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Research article

Development and Performance Analysis of an Improved Biomass Stove for Krajood Dyeing: A Sustainable Appropriate Technology Approach

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Abstract: This research developed an improved biomass stove for dyeing Krajood (*Lepironia articulata*) as a sustainable, appropriate technology for small-scale industry applications. The new design features an integrated water reserve tank, improved combustion chamber, heat shield, and robust support structure while maintaining operational simplicity. Performance evaluation revealed the improved stove reduced PM2.5 emissions at the operator position by 72.25% (from 191±16 to 53±7 μg/m^3, p=0.0002), decreased water boiling time by 32.73% (from 55±6 to 37±3 minutes, p=0.0097), shortened dyeing time by 52.43% (from 103±7 to 49±3 minutes, p=0.0006), and lowered ambient temperature at the operator position by 46.45% (from 62.0±4.8°C to 33.2±1.7°C, p=0.0003). These improvements collectively enabled a five-fold increase in daily production capacity from 20 bundles (44 kg) to 100 bundles (220 kg) in an 8-hour workday. Colorimetric analysis confirmed no significant differences in L*a*b* values between traditionally and newly dyed Krajood at all measurement positions (p>0.05), ensuring quality preservation despite the process modifications. Economic assessment indicates the 71.4% higher initial investment (12,000 vs. 7,000 THB) is rapidly offset by productivity gains. The design exemplifies appropriate technology principles through its simplicity, local material utilization, and alignment with existing production knowledge. This improved stove addresses critical health and efficiency constraints in traditional Krajood processing while preserving product quality, demonstrating how targeted technological interventions can enhance traditional craft productivity and worker wellbeing in rural communities.

Keywords: Biomass stove; krajood dyeing; appropriate technology; sustainable development; particulate matter reduction

1. Introduction

Krajood (*Lepironia articulata*) is a sedge plant that grows in wetland areas, characterized by its cylindrical green stems reaching heights of 1-2 meters. This plant possesses natural qualities of durability, flexibility, and resilience that make it particularly suitable for creating woven products [1]. In Thailand, especially in the central southern provinces of Nakhon Si Thammarat and Phatthalung, communities have developed a cultural heritage of transforming Krajood into various handicraft items, including bags, mats, baskets, fans, hats, and coasters. The economic significance of Krajood extends beyond preserving traditional knowledge; it represents a primary source of income for communities in areas such as Thale Noi, Phanang Tung, and Chai Buri districts in Phatthalung Province. These crafts embody local wisdom passed down through multiple generations and contribute significantly to sustainable rural livelihoods [1]. The integration of Krajood crafting into creative economic development initiatives has further enhanced its importance in community-based production systems.

The transformation of Krajood into marketable products involves several processing steps, including harvesting, selection by length and size, mud soaking to enhance durability, sun drying, pressing, dyeing for aesthetic appeal, weaving, and final decoration. Among these processes, the dyeing step presents challenges in traditional production systems. The conventional dyeing method employs local wisdom techniques that utilize a rectangular container placed on brick supports referred to as a "Sao stove." This setup uses firewood as a heat source, with limited control over combustion efficiency. The traditional method can typically process only 20 bundles (approximately 44 kilograms) of Krajood within one working day (8 hours), creating a production bottleneck. Additionally, this open-flame design exposes operators to significant heat stress and particulate matter emissions, potentially compromising both health and working comfort. The traditional Krajood dyeing system suffers from numerous inefficiencies, including limited production capacity, prolonged boiling and dyeing times, high PM2.5 emissions that pose health risks, excessive heat exposure for operators, substantial thermal energy loss to the environment, and inability to maintain water temperature between dyeing batches, all of which reduce productivity and worker comfort.

Appropriate technology represents an approach to technological development that prioritizes solutions aligned with the specific needs, resources, and context of users. According to Dezord *et al*. [2], appropriate technology is characterized by design adaptations that suit user requirements while maintaining low costs, easy maintenance, and accessibility through locally available resources. This concept extends beyond mere technical functionality to encompass contextual suitability, sustainability, environmental friendliness, and the ability to address real community problems [3]. The fundamental principles of appropriate technology emphasize simplicity and sustainability. As noted by Lyman and Chung [4], effective appropriate technology incorporates participatory design elements that enhance social impact through direct engagement with community needs and capabilities. This approach ensures that technological interventions remain relevant, adoptable, and maintainable within local contexts. In the context of Krajood dyeing, appropriate technology must address the specific challenges faced by artisans while respecting cultural practices and economic constraints. The development of improved biomass stoves represents an opportunity to enhance productivity and working conditions without disrupting established production knowledge or requiring prohibitive investments.

This research aims to develop an enhanced biomass stove system for dyeing Krajood that increases work efficiency while adhering to appropriate technology principles. The specific design goals include creation of a dyeing system with minimal complexity to facilitate ease of use and maintenance, development of a configuration that reduces operator exposure to heat and harmful emissions, integration of a water reserve system to minimize waiting time between dyeing batches, design of a combustion chamber that improves fuel efficiency and heat transfer, implementation of features that maintain consistent dyeing quality compared to traditional methods, utilization of locally available materials to enable local production and repair, and ensuring affordability and economic viability within the context of small-scale Krajood production.

2. Materials and Methods

2.1 Design and construction of the new biomass stove

The traditional biomass stove for Krajood dyeing consists of a simple open fire stove (Figure 1a). This traditional biomass stove was made of a concrete brick with a height of 27 cm that elevates the container and creates a combustion space, and an open combustion area beneath the container for burning biomass fuel (typically wood). The dyeing container is a rectangular metal steel with a size of 25 cm × 70 cm × 25 cm. This traditional design represents local wisdom but suffers from several limitations, including heat loss, smoke exposure, and limited production capacity, as noted by Zube [5] in studies of similar open-design biomass cooking systems. The improved biomass stove design (Figure 1b) incorporates several significant modifications while maintaining operational simplicity in accordance with appropriate technology principles [2]. Key design features include Integrated dyeing and water reserve containers: A corrosion-resistant metal sheet container (65 cm width × 100 cm length × 35 cm height) divided into two sections—a 40 cm wide dyeing chamber and a 25 cm wide hot water reserve chamber. This design allows for continuous operation by maintaining a supply of pre-heated water. Elevated support frame: A metal frame support structure (65 cm width × 100 cm length × 50 cm height) constructed from welded metal bars, featuring four corner posts extending 25 cm above the frame to secure the dyeing container and a 1.5 mm thick metal sheet (65 cm width × 45 cm height) installed at the rear to shield operators from heat. The biomass stove is made of 1.2 mm steel, providing better thermal conductivity, reflection, and radiation properties than the simple open fire stove [6-7] and is formed into a cylindrical container with a diameter of 58 cm and a height of 45 cm. The upper side wall opens a 40 cm wide and 15 cm high rectangular compartment to serve as a biomass fuel feeder, and a plate is installed at the bottom of the compartment to help support the biomass fuel. Inside the biomass stove, there is a steel frame reinforced with angle steel and round bars, and an expanded metal grate to support the biomass fuel. It is 20 cm high from the bottom of the biomass stove. Improved combustion chamber: A redesigned biomass stove positioned beneath the support frame, featuring controlled air intake to enhance combustion efficiency similar to designs evaluated by Bentson *et al*. [8]. Biomass support system: An extended rack to support longer pieces of biomass fuel, preventing spillage and enabling more effective fuel feeding. The new design prioritizes simplicity for ease of maintenance and repair while addressing the core inefficiencies of the traditional system. All materials were selected based on local availability to ensure sustainability and economic feasibility.

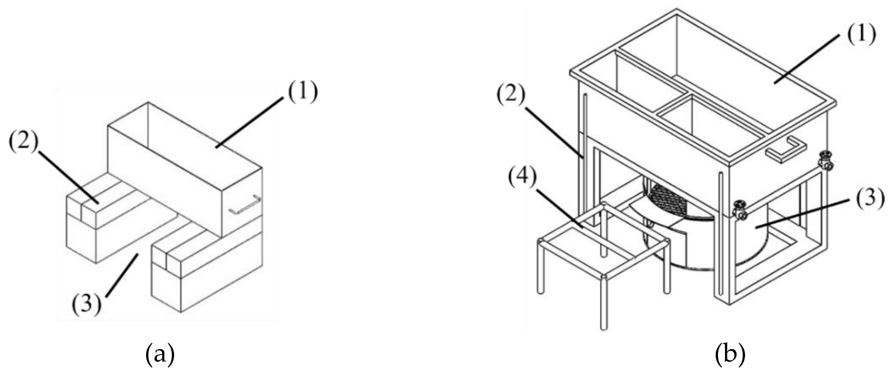

Figure 1. The design of a set of biomass stoves for krajood dyeing. (a) traditional biomass stove (b) improve biomass stove

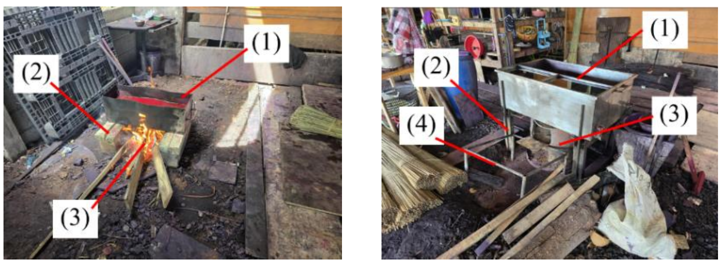

Figure 2. Dyeing of krajood using a biomass stove. (a) traditional stove (b) improve biomass stove

2.2 Experimental setup and testing procedures

The experimental evaluation followed a comparative methodology to assess performance differences between the traditional and improved biomass stove designs. The testing procedures were conducted under controlled conditions with the following protocol. Preparation of test materials: Three bundles of Krajood, each weighing 2.2 kilograms (6.6 kilograms total), measured using a digital scale (CTS model DRC-15), 25 liters of water at ambient temperature for each dyeing test, and Standard dyeing agents prepared according to traditional formulations. Testing sequence: Both stove types were prepared and ignited with equivalent biomass fuel. Water was heated to the boiling point with measurements recorded continuously, Krajood bundles were processed through complete dyeing cycles, and Dyed Krajood samples were dried under standardized conditions for color evaluation. Replication: Tests were repeated three times for each stove design to ensure statistical reliability, and environmental conditions (ambient temperature, humidity) were recorded and maintained within a controlled range across all tests.

2.3 Measurement parameters and analytical methods

Particulate matter (PM2.5) concentrations were measured at the operator's position using a portable particle counter (CEM model DT9881) in accordance with methodologies used by Bentson *et al.* [8] for biomass combustion systems. Measurements were recorded at 15-minute intervals throughout the dyeing process to capture variations during different operational phases. Thermal performance was evaluated through multiple parameters:

1. Water boiling time: The time required to bring 20 liters of water from an ambient temperature to boiling point (100°C) was measured using a digital timer.

2. Operator position temperature: Ambient temperature at the standard operator position (0.5 meters from the stove at a height of 1.5 meters) was measured using a Fluke 54-2B thermometer with a Fluke 80pk-22 probe as utilized in similar studies by Hafner *et al.* [9].

3. Dyeing time: The total processing time for completing the dyeing cycle for all three Krajood bundles (6.6 kg) was recorded.

The color quality of dyed Krajood was analyzed using a colorimeter (Hunter Lab, Konica; Japan) to measure L* *a** b* color values [10]. Measurements were taken at three positions on each Krajood sample base section (closest to the root), middle section, and end section (tip of the Krajood). This comprehensive color analysis approach was used to determine whether the improved stove design maintained consistent dyeing quality compared to the traditional method. Statistical analysis was performed using independent t-tests at a significant level of 0.05. Production capacity was calculated based on the dyeing cycle time and the maximum loading capacity of each stove design. This was extrapolated to determine the number of Krajood bundles that could be processed in a standard 8-hour workday, providing practical data for economic assessment of the technology. Cost-benefit analysis was conducted by comparing initial investment costs for both stove designs, operational costs including fuel consumption and labor requirements, productivity differences in terms of throughput capacity, and expected service life based on construction materials and design. This economic assessment followed approaches recommended by Lyman and Chung [4] for appropriate technology evaluation in community-based production systems.

3. Results and Discussion

3.1 Reduction in PM2.5 emissions

The comparative analysis of PM2.5 emissions between the traditional and improved biomass stoves revealed significant differences in particulate matter concentrations at the operator position. As illustrated in Figure 3, the improved biomass stove design produced substantially lower PM2.5 emissions (53±7 $\mu g/m^3$) compared to the traditional design (191±16 $\mu g/m^3$). Statistical analysis confirmed that this 72.25% reduction was significant at the $p = 0.0002$ level. The substantial decrease in PM2.5 emissions can be attributed to several design improvements in the new stove. First, the improved combustion chamber incorporated dedicated air intake channels that enhanced combustion efficiency. This finding aligns with research by Bentson *et al*. [6], who demonstrated that forced jets of primary air in biomass cookstoves significantly improved combustion completeness, thereby reducing particulate emissions. The presence of controlled airflow into the combustion chamber of the improved design facilitated more complete burning of volatile compounds that would otherwise contribute to PM2.5 formation. Second, the installation of a heat shield at the operator's position in the improved design effectively redirected smoke and particulate flow away from the user. This simple structural modification substantially reduced operator exposure to combustion byproducts. As noted by Hafner *et al*. [9], even modest modifications to stove structure can significantly alter heat and emission pathways, resulting in improved operator safety without necessarily requiring complex technological interventions. It is worth noting that while the improved design achieved a substantial reduction in PM2.5 emissions, the measured concentration (53±7 μg/m³) still exceeds the World Health Organization's recommended 24-hour exposure limit of 15 μg/m³ [11]. This suggests that while significant improvements have been achieved, additional modifications, such as a chimney system or further combustion optimization, might be warranted in future iterations to further reduce operator exposure to particulate matter.

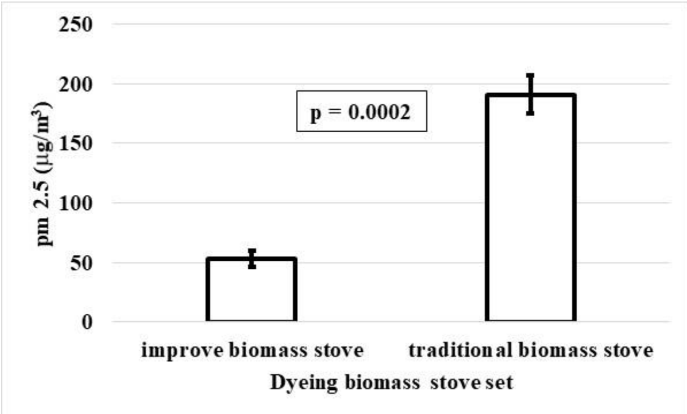

Figure 3. Comparison of PM 2.5 levels from the krajood dyeing process (n = 3).

3.2 Decreased water boiling time

The time required to bring 20 liters of water to a boil showed marked improvement with the new stove design. As shown in Figure 4, the improved biomass stove achieved boiling in 37±3 minutes compared to 55±6 minutes for the traditional design. This 32.73% reduction in boiling time was statistically significant ($p = 0.0097$). This decrease in water boiling time can be attributed to two primary design factors. First, the combustion chamber walls in the improved design effectively contained and directed heat upward toward the container, minimizing lateral heat loss to the surrounding environment. This improvement is due to the superior thermal conduction, reflection, and radiation characteristics of the metal-steel combustion chamber in the improved biomass stove compared to traditional biomass open-fire stoves [6-7]. Zube [5] identified similar principles in improved cooking stove designs, noting that heat transfer efficiency is substantially improved when combustion is contained within a defined chamber rather than in an open configuration. Second, the elevated grate design in the improved stove facilitated better air circulation beneath the fuel, promoting more complete combustion and higher flame temperatures. This design element creates what Bentson *et al*. [8] describe as a "high-power combustion zone" where primary air mixes with fuel gases to achieve more efficient burning. The result is more effective heat transfer to the dyeing container and, consequently, faster water heating. The practical implication of this reduced boiling time is significant for production workflow, as it reduces the initial setup time before dyeing can begin and increases the number of dyeing cycles that can be completed in a workday.

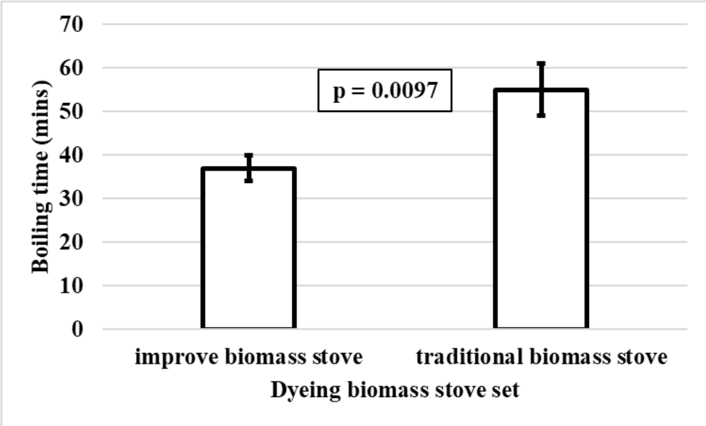

Figure 4. Comparison of the boiling time of water (n = 3).

3.3 Shortened dyeing time

The total time required to complete the dyeing process for three bundles of Krajood (6.6 kg) showed the most dramatic improvement among all measured parameters. As presented in Figure 5, the improved stove completed the dyeing process in 49±3 minutes, while the traditional stove required 103±7 minutes. This represents a 52.43% reduction in processing time ($p = 0.0006$). The substantial time savings can be primarily attributed to the integration of the hot water reserve tank in the improved design. This innovative feature maintains a continuous supply of pre-heated water that can be immediately transferred to the dyeing chamber when needed. In contrast, the traditional method requires operators to add ambient temperature water when levels decrease, necessitating additional heating time before dyeing can resume. This finding highlights how relatively simple design modifications can dramatically improve process efficiency when applied with careful consideration of workflow bottlenecks. The principle aligns with appropriate technology concepts described by Dezord *et al.* [2], where modest technological adaptations targeted at specific workflow constraints can yield disproportionate productivity benefits. The practical implication of this time reduction is substantial. Under an 8-hour workday scenario, the improved stove enables processing of approximately 100 bundles (220 kg) of Krajood compared to just 20 bundles (44 kg) with the traditional system—a five-fold increase in productivity.

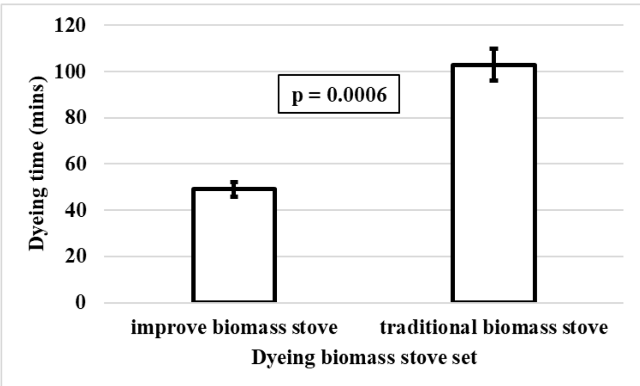

Figure 5. Comparison of dyeing time of krajood (n = 3).

3.4 Lower operating temperature

Ambient temperature measurements at the operator position revealed significant differences between the two stove designs. As shown in Figure 6, the improved stove design maintained a substantially lower temperature at the operator position (33.2±1.7°C) compared to the traditional stove (62.0±4.8°C). This 46.45% reduction in ambient temperature was statistically significant ($p = 0.0003$). The marked reduction in operator-position temperature can be attributed primarily to the 1.5 mm thick metal heat shield installed at the rear of the improved stove design. This barrier effectively blocks direct thermal radiation from the combustion chamber and redirects it away from the operator. This result is in good agreement with the previous reports [9, 12, 6, 13]. Hafner *et al*. [9] observed similar benefits from heat shielding in improved cooking stove designs, noting that strategic placement of simple barriers can significantly improve operator comfort without compromising thermal efficiency. Liu *et al*. [12] discovered that installing a radiation shield between the combustion chamber walls would effectively control the temperature outside the stove. MacCarty and Bryden [6] reported that the shield can reduce the heat energy loss from the flame of a biomass stove. Yunusa *et al*. [13] have reported that the use of a shield to reflect heat radiation prevents heat radiation from being released to the outside. In contrast, the traditional brick support system creates an open combustion area that allows heat to radiate freely in all directions, resulting in substantially higher temperatures at the operator position. This unrestricted heat transfer not only creates uncomfortable working conditions but also represents wasted thermal energy that could otherwise contribute to the dyeing process. The lower operating temperature has important implications for both worker comfort and safety. Extended exposure to high temperatures can contribute to heat stress and fatigue, particularly in tropical environments where ambient temperatures are already elevated. The improved design creates more tolerable working conditions that may contribute to sustained productivity over full workdays.

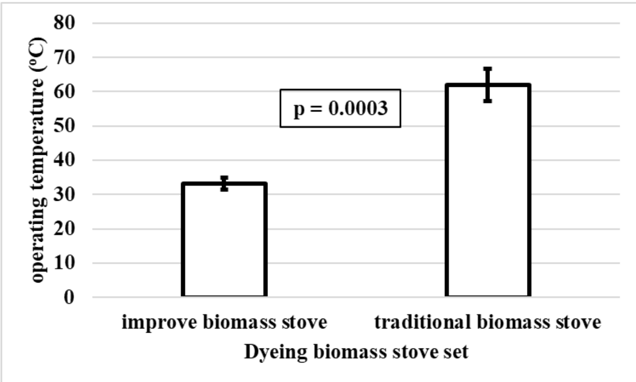

Figure 6. Comparison of the krajood dyeing operating temperature (n = 3).

3.5 Color quality comparison

A critical requirement for any improved Krajood dyeing technology is the maintenance of product quality. The color quality analysis aimed to determine whether the improved stove design affected the dyeing outcomes compared to the traditional method. As presented in Table 1, comprehensive colorimetric measurements (L*a*b* values) were taken at three positions on the Krajood (base, middle, and end). Statistical analysis using independent t-tests revealed no significant differences in color values between Krajood dyed using the traditional and improved stoves at any measurement position (all p-values > 0.05). This finding confirms that the improved stove maintains dyeing quality while delivering substantial efficiency improvements. The consistency in color outcomes despite the significant changes in processing time and temperature profiles suggests that the critical dyeing parameters (temperature and dye concentration) were effectively maintained in the improved system. Figure 7 provides a visual comparison of dyed Krajood samples, further illustrating the comparable color outcomes between the two methods. This quality preservation is particularly important for market acceptance of products made from Krajood dyed using the improved technology. As Kaewpradit *et al.* [1] noted, consistent quality is essential for maintaining the commercial value of traditional craft products when production processes are modified.

Table 1. Comparison of L* a* b* values measured at different parts of Krajood (base, middle, and end) using dyeing using a traditional biomass stove and dyeing using an improved biomass stove set (L* a* b* values (mean of three positions on each Krajood sample base, middle, and end section)).

	Biomass stove	Mean	S.D.	t	p value
L*_base	Improve the biomass stove	35.14	0.77	1.046	0.326
	Traditional biomass stove	34.65	0.69		
a*_base	Improve the biomass stove	32.30	2.88	-0.042	0.968
	Traditional biomass stove	32.36	1.26		
b*_base	Improve the biomass stove	11.28	1.94	-0.493	0.642
	Traditional biomass stove	11.74	0.80		
L*_middle	Improve the biomass stove	33.37	0.91	1.016	0.339
	Traditional biomass stove	32.91	0.42		
a*_middle	Improve the biomass stove	29.46	1.65	1.03	0.333
	Traditional biomass stove	28.50	1.30		
b*_middle	Improve the biomass stove	9.75	1.36	1.302	0.229
	Traditional biomass stove	8.91	0.50		
L*_end	Improve the biomass stove	33.60	0.18	0.876	0.429
	Traditional biomass stove	33.02	1.47		
a*_end	Improve the biomass stove	29.09	1.17	-0.087	0.933
	Traditional biomass stove	29.20	2.33		
b*_end	Improve the biomass stove	9.16	1.15	0.176	0.865
	Traditional biomass stove	9.04	1.07		

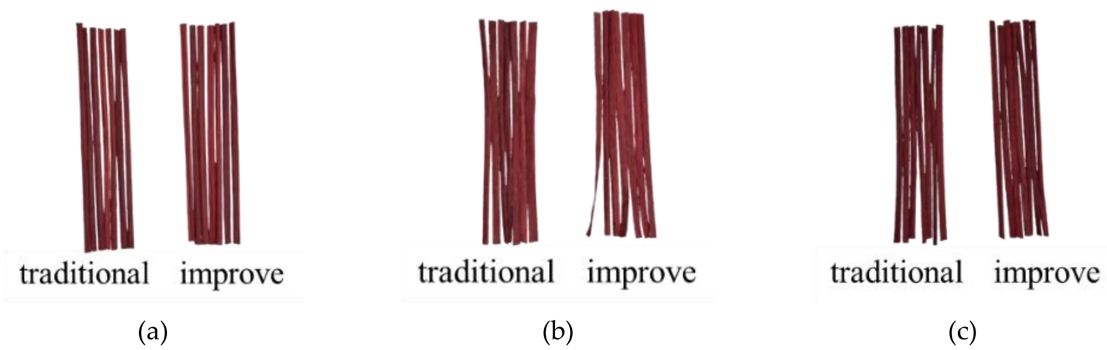

Figure 7. Comparison of colors obtained from the traditional biomass stove and the improved biomass stove of dyeing krajood at base (a), middle (b) end (c) on the krajood threads.

Figure 8. Krajood products are made from the improved biomass stove.

3.6 Economic viability

The economic analysis considered both the initial investment costs and operational benefits of the improved stove design. The traditional biomass stove costs approximately 7,000 THB, while the improved design costs 12,000 THB, representing a 71.4% increase in initial investment. However, this higher initial cost must be considered against the five-fold increase in production capacity (from 20 to 100 bundles per day). Assuming consistent market demand, this productivity improvement translates to significantly reduced labor costs per unit of production. Although this assumption streamlines the model, it might not accurately represent the dynamics of the actual market. The real economic results may be impacted by seasonal variations, competition, and variations in customer demand. As a result, given these possible market uncertainties, the anticipated profitability should be interpreted cautiously. Additionally, the more efficient combustion in the improved design is likely to reduce fuel consumption per unit of output, though this was not specifically quantified in the current study. A simple return-on-investment calculation indicates that the 5,000 THB additional investment could be recovered within a short operational period due to the substantial productivity gains. This economic viability is essential for the adoption of appropriate technology in small-scale industrial settings, as emphasized by Lyman and Chung [4]. Furthermore, the non-monetary benefits of reduced PM2.5 exposure and improved working conditions represent additional value that may contribute to long-term health benefits for operators, though these effects would require longitudinal studies to quantify fully.

Table 2. Cost-benefit analysis of biomass stove technologies.

Parameter	Traditional Stove	Improved Stove	Difference
Initial investment (THB)	7,000	12,000	+5,000
Daily production capacity (bundles)	20	100	+80
Daily production capacity (kg)	44	220	+176
Production increase factor	-	5x	-
Estimated daily revenue (THB)*	2,000	10,000	+8,000
Estimated payback period	-	<1 day	-

*Assuming 100 THB profit per bundle

4. Conclusions

This research has successfully developed and evaluated an improved biomass stove for Krajood dyeing that embodies the principles of sustainable appropriate technology. The new design maintains operational simplicity while achieving substantial performance improvements across multiple parameters. The most significant enhancements include a 72.25% reduction in PM2.5 emissions at the operator position, a 32.73% decrease in water boiling time, a 52.43% reduction in dyeing time, and a 46.45% lower operating temperature. These improvements collectively enabled a five-fold increase in production capacity from 20 to 100 bundles (44 kg to 220 kg) per eight-hour workday. The improved stove design demonstrates how targeted modifications based on appropriate technology principles can simultaneously address health, efficiency, and productivity concerns without compromising traditional product quality. The integration of a water reserve tank, improved combustion chamber, and heat shield required only modest additional investment while delivering significant operational benefits. Importantly, the colorimetric analysis confirmed that the improved system maintained consistent dyeing quality, with no statistically significant differences in Lab* values between the traditional and improved methods. For small-scale Krajood processing enterprises, this technology offers particularly compelling advantages. The five-fold increase in production capacity enables microenterprises to scale operations without proportional increases in labor or workspace. This productivity enhancement strengthens their competitiveness in market environments where traditional crafts face pressure from mass-produced alternatives. Additionally, the significant reductions in ambient temperature and PM2.5 emissions create considerably healthier working conditions for artisans, potentially reducing occupational health risks associated with long-term exposure to heat and particulate matter. From a sustainability perspective, the improved stove represents a balanced approach to technological advancement that respects local capabilities and resources. The design uses locally available materials and maintains a level of simplicity that enables community-based production and maintenance. While not quantified in this study, the improved combustion efficiency likely reduces biomass fuel consumption per unit of output, contributing to resource conservation. Furthermore, by enhancing the economic viability of traditional Krajood processing, the technology supports the preservation of cultural heritage and sustainable livelihoods in rural communities. Future research directions should include long-term durability assessment, precise quantification of fuel efficiency improvements, and exploration of further PM2.5 reduction strategies such as chimney systems. The design principles demonstrated in this study may also be transferable to other natural fiber dyeing processes with similar technological challenges.

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