



Ergonomic and Thermal Optimization of Modified Stoves for Brown Sugar Artisans in Rural Bali

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Abstract: Traditional kitchen designs in rural Bali result in workers exposed to elevated temperatures and air pollution. These conditions have an impact unfatigued levels and decreased productivity. This study aims to redesign and evaluate the effectiveness of cooking stove modifications based on ergonomic and anthropometric considerations, thereby improving worker comfort, energy efficiency, and environmental quality. The study used a participatory approach involving local brown sugar craftsmen in the village of Besan, Kelungkung Bali. The experiment conducted by comparing the existing traditional stove with a modified traditional stove. The parameters measured included air temperature, humidity, lighting, air velocity, pollutant concentration (CO, CO₂, HCHO, PM_{2.5}, PM₁₀, TVOC), and fuel consumption. The results of the study found that the modified stove had a significant impact in reducing cooking time (19.8%), increasing fuel efficiency (14.6%), reducing cumulative pollutants (0.41%), and increasing productivity (3.15%). These results indicate that an ergonomic redesign that integrated with local ethnosience can improve occupational health and sustainable rural production systems.

Keywords: Ergonomic design; indoor air quality; biomass stove; rural industry; productivity.

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1. Introduction

Indoor air pollution (IAP) remains a significant health and productivity issue in low-income rural areas, especially where dependence on biomass fuels for cooking and production is still dominant (Okuthe & Akotsi, 2014; Suresh et al., 2016; World Health Organization, 2025). Wood burning in *pawon* (traditional Balinese kitchens) creates a closed thermal and chemical environment characterized by elevated temperatures, particulate accumulation, and hazardous gas emissions. These conditions often exceed the exposure thresholds recommended by the World Health Organization and national occupational safety standards (World Health Organization, 2024). Beyond environmental aspects, IAP in the context of traditional production reflects broader systemic issues, particularly technological stagnation, and a lack of attention to ergonomic principles in culturally rooted non-mechanized practices (Munyao et al., 2022; Okuthe & Akotsi, 2014; Suresh et al., 2016). The physical characteristics of rural kitchens—minimal openings, inadequate ventilation, and the use of heat-absorbing materials—exacerbate the accumulation of thermal energy and pollutants (Jirapongsuwan et al., 2023; Quansah et al., 2015; Salve et al., 2024). This situation contributes to a double burden for workers in the form of thermal discomfort and respiratory risks, as

well as decreased performance due to eye irritation, mild hypoxia, and muscle fatigue (Balmes, 2019; Liu et al., 2021; Pratiti, 2021).

Women and home-based workers—groups that dominate the household agro-industrial sector such as brown sugar production—most intensely exposed to these risks. Prolonged interaction with open fire stoves not only increases the impact of cooking the probability of chronic respiratory diseases but also reinforces socio-economic vulnerability through reduced productivity and increased demand for health services (Akteruzzaman et al., 2023; Quansah et al., 2015; Utami et al., 2022). Thus, the sustainability of traditional biomass-based cooking technology is not merely a technical or ecological issue, but rather a spatial, ergonomic, and socio-cultural challenge that requires an integrated approach through design innovation, anthropometric adjustments, and the utilization of local ethnosience.

The intergenerational of artisans in Besan Village, Klungkung, have maintained a household agroindustry based on palm sugar production, which is one of the most sustainable representations of vernacular industrial space in Bali. However, the spatial configuration of the production area—particularly the cooking area—has retained its traditional form. The workspace still characterized by low-positioned stoves, minimal cross ventilation,



and limited hot zones, exacerbating thermal stress and pollutant concentrations. These spatial and technological deficiencies have direct implications for ergonomic strain, respiratory exposure, and decreased labor efficiency (Jirapongsuwan et al., 2023; Munyao et al., 2022; Silva et al., 2024; Suresh et al., 2016).

From an architectural and environmental ergonomics perspective, these conditions indicate a mismatch between inherited ethnoscientific practices and contemporary work sustainability demands. *pawon* designed for sporadic domestic use, not for high-temperature, continuous production cycles. Consequently, the working postures required to operate the stove often exceed biomechanical tolerance limits, triggering musculoskeletal fatigue and chronic discomfort (Carlett & Clark, 2017). The absence of adaptive design elements—such as furnace height that follows anthropometric parameters, airflow regulation, or isolated combustion chambers—further exacerbates heat retention and combustion inefficiency, resulting in higher emissions of CO, CO₂, PM_{2.5}, and volatile organic compounds (Akteruzzaman et al., 2023; Quansah et al., 2015; Salve et al., 2024; World Health Organization (WHO), 2024).Click or tap here to enter text.

This study critically examines these issues by integrating local ethnoscience principles and contemporary ergonomics through the redesign of energy-efficient and context-appropriate stove models. This approach aims not only to improve physical comfort and environmental performance, but also to preserve the cultural logic of the production space. Thus, this study responds to broader challenges in sustainable rural design: modernizing vernacular production environments without eroding their socio-cultural identity or ecological balance (Collste et al., 2023; Munyao et al., 2022; Okuthe & Akotsi, 2014; Onyeneke et al., 2019; Pratiti, 2021; Quansah et al., 2015; Rosenthal et al., 2018; Salve et al., 2024;

Silva et al., 2024; Suresh et al., 2016; Utami et al., 2022). Overall, this study investigates how the ergonomic redesign of furnaces and workstations can reduce environmental stressors, improve combustion efficiency, and support handicraft productivity while maintaining local cultural integrity.

2. Methodology

This research conducted from April to September 2025 in Besan Village, Dawan District, Klungkung, Bali, an area known as the center of household-scale palm sugar agroindustry. This environment represents a traditional production kitchen typology with intertwined issues of ergonomics and work environment quality. Five palm sugar producing households selected through purposive sampling to represent cross-generational craft practices. All participants were women aged 35–55 years with at least five years of work experience, reflecting gender-based work patterns and elevated levels of exposure to heat and pollutants in confined spaces.

The intervention evaluated using an intra-subject experimental design, whereby each participant functioned as their own control. This design allowed for more accurate detection of pre- and post-intervention changes and reduced individual variability. All testing conducted under controlled environmental conditions, including firewood moisture content and air temperature, to maintain consistency of results. The intervention designed through a participatory approach, resulting in a modified stove prototype based on user anthropometric data (elbow height 96 cm, forward reach 37 cm). The stove height adjusted to 70 cm to support a neutral working posture, while lower combustion chamber ventilation added to improve airflow, combustion efficiency, and smoke accumulation reduction. (see Table 1)

Table 1. Anthropometry-Based Ergonomic Design Parameters

Anthropometric Data	Value	Design Output	Ergonomic Rationale
Mean elbow height	96 cm	Stove height = 70 cm	Supports neutral posture (5–10 cm below elbow).
Forward reach (5th percentile)	37 cm	Pot–stove distance optimized	Prevents forward trunk flexion.
Mean body height	154.9 cm	Visual and reach posture adjusted	Reduces neck flexion >20°.
Lifting and handling tasks	6 L boiling sap	Working height adjusted	Reduces lumbar load and excessive bending.

The main parameters were measured using calibrated instruments: JSM 131 SC for HCHO, CO, CO₂, PM_{2.5}, PM₁₀, and TVOC; HTC-2 thermo-hygrometer for temperature and humidity; Kuber lux meter for lighting; and thermocouples and stopwatches for fuel efficiency and cooking time (see Table 2). Data analysed descriptively and through paired comparisons to identify

significant changes after the intervention. Findings examined with reference to Indonesian National Standards (SNI) related to work comfort and WHO indoor air quality guidelines (World Health Organization, 2024) to ensure compliance with national and international standards.

Table 2. Instruments and Measured Parameters

Instrument	Measured Parameters	Units	Purpose
JSM 131 SC Air Quality Monitor	HCHO, TVOC, CO, CO ₂ , PM _{2.5} , PM ₁₀	mg/m ³ , ppm, µg/m ³	Assess indoor air quality
HTC-2 Thermo-Hygrometer	Temperature, humidity	°C, %	Assess thermal environment
Kuber Digital Lux Meter	Light intensity	lux	Evaluate lighting adequacy
Thermocouple	Heating temperature	°C	Measure thermal efficiency
Digital scale & stopwatch	Fuel mass, heating time	kg, minutes	Evaluate stove performance
Lignomat Moisture Meter	Firewood moisture level	%	Control fuel variability

The following flowchart illustrates the sequential stages of the research methodology used in this study (see Figure 1). This diagram summarizes how the research was conducted, starting from the initial problem identification and sample selection, baseline measurement, participatory stove redesign,

implementation of the modified prototype, to post-intervention evaluation. This structure provides a clear picture of the systematic and controlled procedures used to assess the ergonomic and environmental impacts of the intervention.

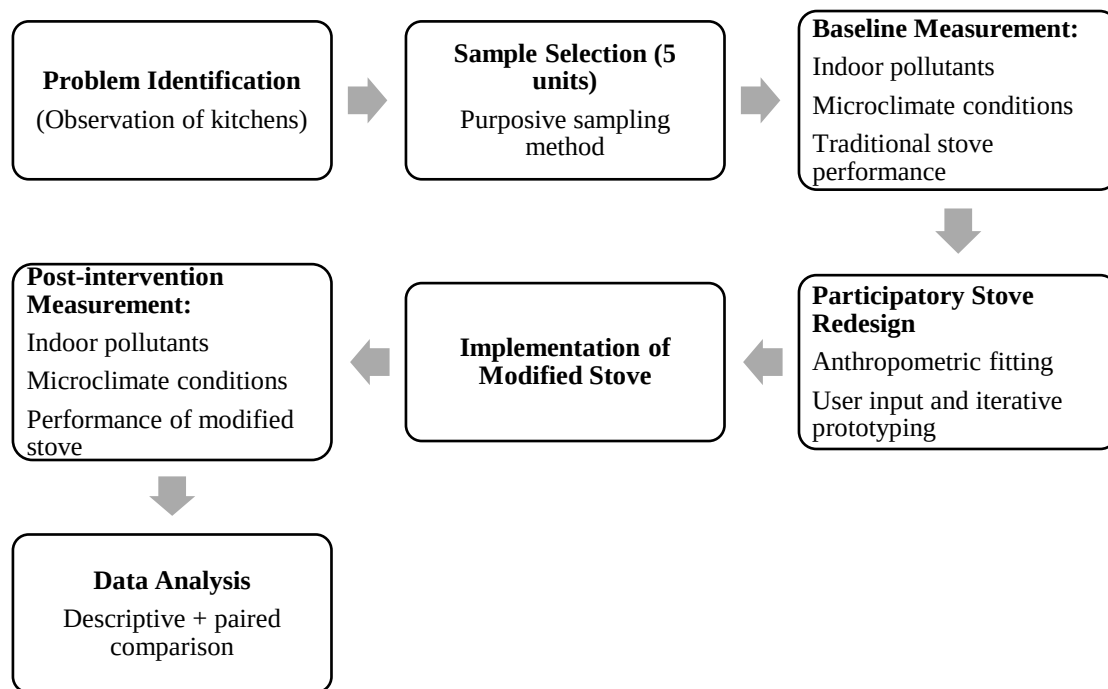


Figure 1. Sequential Flow of Research Stages in the Evaluation of Modified Stove Intervention

3. Result

Ergonomic Adjustments

Adjusting the height of the stove to 70 cm resulted in substantial improvements in the working posture, comfort, and operational efficiency of palm sugar artisans in Besan Village. Prior to the intervention, artisans worked in a half-squatting or bent-over position due to the extremely low configuration of traditional stoves—often flush with the floor. This posture required repeated and prolonged trunk flexion during heating and stirring activities, which then caused static loads on the lumbar segment and triggered musculoskeletal fatigue after a couple of hours.

After the intervention, postural observations showed a significant decrease in the degree of trunk flexion and increased upper body

stability during stirring and lifting activities. Participants were able to maintain a more upright posture, thereby reducing tension in the lower back and lower extremities. Subjective reports indicated reduced physical fatigue, especially in the waist, shoulders, and knees, as well as increased ease in handling pots containing hot liquids during the boiling stage. In addition, the increased height of the stove allowed for better visibility of the pot surface, facilitating monitoring of the cooking process.

Field documentation also noted more efficient workflows, reduced rest frequency, and shorter transition times between the heating and pouring stages. These behavioural changes reflect an increase in work rhythm and physical endurance. Overall, these findings confirm that the ergonomic modifications implemented were able to improve physical comfort, movement quality, and production process efficiency. (see Figure 2)

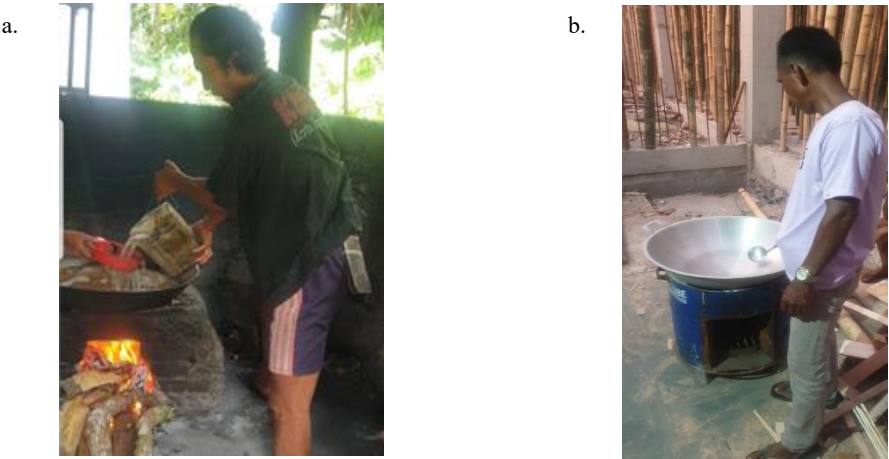


Figure 2. a). Stooped working position, repeated trunk flexion, and musculoskeletal complaints among brown sugar kitchen workers using traditional stoves, b). Modification of stoves where the height can be adjusted according to the anthropometry of the user.

Environmental and Air Quality Improvement

The application of modified stoves in production kitchens in Besan Village showed measurable improvements in microclimate conditions and a reduction in indoor air pollutant concentrations. A comparison between traditional and re-engineered systems showed consistent improvement trends in all key environmental parameters. The working room temperature decreased from 30.9°C to 30.2°C, or a 2.3% reduction in heat accumulation, indicating more efficient combustion and reduced heat release into the environment. Simultaneously, the airflow velocity increased from 0.28 m/s to 1.20 m/s after the addition of bottom and side air ducts to the combustion chamber. This increase in airflow not only supports thermal comfort but also improves the dilution and smoke removal processes during boiling. In terms of lighting, light intensity increased from 61 lux to 136 lux (approximately 41%), influenced by the rearrangement of the stove area and the use of reflective surfaces that enhance light diffusion. This improvement

in visibility contributes to safer and more precise stirring and pouring activities and reduces visual fatigue.

Air quality analysis shows a more pronounced positive impact. Carbon monoxide (CO) concentrations decreased from 31 ppm to 29 ppm, while carbon dioxide (CO₂) decreased from 1,579 ppm to 1,510 ppm. Although the reductions are small (6.5% and 4.4%), the results indicate improved combustion and ventilation efficiency. The reduction in formaldehyde (HCHO) from 0.42 mg/m³ to 0.16 mg/m³—a 54% reduction—marks a significant decrease in volatile organic compound emissions. Particulate concentrations also decreased: PM_{2.5} decreased from 284 µg/m³ to 258 µg/m³, and PM₁₀ from 393 µg/m³ to 372 µg/m³. Although these decreases were moderate (5–9%), the results are important given the elevated levels of particulates in biomass-fuelled kitchens. Lower TVOC readings also indicate cleaner combustion conditions. (see Figure 3)

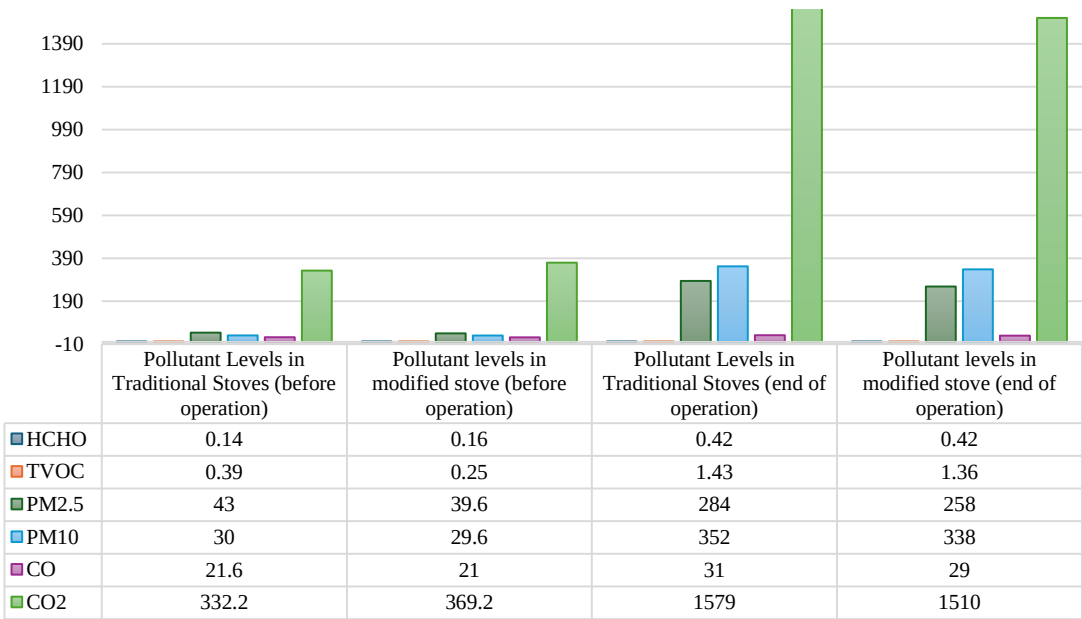


Figure 3. Pollutant Concentration Matrix in Traditional Stoves and Modified Stoves (before - end of operation)

Overall, aggregate pollutants decreased by approximately 0.41%, accompanied by significant improvements in thermal comfort, air circulation, and lighting. These findings suggest that ergonomic and thermal redesign of stoves not only improves user comfort but

also results in healthier indoor air conditions. The results confirm that small-scale spatial and technological interventions can have a real impact on the environmental quality of traditional production spaces. (see Table 3)

Table 3. Environmental and Air Quality Improvements Before–After Stove Modification

Parameter	Before Intervention	After Intervention
Temperature (°C)	30–31.5°C	29–30°C. Slight reduction; improved thermal comfort
Relative Humidity (%)	74–86% (peaking 86%)	70–82%. Lower humidity; less moisture accumulation
Lighting (lux)	7–10 lux (below SNI minimum 200 lux)	12–15 lux. Slight improvement but still below SNI
PM _{2.5} (µg/m³)	Elevated during boiling stage (qualitative documentation)	Lower peak concentration. Reduced particulate emissions due to improved combustion airflow
PM ₁₀ (µg/m³)	High during heating cycle (qualitative)	Lower dispersion into workspace. Reduced coarse particulate spread
CO (ppm)	Higher during active burning (qualitative)	Lower because of increased ventilation in combustion chamber. Reduced incomplete combustion
CO ₂ (ppm)	Increased with poor air movement (qualitative)	More stable readings. Improved air exchange
TVOC (mg/m³)	High due to smoke accumulation (qualitative)	Reduced. Improved air cleanliness
Firewood Efficiency (kg/session)	Higher firewood use (qualitative)	Lower consumption with better airflow. Higher fuel efficiency
Smoke Distribution	Dense near working zone; stagnant under roof beams	More directed flow; reduced smoke stagnation. Reduced indoor smoke exposure

Thermal and Energy Performance

Modifications to the cooking stove showed a significant increase in thermal efficiency and a decrease in energy consumption during the palm sugar production process. Temperature measurements show that the modified furnace can reach and maintain a higher

and more stable combustion temperature—around 900 °C compared to ±700 °C in traditional furnaces. This increase in temperature also reflected in the change in flame characteristics, which shift from dark red to pinkish orange, indicating a more complete combustion process. (see Table 4)

Table 4. Thermal and Energy Performance Before–After Stove Modification

Parameter	Before Intervention (Traditional Stove)	After Intervention (Modified Stove)	Improvement
Thermal Efficiency	Lower thermal retention: heat dissipates through gaps and low wall height	Improved heat concentration due to optimized pot–stove gap and elevated stove height	↑ Higher heating efficiency and reduced heat loss
Heating Time per Cycle	Longer heating time due to unstable flame and insufficient airflow (qualitative)	Faster heating cycle: flame stabilizes due to added lower ventilation	↓ Shorter boiling time
Fuel Consumption (kg/session)	Higher use of firewood due to incomplete combustion and low stove geometry (qualitative)	Reduced firewood consumption as airflow improves combustion efficiency	↓ Increased fuel efficiency
Heat Transfer to Pot (Thermocouple Observation)	Significant heat escapes sideways because the pot does not sit flush with the stove wall	Pot sits closer to the combustion chamber, improving conductive and convective heat transfer	↑ More effective heat delivery
Flame Stability	Fluctuating flame; sensitive to wind direction and airflow blockages	More stable flame profile: airflow inlet maintains consistent oxygen supply	↑ Stable and efficient combustion
Work Surface Temperature	Increased diffuse heat around the worker due to inefficient heat direction (qual.)	Lower unwanted lateral heat exposure: more heat directed toward pot	↓ Reduced ambient thermal load
Process Workflow	Longer transition time between boiling and pouring stages; frequent pausing due to heat inconsistencies	Smoother workflow with fewer delays; heat remains stable across stages	↑ Faster and continuous work rhythm

Optimization of air supply and combustion chamber geometry improved oxygen circulation and heat transfer quality, allowing heat to be transferred more quickly and evenly to the boiling pan. As a result, cooking time reduced by an average of 19.8%, shortening the overall production cycle. Fuel efficiency increased by approximately 14.6%, as indicated by a decrease in wood usage for the same volume of sap. This improvement also implies a reduction in physical workload and duration of excessive heat exposure.

Artisans reported improved thermal comfort and process stability, with less need to adjust the flame and more consistent temperatures during boiling. This thermal stability results in more uniform sugar quality and reduces incidents of overcooking or burning that often occur in traditional stoves. Overall, these findings indicate that ergonomic and structural modifications effectively improve the thermal performance and operational efficiency of stoves, while reducing their environmental impact.

Productivity Impact and Work Performance

Ergonomic and thermal modifications to the furnace redesign resulted in measurable improvements in the productivity of palm sugar artisans in Besan Village. Based on field observations and quantitative analysis, production efficiency increased by an average of 3.15% compared to pre-intervention conditions. This improvement reflected in reduced processing time per batch and increased product quality consistency.

Artisans reported that the workflow became more efficient, with fewer interruptions during the boiling and crystallization stages. The stability of combustion and the height adjustment of the furnace allowed for a more consistent stirring rhythm and reduced unnecessary movements due to bending over or repeated temperature adjustments. Improved ergonomic comfort—particularly reduced strain and fatigue on the lower back—has enabled workers to maintain longer continuous working hours without breaks, thereby supporting increased output.

Qualitative feedback also indicates improved work precision and focus. Better visibility in the production area, supported by adequate lighting and reduced smoke and glare, facilitates artisans in assessing the viscosity and color changes of sugar at the critical final stage of cooking. This results in a more uniform product texture and reduces the frequency of reprocessing previously triggered by overheating or suboptimal crystallization. In addition, reduced thermal stress and exposure to pollutants create a more comfortable working environment, allowing artisans to maintain a more stable level of concentration throughout the production cycle.

4. Discussion

This study shows that even small-scale ergonomic and thermal interventions can have a substantial impact on health, environmental quality, and productivity in traditional production systems. Adjusting the height of the stove—set at 70 cm based on anthropometric data related to elbow height and working reach—successfully shifted the work surface to the neutral reach zone, thereby minimizing repetitive trunk flexion and reducing static muscle load. This configuration reduced tension in the lumbar and shoulder areas, in line with established ergonomic workstation design principles (Carlett & Clark, 2017; Konz, 2017). Improved postural comfort, reduced fatigue, and smoother workflow

collectively enhance continuity and precision of operations during the lengthy boiling stage.

The physical impact goes beyond mere comfort improvements. Integrating ergonomic principles into a culturally significant workspace encourages behavioural and perceptual changes among artisans. This redesign bridges local ethnoscientific knowledge with evidence-based ergonomic practices, demonstrating that a participatory approach can maintain cultural authenticity while adopting scientific standards. In the context of the *pawon*—historically designed for domestic needs rather than intensive production—this spatial recalibration marks a shift from productivity based on physical endurance to productivity based on comfort. For the female artisans who dominate this sector, the intervention serves as a form of spatial empowerment, transforming the workspace from an uncomfortable environment to one that is more controlled, efficient, and agency oriented.

From an environmental perspective, this ergonomic redesign also significantly improved the microclimate and air quality. A 2.3% decrease in ambient temperature and a 20% increase in airflow velocity reflect the successful integration of ergonomic and thermal principles in addressing two key issues—inefficient heat dissipation and limited air circulation. Improved ventilation not only enhances thermal comfort but also reduces pollutant concentrations, including a 54% reduction in formaldehyde and a 9.2% reduction in PM_{2.5}. Although these percentages appear moderate, their physiological implications are significant in high-temperature enclosed spaces. These findings are consistent with research on biomass stove innovations, which shows that minor modifications to geometry and air dynamics can reduce emissions without changing traditional fuels (Akteruzzaman et al., 2023; Munyao et al., 2022; Pratiti, 2021; Quansah et al., 2015; Salve et al., 2024; Suresh et al., 2016).

From an environmental ergonomics perspective, improvements in air quality and lighting—with light intensity increasing by 41%—directly affect cognitive and sensory performance. Reduced exposure to pollutants and improved visual conditions reduce eye strain, increase visual perception accuracy, and support more stable focus during the sugar crystallization phase. These results reinforce the idea that environmental comfort is a key supporting factor for precision and safety in artisan workspaces (Balmes, 2019; Liu et al., 2021; Robert Bridger, 2003).

Further improvements in thermal and energy performance underscore the role of design optimization in improving the efficiency and sustainability of the combustion process. The combustion temperature in the modified stove increased from approximately 700°C to 900°C, followed by a 19.8% acceleration in cooking time and a 14.6% increase in fuel efficiency. These results indicate increased oxygen dynamics and heat transfer stability, reinforcing the argument that simple modifications to combustion chamber geometry can yield thermodynamic and environmental benefits. In the context of wood-based rural economies, such efficiency gains not only reduce energy consumption but also lessen pressure on forest resources and exposure to heat and smoke for workers. These findings are consistent with the literature emphasizing that improvements in combustion patterns and air-fuel ratios can result in energy savings and better emission control (LaFave et al., 2021; Munyao et al.,

2022; Okuthe & Akotsi, 2014; Pratiti, 2021; Salve et al., 2024; Suresh et al., 2016).

Cumulatively, these ergonomic, environmental, and thermal interventions resulted in a 3.15% increase in productivity. Although this figure may seem small, it is significant in the context of a household industry whose production capacity is based on human labor. Improved posture, reduced fatigue, and improved air quality together create a more ergonomically optimal work environment, increasing individual and system efficiency. The shift from reactive responses to discomfort toward more proactive work management—enabled by thermal stability and reduced physical load—reflects a stronger synchronization between human performance and environmental conditions. This supports the theoretical premise that sustainable production is underpinned by human-environment harmony, not merely mechanical optimization (Carlett & Clark, 2017; Jirapongsuwan et al., 2023; Konz, 2017; Silva et al., 2024).

Beyond its immediate technical benefits, this study emphasizes the importance of integrating technological innovation and socio-cultural continuity in sustainable rural design. The stove modifications were not a form of disruptive modernization, but rather an evolutionary adaptation rooted in participatory dialogue and local skills. This contextual approach Collste et al. (2023) and Utami et al. (2022), innovations embedded in cultural contexts form the foundation of rural technological resilience, where sustainability is achieved through incremental and inclusive changes.

However, this study also highlights several limitations. Despite a reduction in pollutants, CO₂ and PM concentrations remain above WHO (World Health Organization, 2024)) thresholds, indicating the need for further development, such as the integration of passive exhaust systems or secondary combustion chambers, to achieve safer emission standards. Long-term monitoring is also needed to assess the cumulative exposure effects and structural resilience of stoves under various operational conditions.

Overall, these findings suggest that ergonomically and thermally redesigned traditional stoves can simultaneously improve occupational health, environmental quality, and productivity without sacrificing local knowledge. The integration of anthropometric data, thermodynamic optimization, and participatory design has resulted in a replicable model of rural technological innovation—an approach that combines human-centered design with cultural sustainability. Through this synergy, Besan Village is moving towards a form of production that reflects sustainable adaptation, gender equality, and technological resilience.

5. Conclusion

This study confirms that ergonomic and thermal redesign of traditional stoves can improve work comfort, environmental quality, and productivity in rural craft industries. Adjusting the stove height to 70 cm, combined with improved ventilation and combustion geometry, effectively reduces postural strain, lowers pollutant concentrations, and improves energy performance. Empirical results—including a 19.8% reduction in cooking time, a 14.6% increase in fuel efficiency, and a 3.15% increase in productivity—show that small-scale, low-cost design interventions can yield multidimensional benefits.

More than just a functional improvement, this intervention represents a cultural and spatial transformation. By integrating anthropometric data with local ethnoscientific knowledge, this redesigned stove redefines the *pawon* as a healthier and more empowering workspace, especially for the women artisans who sustain Bali's brown sugar production. This underscores that ergonomic reforms in vernacular environments are not merely technical endeavours, but also a path toward gender-equitable and culturally grounded sustainability.

The persistence of certain pollutants above WHO thresholds indicates the need for further refinements—such as the addition of passive exhaust systems or secondary combustion chambers—and long-term evaluation of health outcomes. Nevertheless, these findings confirm that context-sensitive participatory design offers a replicable model for sustainable rural innovation. This study contributes to the broader discourse that true sustainability in small-scale production does not arise from mechanization, but rather from the alignment of human, environmental, and cultural dimensions through design intelligence.

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