ORIGINAL ARTICLE

PATCHOULI DISTILLATION WASTE–RICE HUSK BIOBRIQUETTES: BIOMASS COMPOSITION EFFECTS ON FUEL QUALITY

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ABSTRACT
Growing energy demand and the accumulation of agricultural and agro-industrial residues motivate the development of solid biofuels from locally available biomass. This study evaluated how three ratios of patchouli oil distillation waste (PW) and rice husk (RH)—20:80, 30:70, and 40:60—affected biobriquette moisture content, ash content, volatile matter, and combustion rate. Each formulation contained 12% tapioca adhesive and was compacted at 4,252 kPa. Three reported laboratory measurements per formulation were summarized descriptively as mean ± standard deviation, while combustion rate was represented by one reported value per formulation. Moisture increased from 12.78 ± 0.30% to 19.39 ± 0.61%, ash decreased from 41.19 ± 0.30% to 29.81 ± 1.79%, and volatile matter increased from 33.39 ± 0.20% to 47.07 ± 2.45% as the PW proportion increased. The reported combustion rate increased from 0.3028 to 0.5849 g/s. The 20% PW–80% RH formulation offered the lowest moisture content and slowest mass loss but the highest ash content, indicating a clear property trade-off rather than a universal optimum. All formulations exceeded the study's SNI 01-6235-2000 benchmark limits for moisture, ash, and volatile matter. The findings support this waste combination as a preliminary biomass-valorization pathway and identify drying, carbonization, binder optimization, and broader fuel-quality testing as priorities before practical deployment.

Keywords: biobriquettes, biomass composition, patchouli distillation waste, renewable energy, rice husk

INTRODUCTION

The transition from fossil-intensive energy systems toward renewable alternatives has increased interest in agricultural and agro-industrial residues as locally available bioenergy resources. Loose lignocellulosic biomass is often difficult to handle because of low bulk density, heterogeneous particle structure, high transportation volume, and variable moisture, whereas densification can convert such residues into more uniform solid fuels with improved handling and storage characteristics (Kaliyan & Morey, 2009; Tumuluru et al., 2011; Kpalo et al., 2020). At the system level, briquetting can also support waste valorization and decentralized energy supply, although its environmental and economic advantages depend on process energy, feedstock logistics, equipment scale, and end-use performance rather than densification alone (Hu et al., 2014; Bot et al., 2022).

Biobriquette quality is multidimensional. Moisture content, ash content, volatile matter, fixed carbon, calorific value, density, compressive strength, durability, ignition behavior, burning rate, and emissions are commonly used to characterize whether a densified biomass fuel is technically suitable for a particular application. These properties are controlled by feedstock composition and by process variables such as particle size, moisture, pressure, temperature, binder type, and binder concentration. Classical experimental work has shown that compressive force, particle size, and moisture condition influence the mechanical response of densified biomass (Mani et al., 2006), while species and compacting pressure can change relaxed density and compressive strength (Mitchual et al., 2013). Reviews of briquetting research similarly identify pressure, feedstock moisture, granulometry, temperature, and binder behavior as recurrent determinants of product quality (Marreiro et al., 2021; Obi et al., 2022).

Binder selection is particularly important when briquettes are produced under relatively low compaction pressures. Starch-based and other organic binders can improve particle adhesion and durability, but binder addition may also modify density, moisture, ash, ignition, and combustion behavior. Muazu and Stegemann (2015) showed that blending rice husk and corn cob and changing operating variables altered briquette durability, while their later work demonstrated that different binders produced distinct effects on density, strength, energy value, and combustion characteristics (Muazu & Stegemann, 2017). Experimental studies with molasses and other binders likewise show that binder proportion and applied pressure can influence density and burning behavior (Thabuot et al., 2015; Tanui et al., 2018). These findings indicate that a fixed binder level should be interpreted as one element of a larger formulation system rather than as an isolated processing choice.

Rice husk is a relevant feedstock because it is abundant in rice-producing regions and contains a combustible lignocellulosic fraction, but it also presents a recurring challenge: its mineral content can yield high ash after combustion or carbonization. Rice-husk briquette studies have demonstrated that binder type and moisture condition influence physical and thermal properties (Arewa et al., 2016; Saeed et al., 2021). Cold densification studies further show that particle size, mold conditions, and blending with sawdust can change density, durability, heating value, and ash content (Rahaman & Salam, 2017). Deshannavar et al. (2018) also demonstrated that binder percentage influences density and compressive properties in rice-husk-based briquettes. More recent work has reported ash contents in the mid-40% range for rice-husk biochar briquettes, illustrating the importance of the silica-rich mineral fraction when interpreting rice-husk-dominant formulations (Lubwama et al., 2024).

The influence of raw-material composition extends beyond ash. Combustion studies using highly densified briquettes indicate that biomass type affects flaming and char-combustion duration through differences in composition, density, surface area, and fixed-carbon behavior (Ito et al., 2022). Carbonization conditions can further change ignition and combustion characteristics of rice-husk briquettes (Kipngetich et al., 2023). Research on mixed rice-husk or rice-husk-char briquettes has also documented changes in combustion rate and gaseous emissions when binder or additive composition is modified (Wongwuttanasatian & Sakkampang, 2016). Studies of charred agricultural-waste briquettes likewise demonstrate that particle size and compaction pressure influence proximate, mechanical, and combustion properties (Sunnu et al., 2023). Accordingly, a composition experiment should be interpreted as a coupled feedstock–process system even when only the biomass ratio is intentionally varied.

Blending is nevertheless a practical strategy for improving selected fuel properties because one residue can compensate for an unfavorable characteristic of another. For example, mixed-biomass briquettes have shown composition-dependent changes in moisture, ash, volatile matter, calorific value, and emissions (Rezania et al., 2016; Rudiyanto et al., 2023). Studies involving rice straw have also shown that binder type, hot-pressing temperature, particle size, and biomass-to-binder ratio can be optimized simultaneously rather than one variable at a time (Chou et al., 2009). Recent blended rice-husk research similarly indicates that reducing or combining the rice-husk fraction with other biomass can substantially alter ash and energy properties (Lichinga et al., 2026). This literature establishes a strong rationale for testing underused residues as co-feedstocks, while also emphasizing the need to avoid overgeneralizing from a small number of formulations.

Patchouli oil distillation generates a solid residue that remains an underutilized lignocellulosic by-product in many producing areas. The original manuscript identified substantially more briquette research on rice husk combined with coconut shell, bioslurry, coffee waste, cassava-derived binders, and other biomass than on direct blending of patchouli distillation waste with rice husk. Indonesian studies confirm that biomass composition, particle size, and adhesive concentration can alter briquette quality (Harnawan & Radityaningrum, 2019; Satriawan et al., 2024), but they do not directly resolve the performance of the PW–RH pair used here. The novelty of the present work is therefore application-specific rather than technological: it evaluates a relatively underreported combination of two waste streams and maps how three composition ratios shift four measured fuel-quality indicators. This positioning is consistent with broader reviews that emphasize feedstock-specific characterization and process optimization as prerequisites for reliable briquette design (Sanchez-Roque et al., 2025).

Accordingly, this study aimed to determine how three patchouli oil distillation waste–rice husk compositions (20:80, 30:70, and 40:60) influence moisture content, ash content, volatile matter, and combustion rate, and to identify which formulation offers the most favorable performance within the tested conditions. Because the study measures only four fuel-quality indicators and does not establish an application-specific weighting system, the term "most favorable" is used comparatively rather than as evidence of standards compliance, commercial readiness, or universal superiority.

METHOD

This study used a quantitative laboratory experimental design conducted from March to June 2026. Biobriquette preparation was carried out at the Mechanical Engineering Laboratory of Manado State Polytechnic, whereas characterization was performed at the Manado Standardization and Industrial Services Center (BSPJI) laboratory and the Manado State Polytechnic laboratory. Two biomass feedstocks were used: patchouli oil distillation waste (PW) and rice husk (RH). Three formulations were evaluated: 20% PW–80% RH, 30% PW–70% RH, and 40% PW–60% RH. Each formulation contained 12% tapioca adhesive and was compacted at a reported pressure of 4,252 kPa.

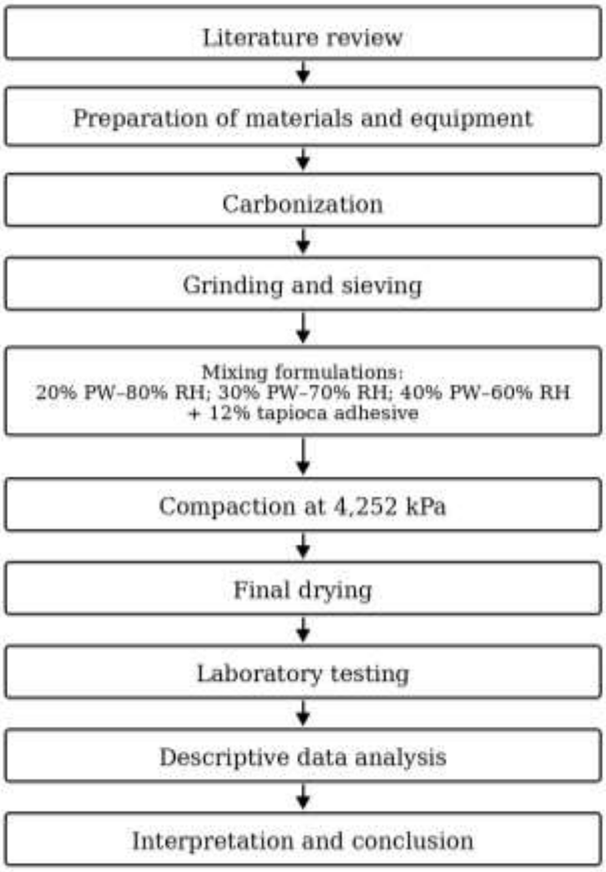

Figure 1. Experimental workflow for patchouli distillation waste–rice husk biobriquettes

The documented production sequence comprised preparation of materials and equipment, carbonization, grinding and sieving, formulation mixing, briquette compaction, final drying, laboratory testing, descriptive data analysis, and interpretation. The experimental record did not report carbonization temperature and duration, final drying temperature and duration, particle-size range, briquette dimensions or target mass, mixing duration, or exact equipment models used for the individual tests. These details are therefore reported as not documented rather than reconstructed from assumptions. This limitation is material because the literature shows that moisture, particle size, pressure, binder conditions, and thermal pretreatment can substantially alter briquette structure and performance (Mani et al., 2006; Kaliyan & Morey, 2009; Tumuluru et al., 2011; Chou et al., 2009). Figure 1 summarizes the process steps that are supported by the available experimental record.

Moisture content, ash content, and volatile matter were recorded for three reported measurements within each formulation (V1.1–V1.3, V2.1–V2.3, and V3.1–V3.3). The experimental record does not establish whether these observations represent independent production batches, technical repeats, or subsamples; they are therefore treated in this revision as replicate laboratory measurements rather than independent experimental units. Combustion-rate data were available as one reported observation for each formulation. The study used SNI 01-6235-2000 as a comparative quality benchmark and applied maximum limits of 8% for moisture, 8% for ash, and 15% for volatile matter. The standard is titled Briket arang kayu (wood-charcoal briquettes); therefore, the comparison is treated as a screening benchmark and not as evidence of formal product certification for mixed agricultural-residue briquettes (Badan Standardisasi Nasional, 2000).

The combustion-rate values in the source dataset are numerically consistent with $r = (M0 - M1)/t$, where M0 is initial mass (g), M1 is final mass (g), and t is elapsed combustion time (s). Because the recorded mass is expressed in grams and time in seconds, the corresponding unit is g/s. Temperature values are retained as reported in the laboratory dataset, but the source record does not specify the measuring instrument or whether the value represents a peak, mean, or endpoint temperature. For moisture, ash, and volatile matter, the three reported measurements were summarized using the arithmetic mean and sample standard deviation. No inferential statistical test was applied because independence of the three measurements was not established and the combustion-rate dataset contains only one value per formulation. Consequently, the findings are interpreted descriptively and terms implying statistical significance are avoided.

For interpretation, the four measured outcomes were not combined into a single composite score because the manuscript record did not specify a weighting scheme and because combustion rate is application-dependent. Lower moisture, ash, and volatile matter were evaluated relative to the benchmark limits applied in the original study, while combustion rate was interpreted as a mass-loss indicator rather than as an independent measure of thermal efficiency. This approach is consistent with the broader briquetting literature, which treats fuel quality as a combination of mechanical, proximate, thermal, and combustion properties rather than a single parameter (Obi et al., 2022; Kpalo et al., 2020).

The study involved biomass materials only; no human participants, animals, personal data, or participant consent were involved. Human- or animal-participant ethics procedures were therefore not applicable to the reported experiment. The numerical data used in the analysis are presented in Tables 1 and 2. Equipment-calibration identifiers and laboratory quality-control records were not provided in the manuscript record and are consequently not claimed in this article.

RESULTS AND DISCUSSION

The laboratory data show a consistent directional change across the three formulations (Table 1). As the PW proportion increased from 20% to 40%, mean moisture content rose from 12.78% to 19.39%, mean ash content declined from 41.19% to 29.81%, and mean volatile matter rose from 33.39% to 47.07%. These patterns are descriptive and should not be interpreted as statistically significant differences because the independence of the replicate observations was not established and no inferential test was performed.

Table 1. Laboratory results and descriptive summaries for proximate-quality parameters

Formulation	Replicate	Moisture content (%)	Ash content (%)	Volatile matter (%)
20% PW–80% RH	V1.1	13.10	40.86	33.23
	V1.2	12.75	41.29	33.61
	V1.3	12.50	41.43	33.32
	Mean ± SD	**12.78 ± 0.30**	**41.19 ± 0.30**	**33.39 ± 0.20**
30% PW–70% RH	V2.1	14.91	38.41	34.86
	V2.2	14.73	38.89	35.37
	V2.3	13.97	38.71	35.51
	Mean ± SD	**14.54 ± 0.50**	**38.67 ± 0.24**	**35.25 ± 0.34**
40% PW–60% RH	V3.1	18.73	30.79	45.27
	V3.2	19.92	27.74	49.86
	V3.3	19.52	30.89	46.08
	Mean ± SD	**19.39 ± 0.61**	**29.81 ± 1.79**	**47.07 ± 2.45**

Moisture Content

The 20% PW–80% RH formulation had the lowest mean moisture content (12.78 ± 0.30%), followed by 30% PW–70% RH (14.54 ± 0.50%) and 40% PW–60% RH (19.39 ± 0.61%). Thus, increasing the proportion of patchouli distillation waste was associated with higher final moisture under the tested processing conditions. Moisture is a critical briquetting variable because water affects particle deformation, bonding, storage stability, ignition, and the amount of heat diverted to evaporation. Mani et al. (2006) demonstrated that moisture interacts with compressive force and particle size in densified biomass, while Saeed et al. (2021) found that controlled initial moisture materially influenced the density, durability, and calorific performance of rice-husk briquettes. Reviews likewise emphasize that neither extremely dry nor excessively wet feedstock is desirable because the optimum moisture range depends on biomass type, binder, temperature, and pressure (Kaliyan & Morey, 2009; Marreiro et al., 2021). In the present experiment, all three formulations exceeded the 8% moisture benchmark. The result therefore points to final drying, initial feedstock conditioning, and binder-water management as priority variables for the next optimization stage rather than proving that PW itself is intrinsically unsuitable.

Ash Content

Mean ash content decreased as the PW proportion increased: 41.19 ± 0.30% at 20% PW–80% RH, 38.67 ± 0.24% at 30% PW–70% RH, and 29.81 ± 1.79% at 40% PW–60% RH. The direction of this trend is consistent with the possibility that the rice-husk fraction contributed substantially to the mineral residue; however, the present experiment did not measure silica or elemental composition, so the mechanism cannot be established directly. High ash is a well-recognized challenge in rice-husk-based solid fuels. Lubwama et al. (2024) reported ash contents of approximately 44–47% for rice-husk biochar briquettes and related the high residual fraction to the mineral-rich characteristics of rice husk. Deshannavar et al. (2018) and Arewa et al. (2016) likewise showed that rice-husk briquette properties can vary substantially with binder system and formulation. Recent blended-biomass research indicates that combining rice husk with lower-ash co-feedstocks can reduce ash and improve some energy properties, although the outcome depends on the blending ratio and process route (Lichinga et al., 2026). Despite the decline observed here, every formulation remained far above the 8% ash benchmark. Therefore, the lower ash value of the 40% PW formulation represents a relative improvement within the experiment, not standards compliance.

Volatile Matter

Mean volatile matter increased from 33.39 ± 0.20% in the 20% PW–80% RH formulation to 35.25 ± 0.34% in the 30% PW–70% RH formulation and 47.07 ± 2.45% in the 40% PW–60% RH formulation. This trend indicates that the two feedstocks and/or their thermal histories contributed differently to the material released during heating. The present experiment did not characterize volatile compounds or the cellulose, hemicellulose, lignin, and extractive fractions of the feedstocks; consequently, the increase cannot be attributed directly to a specific patchouli-derived compound. Carbonization is an important alternative explanation. Kipngetich et al. (2023) showed that carbonization changes the combustion behavior of rice-husk briquettes, and Sunnu et al. (2023) demonstrated that pyrolysis, particle size, and pressure influence proximate and combustion characteristics of charred agricultural-waste briquettes. Because carbonization temperature and duration were not documented in the available record, thermal-processing history must be treated as an uncontrolled explanatory factor. All formulations exceeded the 15% volatile-matter benchmark, reinforcing the need for documented and optimized carbonization conditions.

Combustion Rate

Table 2 presents the reported mass-loss and temperature data. The combustion-rate values increased from 0.3028 g/s at 20% PW–80% RH to 0.4543 g/s at 30% PW–70% RH and 0.5849 g/s at 40% PW–60% RH. These values correspond to the recorded mass difference divided by elapsed time in seconds.

Table 2. Reported combustion-rate test data

Formulation	M0 (g)	M1 (g)	Time (s)	Recorded temperature (°C)	Combustion rate (g/s)
20% PW–80% RH	58	31	89.18	347.6	0.3028
30% PW–70% RH	68	30	83.65	392.2	0.4543
40% PW–60% RH	84	31	90.61	357.7	0.5849

The increase in combustion rate occurred in the same direction as the increase in volatile matter, but the dataset is too small to establish a statistically meaningful correlation. The relationship is nevertheless plausible in the context of previous combustion research. Ito et al. (2022) demonstrated that raw-material composition, density, specific surface area, holocellulose, and fixed carbon contribute to flaming and char-combustion duration in highly densified biomass briquettes. Wongwuttanasatian and Sakkampang (2016) also reported composition-dependent changes in combustion rate and emissions for rice-husk-based briquettes containing molasses and glycerin. Thabuot et al. (2015) found that pressure and binder proportion influenced density, calorific value, and burning rate in holey biomass briquettes. These studies support interpreting the present mass-loss trend as a formulation-related combustion response, while also showing why a single combustion-rate value cannot substitute for ignition time, thermal efficiency, calorific value, or emission testing. A lower mass-loss rate may be desirable for longer-duration combustion, whereas a higher rate may be useful where rapid heat release is preferred; the application determines which profile is advantageous.

Integrated Interpretation and Practical Significance

The four indicators reveal a distinct formulation trade-off. Increasing PW from 20% to 40% reduced ash, which is favorable relative to the benchmark, but simultaneously increased moisture, volatile matter, and combustion rate. Conversely, the 20% PW–80% RH formulation had the lowest moisture and slowest mass loss but the highest ash. The 30% PW–70% RH formulation occupied an intermediate position across the measured variables. On this basis, the phrase “best formulation” would be too broad unless a weighting rule is defined. The 20% PW–80% RH formulation is more accurately described as the most favorable among the tested conditions for the combined criteria of lower moisture and slower mass loss, whereas the 40% PW–60% RH formulation is comparatively favorable for lower ash. None of the formulations met all three proximate-quality benchmark thresholds.

This multidimensional interpretation is consistent with prior densification studies. Muazu and Stegemann (2015) found that biomass blending and operating variables can improve one performance dimension while imposing trade-offs in others, and their binder study showed that materials enhancing durability or density do not necessarily maximize all combustion characteristics simultaneously (Muazu & Stegemann, 2017). Rahaman and Salam (2017) similarly demonstrated that adding sawdust to rice-straw briquettes could improve stable density, heating value, and ash performance, but the result depended on particle size, pressure, and mold geometry. Tanui et al. (2018) found that binder proportion strongly affected ash, moisture, density, shatter index, and calorific value, underscoring the need to optimize multiple responses rather than a single outcome. The present PW–RH experiment should therefore be viewed as an initial composition screen that identifies the direction and magnitude of trade-offs requiring subsequent multi-factor optimization.

The benchmark comparison also requires care. SNI 01-6235-2000 is formally a standard for wood-charcoal briquettes (Badan Standardisasi Nasional, 2000). Using its thresholds provides a useful screening reference because moisture, ash, and volatile matter are fundamental solid-fuel properties, but passing or failing those values should not be interpreted as formal certification of a mixed patchouli-residue–rice-husk fuel. Feedstocks differ in mineral composition, carbonization response, ash chemistry, density, and binder requirement. International research demonstrates wide property ranges across briquettes made from rice husk, rice straw, water hyacinth, empty fruit bunch, sawdust, charcoal fines, and other agricultural residues (Rezania et al., 2016; Arewa et al., 2016; Rahaman & Salam, 2017; Lubwama et al., 2024). Therefore, the current noncompliance is best interpreted as evidence that the reported process requires refinement, not as proof that the feedstock combination cannot be developed further.

From a process-design perspective, the next stage should manipulate variables that were fixed or undocumented in the present experiment. Particle size and pressure are logical candidates because densification studies repeatedly show effects on density, strength, and energy demand (Mitchual et al., 2013; Mani et al., 2006). Binder concentration should also be varied because starch-based and alternative binders can materially change durability, density, moisture, combustion behavior, and energy value (Obi et al., 2022; Muazu & Stegemann, 2017). Carbonization temperature and duration should be explicitly controlled because thermal treatment determines volatile matter, fixed carbon, ignition characteristics, and char behavior (Kipngetich et al., 2023; Sunnu et al., 2023). Finally, an optimization design such as a factorial or response-surface experiment would allow the interaction of composition, binder level, particle size, carbonization, pressure, and drying to be quantified rather than adjusted sequentially.

The practical implications extend beyond laboratory fuel quality. Briquetting may improve the usability and transport of agricultural residues, but technical success is only one dimension of sustainable deployment. Hu et al. (2014) demonstrated that agricultural-residue briquetting can produce economic, environmental, and social benefits at an operating-plant scale, while Bot et al. (2022) showed that the energetic and economic viability of residue briquetting depends on the specific feedstock and process energy requirement. Such evidence cautions against translating laboratory feasibility directly into sustainability claims. For PW–RH briquettes, future scale-up should quantify energy consumed in carbonization, drying, grinding, and compaction; usable energy delivered through calorific and thermal-efficiency testing; mechanical losses during handling; emissions during combustion; and the availability and seasonal variability of both residues.

The literature also shows that combustion and emissions must be evaluated together. Wongwuttanasatian and Sakkampang (2016) observed that formulation changes altered both combustion characteristics and gaseous emissions, while Rezania et al. (2016) demonstrated that biomass blending can change proximate properties and flue-gas behavior. Consequently, a faster or slower combustion rate should not be interpreted as an environmental advantage without direct measurement of CO, CO2, NOx, particulate matter, and other relevant emissions. The current experiment did not measure emissions, calorific value, fixed carbon, ignition time, or thermal efficiency, so its sustainability conclusion remains preliminary.

Transferability is another important boundary. Rice-husk mineral content can vary with cultivar, soil conditions, cultivation practices, and processing, while patchouli distillation residue can vary with plant material, distillation intensity, storage, and residual moisture. The reviewed literature repeatedly demonstrates that feedstock identity and preprocessing affect briquette quality (Tumuluru et al., 2011; Kaliyan & Morey, 2009; Sanchez-Roque et al., 2025). The present results therefore describe the materials and laboratory conditions used in this experiment and should not be generalized automatically to other patchouli-producing regions or production scales. Replication with characterized feedstocks from multiple sources would be necessary to determine whether the observed trends are robust.

Relative to the international state of the art, the present study is deliberately narrower than many recent briquette investigations, but that narrowness clarifies its contribution. Several studies have combined proximate analysis with calorific value, durability, density, compressive strength, thermogravimetric behavior, or emission measurements (Deshannavar et al., 2018; Saeed et al., 2021; Lubwama et al., 2024). Others have used systematic optimization of pressing temperature, particle size, binder ratio, or compaction conditions to identify operating windows rather than only composition trends (Chou et al., 2009; Tanui et al., 2018). The PW–RH experiment does not yet reach that level of process optimization; instead, it provides an initial screening result for a feedstock pairing that has received comparatively little direct attention.

Its value is therefore strongest when used to formulate the next experimental questions: whether controlled carbonization can lower volatile matter, whether improved drying can reduce moisture without weakening briquette integrity, whether lower-rice-husk formulations can reduce ash without producing excessive mass loss, and whether binder concentration can be reduced while retaining sufficient mechanical strength. Framing the contribution in this way places the study within the progression from feedstock screening to process optimization and, ultimately, to performance and sustainability validation.

Several methodological limitations should be considered when interpreting the study. Only three PW–RH ratios were tested, all with the same 12% tapioca adhesive and one reported compaction pressure. The experimental record did not specify carbonization temperature and duration, drying conditions, particle-size range, briquette geometry, exact equipment models, calibration information, or whether the three proximate measurements were independent production replicates. Combustion rate was represented by a single observation for each formulation. Calorific value, fixed carbon, density, compressive strength, durability, ignition time, thermal efficiency, and gaseous or particulate emissions were not measured. These limitations prevent inferential claims, restrict reproducibility, and make a definitive ranking of formulations inappropriate. Nonetheless, the data remain useful as an initial screening dataset because they reveal internally consistent composition-related trends and clearly identify the properties that require improvement.

CONCLUSION

The experiment provides descriptive evidence that changing the proportion of patchouli oil distillation waste and rice husk alters the measured quality profile of biobriquettes. Increasing PW from 20% to 40% was accompanied by higher moisture content, higher volatile matter, and a higher reported combustion rate, while ash content decreased. The 20% PW–80% RH formulation had the lowest moisture content and slowest mass-loss rate but also the highest ash content; it should therefore be described as the most favorable formulation only for those selected criteria, not as an overall or standards-compliant optimum. All three formulations exceeded the moisture, ash, and volatile-matter benchmark limits applied from SNI 01-6235-2000. The study's main contribution is empirical evidence on an underreported waste combination and the identification of a composition-dependent property trade-off that can guide subsequent process optimization. Before practical deployment, future studies should document carbonization and drying conditions in full, establish independent production and combustion replication, optimize binder level and particle size, and evaluate calorific value, fixed carbon, density, compressive strength, durability, thermal efficiency, and emissions. Under the current evidence, the PW–RH system is best considered a preliminary waste-to-energy formulation with potential that remains dependent on substantial process refinement.

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