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Thermal Energy and Biomass Consumption Assessment of Traditional Sugar Palm Fruit Boiling: Integrating Local Knowledge and Quantitative Process Analysis

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ABSTRACT

Traditional sugar palm fruit (Arenga pinnata) processing involves prolonged boiling, which may require substantial biomass fuel consumption and careful heat management. In small-scale production communities, boiling practices are commonly guided by experiential knowledge, including visual flame assessment, fuel-feeding routines, and sensory indicators of product readiness. However, these practices are rarely documented alongside quantitative measurements of thermal behavior and fuel consumption. This study aims to characterize traditional sugar palm fruit boiling practices and establish a baseline for biomass energy use by integrating local knowledge documentation with process-level thermal measurements. The proposed study focuses on small-scale sugar palm fruit processors in Kampung Kokolaka, Jatirejo, Gunungpati, Semarang, Indonesia. A mixed-methods approach combines field observations, semi-structured interviews, and measurements of biomass consumption, boiling duration, water temperature, fuel moisture content, and processed fruit mass. Specific fuel consumption is calculated as the ratio of biomass consumed to the mass of fruit processed, with additional moisture-adjusted comparisons where appropriate. Descriptive statistics and thermal profile analysis are used to investigate process variability and identify potential energy-related limitations. Local operating practices are interpreted alongside measured process characteristics to identify parameters relevant to future appropriate technology development. The study is expected to provide an empirically grounded description of traditional boiling practices, a reproducible baseline measurement framework, and preliminary technical requirements for community-oriented thermal process improvement.

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1. INTRODUCTION

Biomass remains an important source of process heat for small-scale food production, particularly where locally available solid fuels are used in traditional cooking and boiling systems. In such settings, thermal processes are shaped not only by the physical properties of fuel and equipment but also by locally developed operating practices. Operators determine when to add fuel, how to maintain a suitable flame, and when a product has reached an acceptable processing condition [1]–[8].

Sugar palm (Arenga pinnata) is a multipurpose palm species found in Indonesia. Its immature fruits are processed into kolang-kaling, a food ingredient used in traditional beverages, desserts, and other

preparations. Thermal treatment is an important stage of processing. Operating conditions may differ according to batch size, fuel characteristics, stove configuration, and local practices [9], [10].

In Kampung Kokolaka, Jatirejo, Gunungpati, Semarang, kolang-kaling processing provides a context for examining how experiential knowledge contributes to thermal management. The existence of locally established practices does not necessarily imply that energy performance has been measured. Potential fuel savings cannot be established without reliable baseline data [11], [12].

A fundamental challenge is the interaction among fuel characteristics, combustion conditions, heat transfer, equipment geometry, and operator behavior. Biomass moisture can affect useful energy availability; fuel-feeding and air supply influence combustion; heat losses influence transfer to the vessel. Variations in batch size and initial conditions complicate comparison [13], [14].

Local knowledge may reflect product quality, production continuity, fuel availability, and operator safety. Evaluating fuel consumption alone risks overlooking the reasons for existing practices. An integrated assessment should connect quantitative measurements with explanations from experienced processors [15].

This observational study therefore documents local boiling procedures, quantifies biomass consumption and thermal profiles, examines variability across cycles, and identifies evidence-based parameters for future community-appropriate thermal technology.

2. MATERIALS AND METHODS

2.1. Study Area and Research Design

The study is designed for Kampung Kokolaka, Jatirejo, Gunungpati, Semarang, Central Java, Indonesia. A convergent mixed-methods design combines observations and semi-structured interviews with quantitative measurements. The two strands will be analyzed separately and then integrated [16], [17].

2.2. Production Unit Selection and Sampling

Production units will be selected purposively based on active production, willingness to participate, and availability for repeated observation. Where feasible, three to five units and at least three boiling cycles per unit will be observed (approximately 9–15 cycles). The production unit and cycle will receive separate identifiers; repeated cycles from one unit will not be assumed independent for statistical inference [18].

2.3. Documentation of Local Knowledge

Observation, semi-structured interviews, and field notes will document fuel selection and preparation, ignition, fire maintenance, fuel additions, sensory indicators of boiling and readiness, responses to environmental changes, and constraints involving safety, labor, time, and quality. Informed consent will be obtained. Local terminology will be retained with contextual explanations. Thematic coding will combine predefined categories with emergent themes [19].

2.4. Thermal and Biomass Measurements

Sensor placement and sampling interval standardized without obstructing production. (Table 1) The cycle start and end points defined before data collection. Completion will follow the processor-defined readiness criterion, with corresponding observable indicators recorded [20].

Table 1. Observation parameters an it's unit.

Parameter	Symbol	Unit	Measurement approach
Initial biomass mass	m_f,0	kg	Digital scale
Added biomass mass	m_f,added	kg	Digital scale
Remaining usable fuel	m_f,r	kg	Digital scale
Fuel moisture content	MC_wb	%	Appropriate moisture determination
Fruit batch mass	m_p	kg	Digital scale
Initial water mass	m_w	kg	Weighing or calibrated volume
Water temperature	T_w	°C	Thermocouple/temperature probe
Ambient temperature	T_a	°C	Temperature sensor
Boiling duration	t_b	min	Stopwatch/data logger
Fuel-feeding events	N_f	count	Observation log

2.5. Specific Fuel Consumption

Biomass consumed: $m_f = m_{f,0} + m_{f,added} - m_{f,r}$. Specific fuel consumption: $SFC = m_f / m_p$ (kg biomass per kg fruit) [2]. For moisture-adjusted comparisons: $m_{f,dry} = m_f \times (1 - MC_{wb} / 100)$; $SFC_{dry} = m_{f,dry} / m_p$ [4]. These indicators quantify fuel use but do not independently measure combustion or thermal efficiency. Any thermal efficiency claim would require a suitable energy balance and fuel calorific value [11], [12].

2.6. Thermal Profile Analysis

Temperature–time profiles will characterize initial heating, time to approach boiling, sustained heating fluctuations, fuel-feeding events, and total process duration. A heating rate may be estimated over a consistently defined interval as $r_T = (T_2 - T_1) / (t_2 - t_1)$ [6].

2.7. Statistical Analysis

SFC, duration, batch mass, fuel moisture, and thermal indicators will be summarized using means and standard deviations or medians and interquartile ranges, as appropriate. Exploratory correlations or regressions will consider repeated observations nested within production units. With a small sample, uncertainty and limited generalizability will be emphasized. Machine learning is not required for the baseline study [13], [14].

2.8. Qualitative–Quantitative Integration

A joint interpretation matrix will compare locally described practices with physical measurements, such as fuel additions and temperature fluctuations or readiness indicators and process duration. The analysis will not assume that each experiential indicator corresponds to a single physical variable [5], [9].

2.9. Ethics and Safety

Participation will be voluntary and based on informed consent. Researchers will not alter normal fire management. Equipment installation will minimize hazards around flames, hot vessels, smoke, and fuel handling. Identifiable quotations or images require appropriate permission [1].

3. RESULT AND DISCUSSION

3.1. Dataset and Descriptive Statistics

A synthetic dataset of 15 boiling cycles (five hypothetical production units, three cycles per unit) was constructed for methodological demonstration (Table 2). The numerical values do not represent observations collected in Kampung Kokolaka. Across the synthetic cycles, mean SFC was 0.346 ± 0.037 kg/kg, mean boiling duration was 107.7 ± 7.3 min, and mean fuel moisture content was 17.5 ± 4.2%. These values are illustrative only and must not be interpreted as empirical process performance.

Table 2. Summary of measurements; means are calculated over three cycles per unit.

Unit	n	Fruit (kg)	Moisture (%)	Duration (min)	SFC mean ± SD (kg/kg)
A	3	32.8	12.6	99.9	0.299 ± 0.008
B	3	36.9	14.5	107.6	0.322 ± 0.009
C	3	37.9	16.2	103.8	0.342 ± 0.013
D	3	40.9	21.3	109.7	0.377 ± 0.012
E	3	42.8	23.0	117.6	0.391 ± 0.023

3.2. Thermal Profiles

Figure 1 illustrates simulated temperature–time profiles for five hypothetical production units, depicting initial heating, approach to boiling, and a near-boiling plateau. The trajectories were generated to demonstrate the proposed thermal-profile analysis and are not field measurements [6], [8].

Variations in heating trajectories may be associated with differences in combustion intensity, fuel moisture content, biomass feeding practices, vessel geometry, and batch size. These factors influence thermal response and energy utilization. However, similar boiling temperatures do not necessarily indicate equivalent thermal efficiency, as differences in fuel consumption and heat losses may persist during sustained boiling. [7], [11]

Temperature-profile analysis provides a quantitative basis for interpreting traditional heat-management practices and identifying opportunities for process improvement. Integrating temperature measurements with biomass consumption, fuel-feeding records, and fruit quality assessments is essential for evaluating energy performance and establishing technical requirements for appropriate technology development. [12], [15]

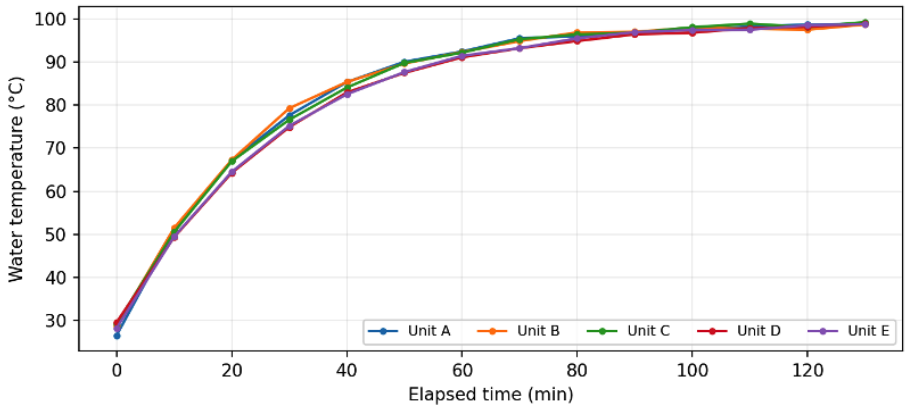


Figure 1. Temperature–time profiles for five hypothetical production units (three cycles averaged per unit).

3.3. Parameter Relationships

In the synthetic dataset, the illustrative Pearson correlations were $r = 0.95$ ($p = 6.12 \times 10^{-8}$) for fuel moisture versus SFC and $r = 0.66$ ($p = 0.00744$) for boiling duration versus SFC. These coefficients and nominal p-values arise from generated observations, not measured field evidence. Moreover, repeated cycles are nested within hypothetical units, so naive cycle-level significance tests should not be used for field inference [13], [14].

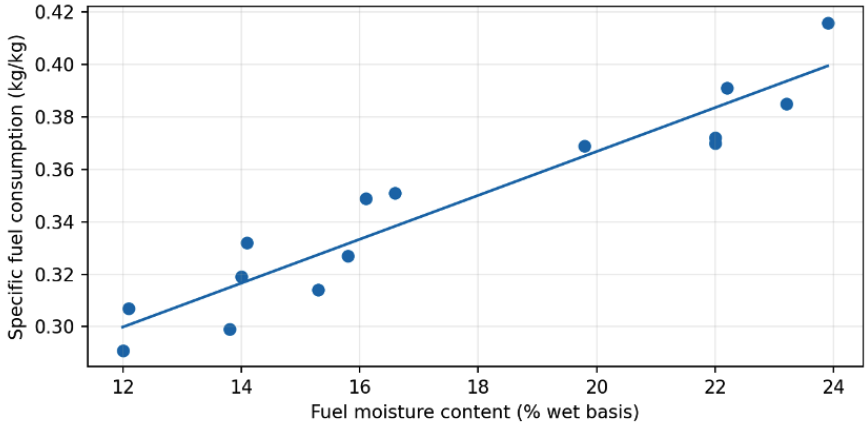


Figure 2. Association between fuel moisture content and specific fuel consumption; fitted line is illustrative only.

From a thermodynamic perspective, higher moisture content reduces the effective energy available from biomass combustion because part of the released heat is consumed in heating and evaporating the water contained in the fuel. Consequently, greater quantities of biomass may be required to maintain the desired boiling conditions. Similarly, prolonged boiling increases cumulative heat demand and environmental heat losses, potentially contributing to higher SFC. Nevertheless, these associations do not establish causality, as fuel characteristics, combustion conditions, vessel geometry, and operating practices may simultaneously influence energy consumption [6], [11].

These synthetic associations motivate testable hypotheses about fuel moisture management and boiling-duration control; they do not establish real-world relationships or achievable energy savings. Future field assessment should evaluate moisture-adjusted SFC and product-quality endpoints [6], [11], [12].

3.4. Interpretation of Local Knowledge and Physical Measurements

Table 3 outlines proposed correspondences between local indicators and physical observations; these are hypotheses for future participatory field validation, not relationships already verified by Kokolaka processors [5], [9], [20].

Table 3. Integration of Local Knowledge Indicators and Physical Measurements in Traditional Kolang-Kaling Boiling

Local indicator	Physical observation	Interpretive
Visual flame intensity	Water temperature and fuel-feed timestamps	Compare reported flame changes with measured heating response
Timing of fuel addition	Fuel mass and timing	Estimate variation in thermal response after additions
Perceived boiling intensity	Water temperature and boiling duration	Check agreement with measurable thermal stages
Fruit readiness assessment	Sensory assessment and batch-specific quality measures	Assess whether equivalent processing endpoints are achieved

Visual flame intensity is associated with the operators' perception of combustion conditions. By comparing reported changes in flame intensity with water temperature profiles and fuel-feeding timestamps, the analysis can examine whether visual assessments correspond to measurable changes in heating behavior. However, water temperature alone cannot fully characterize combustion intensity, particularly when the water approaches its boiling point, because additional heat may primarily contribute to evaporation rather than further temperature increases [7], [9].

The timing of fuel addition provides another important connection between local practices and thermal response. Recording the mass and timing of biomass additions allows changes in temperature trends to be examined before and after each feeding event. These observations may help explain how processors maintain heating conditions during prolonged boiling. Nevertheless, the response may be influenced by fuel moisture content, combustion-air availability, and existing fuel-bed conditions [7], [12].

Perceived boiling intensity reflects the operators' experiential assessment of thermal conditions within the vessel. Comparing these assessments with measured water temperature and boiling duration can help determine whether locally recognized boiling stages correspond to distinguishable process conditions. Because vigorous and gentle boiling can occur at similar water temperatures, additional observations of bubbling behavior or evaporation would improve the interpretation of this indicator [2], [6].

Fruit readiness assessment is particularly important because energy performance must be evaluated alongside processing quality. Traditional sensory indicators can be compared with batch-specific quality measurements, such as texture, appearance, and consistency, to assess whether comparable processing endpoints are achieved. This prevents reduced fuel consumption or shorter processing duration from being interpreted as improvements when the resulting product does not satisfy locally accepted quality requirements [16]–[19].

Collectively, these relationships establish a basis for translating experiential knowledge into measurable process parameters without disregarding its practical and cultural significance. The framework also identifies potential variables for subsequent technology development, including fuel-feeding procedures, thermal stability, processing duration, and product quality. Importantly, the relationships presented in Table 3 should be regarded as hypotheses for field validation rather than experimentally verified findings, because the current quantitative dataset is simulated and independent verification by Kokolaka processors has not yet been documented [9], [20]

Consequently, the integration of community observations and physical measurements is expected to inform the co-design of appropriate biomass-fired boiling technologies that respond to both energy-performance requirements and established local processing practices [15].

3.5. Implications, Limitations, and Validation Requirements

The integration of biomass consumption measurements, thermal profiles, and traditional operating practices provides a systematic framework for evaluating energy utilization in kolang-kaling processing. SFC, boiling duration, and temperature characteristics serve as complementary indicators for identifying factors associated with process performance. These parameters also provide a technical basis for evaluating

potential improvements in fuel management, heat transfer, and operational consistency while considering the practical requirements of local processors.

Nevertheless, SFC represents biomass consumption normalized by processed fruit mass rather than a direct measurement of thermal efficiency. A comprehensive energy assessment requires additional parameters, including biomass calorific value, fuel moisture content, water mass, evaporation losses, and heat-transfer characteristics. Furthermore, variations in stove geometry, batch size, combustion conditions, and operator practices may influence the observed relationships. Standardized measurement procedures, instrument calibration, repeated observations, and appropriate statistical treatment are therefore essential for ensuring reliable comparisons across production units [1], [6], [15].

The findings provide a foundation for developing community-appropriate biomass heating technologies through the integration of scientific measurements and local knowledge. Future validation should involve controlled comparisons between traditional and improved boiling systems under equivalent operating conditions and fruit-quality requirements. Evaluating fuel consumption, thermal performance, operational safety, economic feasibility, and user acceptance will be essential for determining whether proposed technological modifications deliver measurable benefits while remaining compatible with established community practices [13], [14].

4. CONCLUSION

This methods-demonstration study proposes an integrated framework for evaluating thermal characteristics, biomass consumption, and traditional heat-management practices in sugar palm fruit processing. The synthetic numerical example illustrates an analysis workflow but does not establish actual fuel consumption, temperature profiles, or correlations in Kampung Kokolaka.

The proposed framework identifies fuel moisture management, standardized heating measurements, and consistent processing endpoints as priorities for subsequent empirical investigation. Claims of improved efficiency or community impact require field validation and appropriate energy-balance measurements.

Overall, this research framework provides a foundation for the recontextualization of local knowledge into measurable thermal parameters and the subsequent development of community-appropriate biomass heating technologies. Its application is expected to support evidence-based process improvement while preserving traditional knowledge, maintaining product quality, and promoting sustainable energy utilization in small-scale kolang-kaling production.

Data Availability and Research Integrity Statement

The numerical dataset of 15 cycles and the associated temperature profiles, tables, correlations, and plots are synthetic examples created solely to demonstrate the proposed analytical workflow; they are not measurements from Kampung Kokolaka or any actual production units. No participant-level interview or ethnographic dataset is reported in this manuscript. The synthetic dataset may be shared upon reasonable request. Future field data will be collected only after appropriate consent and documented protocols.

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