quality of coffee beans processed using the ACM method. The produced beans had an intense fruity aroma, natural sweetness, and a thick body, which distinguished them from conventional Robusta coffee. This demonstrates that the ACM method can produce premium-quality coffee that meets international standards.

Figure 4. Anaerobic Process Coffee Results

11. Effectiveness of Technical Training
The training proved effective in enhancing the participants' understanding and skills in using the ACM fermentation technology. Evaluations showed that 85% of participants were able to operate the equipment and correctly apply the procedures after the training. This reflects the great potential for implementing this technology at TEFA Polije to improve coffee production capacity and quality.

12. Challenges and Solutions in Implementation
During the training, several challenges arose, such as participants' lack of experience in operating the roasting and hulling machines. The solution was to provide additional hands-on practice sessions and equipment usage simulations with intensive guidance. Post-training evaluations showed improvement in participants' competence after these additional sessions.

13. Economic Analysis and Market Opportunities
The training results indicated that the coffee produced has great potential for being marketed as premium coffee at a higher price. By differentiating the product through the ACM method, TEFA Polije has the opportunity to enter the international specialty coffee market, offering added value and higher revenue.

14. Long-Term Prospects for Implementation
The implementation of ACM technology at TEFA Polije is expected to be widely adopted by local coffee farmers and producers in the surrounding area, providing a positive impact on the local

economy. By establishing a consistent and stable supplier network, TEFA Polije could become a center for high-quality coffee production that can compete in the global market.

15. Recommendations and Follow-up

Based on the results of the training, it is recommended that TEFA Polije continue to expand the training to local coffee farmers to adopt the ACM technology. Furthermore, improving production facilities and the logistics system will support larger and more efficient production scales. With ongoing collaboration and further development, this technology has the potential to become a successful model for the coffee industry development in Indonesia.

CONCLUSION

The conclusion of the training on the application of the Anaerobic Carbonic Maceration (ACM) method at TEFA Polije shows that this technology is effective in improving the quality and competitiveness of Robusta coffee. The method successfully created coffee with a more complex flavor profile and strong aroma, meeting international standards. Training evaluations revealed that 85% of participants were able to operate the equipment and apply ACM procedures correctly, demonstrating that the training program was effective in improving workforce skills.

The optimized fermentation process, proper drying to 12% moisture content, and controlled roasting techniques all contributed to the production of premium-quality coffee. Furthermore, product differentiation through the ACM method opens up broader market opportunities, particularly in the international specialty coffee segment. Therefore, ACM technology is expected to be more widely adopted by local coffee producers and serve as a sustainable strategy to strengthen Indonesia's coffee position in the global market.

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