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Effect of air flow rate on updraft gasification of *Tamarindus indica* L. peel: Reactor performance and syngas characteristics

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ABSTRACT

This study evaluated the updraft gasification of Tamarindus indica (tamarind) peel – an abundant agricultural waste in East Nusa Tenggara, Indonesia – under varying air flow rates. A fixed-bed updraft gasifier (3.2 kg capacity) was operated in batch mode with tamarind peel particles (1–2 cm). Four airflow rates (268, 304, 340, and 389 L/min) were tested. Reactor temperature profiles, syngas ignition delay, syngas flame duration, and stove (burner) flame temperature were measured; syngas was sampled and analyzed for the methane content by gas chromatography. Increasing the air flow rate led to significantly higher reactor and flame temperatures as well as shorter syngas ignition times and burn durations. The maximum flow (389 L/min) yielded ~801 °C in the reactor and ~1256 °C at the stove burner. Gas analysis indicated the produced syngas was almost purely methane (~99% CH_4) in the sampled fraction (reflecting the measurement focus on CH_4). Under these conditions, the cold-gas (energy) efficiency was ~27.7%, with a total syngas energy output of about 1.4 MJ per batch. These results demonstrate that tamarind peel is a viable biomass feedstock for small-scale updraft gasifiers, contributing to renewable energy production and effective waste management in dryland agricultural regions.

Keywords: updraft gasification, *Tamarindus indica* peel, biomass waste, air flow rate, syngas composition, gasification efficiency, renewable energy.

INTRODUCTION

Biomass gasification is a thermochemical process that converts organic material into a combustible gas (syngas) and a solid char residue. Syngas typically contains hydrogen (H_2), carbon monoxide (CO), methane (CH_4), carbon dioxide (CO_2), and other light hydrocarbons. By partial oxidation of biomass, gasification releases energy-rich gases while greatly reducing the volume of waste. Fixed-bed updraft gasifiers (counter-current flow) are known for achieving high carbon conversion and producing syngas with a relatively high heating value. In an updraft design, ambient air is introduced near the combustion zone, driving exothermic reactions that heat the rising gases; this configuration can convert most of the fuel carbon into syngas. However, updraft gasifiers often produce tar-laden syngas because the upper drying zone remains relatively cool. Reactor design and operating parameters (e.g. airflow, temperature) strongly affect gasifier performance and gas quality (Abineno and Koylal, 2018; Basu, 2013; Demirbas, 2005).

Tamarindus indica L. (tamarind) is a tropical fruit tree widely grown in Indonesia and other regions. The edible pulp is used in food and beverages, but the fibrous peel (11–30% of fruit weight) is usually discarded. Large-scale tamarind processing in Nusa Tenggara can generate substantial peel waste annually (Haba Bunga et al., 2024). This peel is often dumped or burned, causing pollution and wasting potential energy. Previous research has highlighted the untapped potential of tamarind waste: for example, Haba Bunga *et al.* (2025) showed that converting leftover tamarind peel into briquettes promotes clean energy use and mitigates waste (Haba

Bunga et al., 2024). Other studies have gasified various agricultural residues (e.g. oil-palm empty fruit bunches, coconut shell) in updraft systems, yielding useful syngas (Abineno and Koylal, 2018; Aprianti et al., 2020). However, direct studies on updraft gasification of tamarind peel are scarce.

This study bridges that gap by investigating how air flow rate affects updraft gasification of dried tamarind peel. The airflow and measure reactor temperature profiles, syngas ignition characteristics (delay and flame duration), stove combustion temperature, and syngas composition (methane content) were systematically varied. From syngas yield and composition, gasification efficiency and energy output were compute. The goal was to identify optimum operating conditions for tamarind-peel gasification and to demonstrate its potential contribution to decentralized renewable energy and sustainable waste management (Aditya et al., 2025).

MATERIALS AND METHODS

Experimental setup

An updraft fixed-bed gasifier (3.2 kg fuel capacity) was used in batch mode. Tamarind peel waste was collected from local sources in East Nusa Tenggara, Indonesia, then washed and oven-dried to <10% moisture content. The dried peels were chopped and sieved to 1–2 cm pieces (a typical size range for gasification feedstock). Before each run, 3.2 kg of prepared peel was loaded into the reactor. Four airflow rates were tested: 268, 304, 340, and 389 L/min (equivalent to 4.46, 5.07, 5.68, and 6.42 L/s, respectively). The air supply was provided by a controllable blower, which was calibrated with a rotameter to ensure accurate flow rates. Each airflow rate was tested in four replicate runs (16 runs total) to allow statistical analysis. No external steam or secondary air was added.

Fuel properties

Proximate analysis of the dried tamarind peel indicated ~5–6% ash content, ~75–80% volatile matter, and ~15–20% fixed carbon (percent of dry mass). The as-loaded moisture content after drying was under 10%. On the basis of these characteristics, the lower heating value (LHV) of the peel was estimated at around 15 MJ per kg (Demirbas, 2005; Kaoke et al., 2024). During gasification, the actual air–fuel ratio in the conducted tests corresponded to an equivalence ratio (ER) of approximately 0.5 at the lowest airflow, increasing to ~0.6–0.7 at the highest airflow. This ER range indicates a sub-stoichiometric combustion environment typical of gasification, although on the higher end of the ER spectrum for fixed-bed systems (Table 1).

Measurements and procedure

For each experiment, after loading the fuel, a small flame was applied at the reactor top to ignite the upper fuel bed. Once steady combustion was established in the reactor, the blower was turned on to supply air at the preset flow rate from the bottom. Thermocouples (K-type) were placed at multiple heights to monitor temperatures in the drying, pyrolysis, combustion, and reduction zones of the bed. Temperature data were logged continuously, capturing both the peak and average values in each zone over the duration of the run (Wasinarom et al., 2023).

A portion of the produced syngas (exiting from the reactor top) was directed via piping to a small burner (stove) for ignition testing. A high-speed timer was used to measure the syngas ignition delay time (the elapsed time from the start of gas flow to the appearance of a stable flame at the burner) and the flame burn duration (the length of time the syngas flame was sustained) for each run. Additional thermocouples recorded the flame temperature at the burner during syngas combustion (Mahdi and Al-Dulaimi, 2022).

Table 1. Proximate analysis and estimated lower heating value (LHV) of *Tamarindus indica* L. peel (dry basis)

Parameter	Value (wt%)	Description
Moisture content	<10%	After oven-drying prior to gasification
Volatile matter	75–80%	High volatile fraction supports good gasification behavior
Fixed carbon	15–20%	Contributes to char combustion and syngas formation
Ash content	5–6%	Moderate ash level typical of fruit-based biomass
Estimated LHV (MJ/kg)	~15	Calculated from proximate values based on biomass models

During stable operation in each trial, gas samples (~12 mL) were extracted from the syngas stream and analyzed for methane (CH_4) concentration using gas chromatography (GC, Shimadzu). Due to instrument configuration, GC quantified primarily CH_4 in the product gas; other major components (H_2, CO, CO_2, etc.) were not detected or were outside the scope of the GC analysis. The measured methane fraction, combined with the measured gas volume, was used to estimate the total syngas yield and its energy content. Cold-gas efficiency was calculated as the ratio of the syngas energy output to the energy content of the consumed biomass on an LHV basis (Basu, 2013). The total energy output (MJ per batch) was computed from the syngas volume and the methane heating value (approximately 36 MJ/m³, using CH_4's LHV at standard conditions) (Mahapatro et al., 2020).

All experimental data are reported as mean ± standard deviation. One-way analysis of variance (ANOVA) at $\alpha = 0.05$ was used to test the effect of airflow rate on each measured response variable (peak reactor temperature, ignition delay, burn duration, stove flame temperature, CH_4 content, cold-gas efficiency, and energy output) (De La Hoz and González, 2024). The assumptions of normality and homogeneity of variance were checked and met. For post-hoc analysis of differences among the four airflow conditions, the Tukey's HSD test was applied. Pairwise comparisons were considered significant at $p<0.05$ (Gutiérrez et al., 2022).

RESULTS AND DISCUSSION

Reactor temperature

Table 2 summarizes the effect of air flow rate on reactor temperature and other performance metrics. As airflow increased, the reactor temperatures rose markedly. At the lowest flow (268 L/min), the mean peak reactor temperature was only 209 ± 5 °C, whereas at the highest flow (389 L/min) the peak temperature reached 801 ± 11 °C. All pairwise comparisons showed statistically significant differences among the four airflow rates (letters "a"–"d" in Table 2 indicate groupings according to Tukey's HSD test, $p<0.05$). Figure 1 illustrates this strong positive trend. The increase in bed temperature with more air is due to intensified oxidation reactions: higher airflow supplies more oxygen, which boosts the exothermic combustion of carbon and volatiles in the fuel. This added heat accelerates biomass pyrolysis and gasification reactions, further raising the reactor temperature (Basu, 2013). Similar trends have been observed in other biomass gasification studies; for example, Aprianti *et al.* (2020) found that increasing the air flow in an updraft reactor led to higher combustion temperatures when gasifying palm empty-fruit-bunch biomass (Aprianti et al., 2020).

Notably, the 209 °C peak observed at 268 L/min corresponded to a thermocouple in the upper drying zone of the reactor. In other words, under the lowest airflow, the fuel bed above the combustion region never exceeded about 209 °C

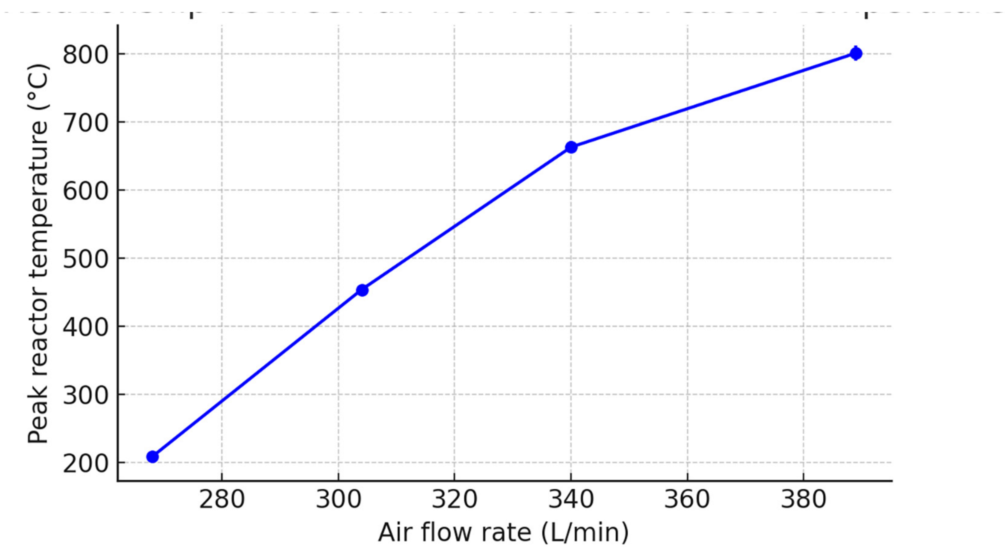

Figure 1. Relationship between air flow rate and reactor temperature (mean peak temperature ± SD at each airflow). Higher air flows intensify exothermic combustion, leading to significantly increased reactor temperatures

Table 2. Effect of air flow rate on reactor performance parameters

Air flow rate (L min⁻¹)	Reactor temperature (°C)	Syngas ignition time (s)	Syngas burning duration (s)	Stove temperature (°C)
268	209 ± 5 [a]	186.25 ± 3.2 [a]	1810 ± 45 [a]	733 ± 18 [a]
304	454 ± 7 [b]	179.75 ± 2.8 [a]	1765 ± 38 [a]	779 ± 22 [a]
340	663 ± 9 [c]	180.25 ± 3.1 [a]	1772.5 ± 41 [a]	948 ± 25 [b]
389	801 ± 11 [d]	165.25 ± 2.5 [b]	1572 ± 36 [b]	1256 ± 31 [c]

Note: values (mean ± SD) followed by different letters in the same column are significantly different ($p < 0.05$).

– indicating that the process at this low air input was largely limited to drying and mild pyrolysis, rather than a vigorous gasification reaction. The core gasification/combustion zone in this case likely did not establish a high-temperature front (active *oxidation* typically requires >600 °C). At the higher airflow rates, by contrast, much hotter temperatures were achieved deeper in the bed (e.g. ~801 °C at 389 L/min), signifying that a well-developed combustion zone and active gasification were taking place under those conditions.

The trend of rising temperature with increased air input implies that higher airflow drives the reactor into a more intense combustion regime. However, excessively high temperatures (as approached in the 389 L/min case) can pose operational challenges: an abundance of oxygen can consume the fuel bed too rapidly and lead to very high heat fluxes that stress the reactor materials. Extremely hot zones also risk ash melting or slag formation from the biomass minerals. Therefore, while more air generally raises temperature and reaction rates, an optimal balance is needed between flame intensity and reactor stability (Abineno and Koylal, 2018, 2021; Demirbas, 2005; McKendry, 2002).

Syngas ignition time and burn duration

Increasing airflow tended to shorten the syngas ignition delay. As it wass shown in Table 2, the ignition time dropped from ~186 s at 268 L/min to ~165 s at 389 L/min (a statistically significant reduction). In general, the higher reactor temperatures achieved with stronger air flow accelerate the release and ignition of volatiles, allowing the produced syngas to reach a flammable mixture sooner. In this study, a significant decrease in ignition delay was confirmed only at the highest flow (389 L/min) compared to the lowest; at intermediate flows (304, 340 L/min) the ignition times were not statistically different from the 268 L/min case (see Table 2). This suggests a threshold effect: once the reactor temperature surpasses a certain point (around 800 °C in the adopted setup), ignition is noticeably accelerated. Aprianti *et al.* (2020) similarly reported reduced ignition delays with higher airflow in updraft gasification of palm biomass (Aprianti et al., 2020). Overall, these results indicate that the air supply rate controls how quickly a combustible syngas is produced and ignited (Basu, 2013).

In contrast, the duration of the syngas flame (burn time) decreased with higher airflow. At 268 L/min the flame burned for ~1810 s on average, but only ~1572 s at 389 L/min (Table 2). Thus, supplying more air resulted in a shorter overall burn duration of the syngas, even though ignition was faster. This outcome can be explained by the more rapid consumption of the fuel under high oxidation rates: a stronger air flow both accelerates combustion and uses up the available fuel in a shorter time. In other words, a high-intensity burn (with ample oxygen) tends to be completed more quickly, whereas a lower-intensity burn lasts longer. This behavior is typical in fixed-bed gasifiers – higher airflow (and thus higher ER) enhances the power output and temperature, but reduces the total residence time of the fuel in the reactor (Demirbas, 2005).

Stove (burner) flame temperature

The syngas flame temperature at the stove burner increased substantially with airflow. As the air flow rose from 268 to 389 L/min, the peak burner temperature climbed from ~733 °C to ~1256 °C (Table 2). This reflects the greater quantity of combustible gas (and higher heating value) produced under higher-temperature gasifier conditions. In effect, the syngas generated with more air contained more chemical energy, yielding a hotter flame when burned. High flame temperatures indicate a strong thermal output, which is advantageous if the gas is used directly for heating or cooking. However, extremely high burner temperatures (in excess of ~1200 °C) could pose material and safety issues for the stove hardware. Thus, while increasing the airflow improves the syngas heating potential and flame temperature, there is again a trade-off: one must balance the goal of maximum heat output with the practical limits of the combustion device and overall system durability (Basu, 2013) (Figure 2).

Syngas composition and energy output

Gas chromatography of the product gas revealed that it was overwhelmingly methane-rich under all test conditions. Once the gasifier was operating stably, the sampled syngas was ~99% CH_4 by volume, with other expected fuel-gas components (H_2, CO, etc.) below detection or not captured by the employed sampling method. This unusually high measured methane fraction likely reflects the limitations of the gas sampling and GC analysis – essentially, only the combustible hydrocarbon fraction (CH_4) was quantified in our measurements, while hydrogen and carbon monoxide were not detected (possibly oxidized or lost) (Basu, 2013). It should be emphasized that the reported high methane content reflects only a partial characterization of the syngas (Shen et al., 2018; Stolecka and Rusin, 2020), as other combustible gases, such as CO and H_2 were not detected due to instrumental

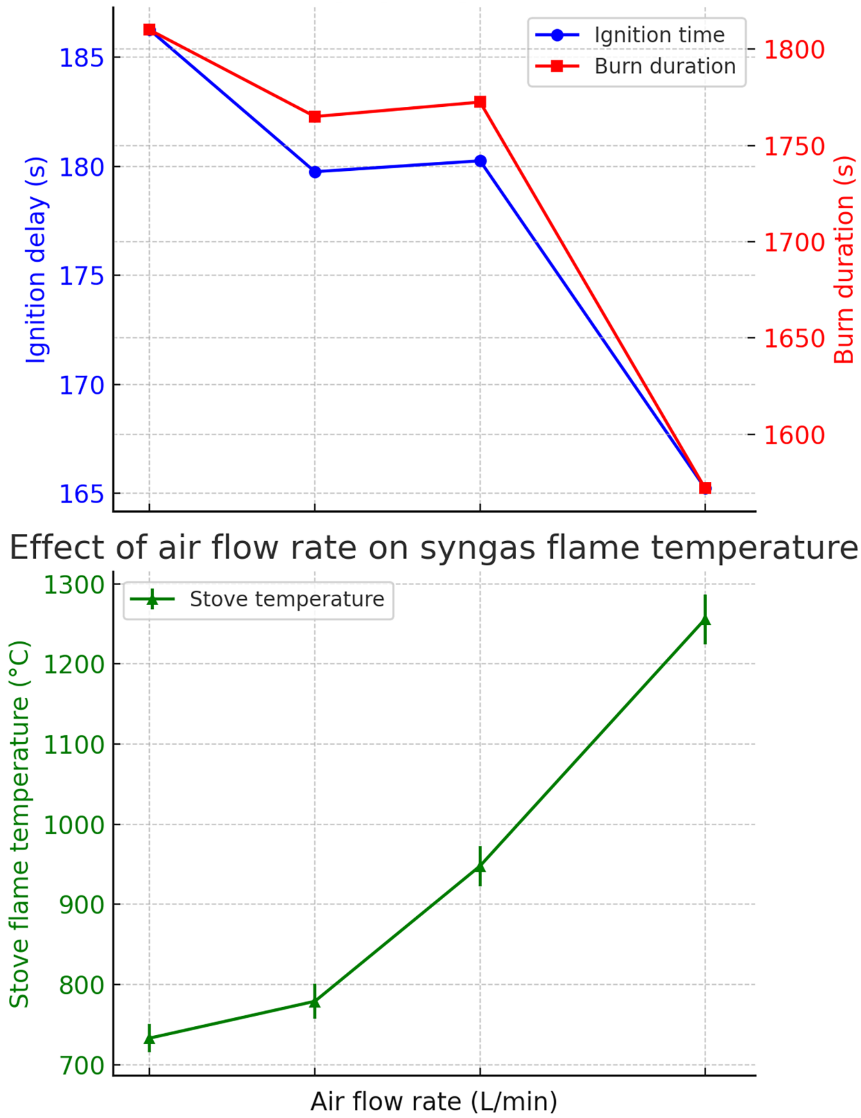

Figure 2. Effect of air flow rate on syngas ignition time and burn duration (top panel), and on syngas flame temperature (bottom panel). Higher airflow shortens the ignition delay and burn time of the syngas (blue circles = ignition delay; red squares = burn duration), while significantly increasing the flame temperature at the burner (green triangles)

limitations. Nevertheless, the finding demonstrates that the syngas from tamarind peel contained a substantial amount of chemically stored energy (primarily in CH_4 form). For context, Aprianti *et al.* (2020) reported syngas compositions from updraft gasification of palm residue with ~22.6% CH_4 and 29.2% CO under their optimal conditions (Aprianti et al., 2020), whereas here the syngas appeared to be almost purely CH_4 (likely because only the combustible fraction was sampled) (Abineno and Koylal, 2018; Basu, 2013). In practical terms, a methane-rich gas has a high heating value per unit volume; however, the absence or low levels of CO and H_2 in our analysis suggest that further process optimization or gas analysis is needed to fully characterize the gas composition.

From the measured gas volumes and composition, the cold-gas efficiency was calculated to be ~27.7% at the highest airflow (389 L/min), with a total syngas energy output of about 1.4 MJ per batch (for 3.2 kg of peel). These values are modest compared to what is reported for larger, continuous gasifiers (which can achieve 50–70% efficiency) (Aprianti et al., 2020; Basu, 2013). The relatively low efficiency in the studied batch system is attributed to short fuel residence times and the lack of any secondary reforming or tar-cracking stage – much of the fuel energy remains in the char and unburned tars, or is lost as heat. Future work could explore ways to improve the gas yield and efficiency (for example, by adding a secondary air injection or a catalytic reformer to crack tars and convert more hydrocarbons into CO/H_2 fuel gases).

Despite the moderate efficiency, the high methane content suggests that the syngas has a useful energy density for direct thermal applications. In the conducted tests, ~1.4 MJ of energy was produced as combustible gas from each batch of ~3.2 kg peel. This energy output, while not large, could be meaningful for small-scale uses (such as cooking or heating) in rural areas. Additionally, the ease of ignition and the high flame temperature (>1200 °C) observed at high airflow indicate that the syngas can be utilized efficiently in a burner. It should be noted that tar and particulate matter were not analyzed in this study – these are important considerations for syngas quality, especially in updraft gasifiers, and will be investigated in future research. The presence of tar or fine char particles in the gas could cause fouling or emission issues if the syngas is used in engines or stoves, so a detailed analysis of tar and particulate content is a priority for subsequent work.

Comparative perspective and implications

In comparison to other biomass fuels, the thermal performance observed here is in line with expectations for a high-volatile agricultural residue. The temperature profiles we measured (up to ~800 °C in the reactor and ~1250 °C in the flame) are comparable to those reported for gasifying other woody wastes (e.g., coconut shell or palm biomass) in updraft configurations (Cardona-Giraldo et al., 2025). The most distinctive aspect of tamarind peel gasification in the obtained findings is the gas composition – namely, the predominance of methane in the product gas. This result suggests that the composition of the tamarind peel (or the specific conditions in the employed updraft reactor) favored the production of CH_4 over other syngas components. One hypothesis is that the high volatile content of tamarind peel leads to substantial release of hydrocarbons that did not undergo complete cracking or oxidation in the updraft setup, thereby exiting largely as CH_4. Another possibility is that the effective equivalence ratio in our trials (ER ~0.5–0.65) was high enough to combust a majority of CO and H_2 as they formed, leaving methane as a surviving fraction from pyrolysis gases. In any case, further analysis would be needed to fully explain the gas composition. It underlines the need to fully characterize the syngas in future experiments, including measurements of H_2, CO, CO_2, and heavier hydrocarbons or tar, under various conditions. For example, introducing secondary air or a catalytic bed might increase the conversion of tars and methane into CO and H_2, raising both the gas quality and the cold-gas efficiency (Aditya et al., 2025; Haba Bunga et al., 2024). Future studies should also examine the particulate and tar content of the syngas (these were not measured in the present work), as well as long-term operating stability and the overall energy balance of the system. Addressing these factors will be important for assessing the feasibility of using tamarind peel gasification in real-world applications.

Overall, the obtained findings support the idea that underutilized agricultural residues like tamarind peel can be converted into useful bioenergy. The updraft gasification process effectively generated a combustible gas with a high flame temperature, while simultaneously reducing a problematic waste biomass. This approach could thus contribute to renewable energy supply and reduce open burning of agricultural waste in the regions where tamarind or similar crops are abundant. With further optimization (e.g., tuning the airflow, improving tar cracking, or heat recovery), small-scale gasifiers fueled by tamarind peel could become a viable component of rural energy systems, improving sustainability and waste.

CONCLUSIONS

Updraft gasification of dried *Tamarindus indica* (tamarind) peel was found to be strongly influenced by the air flow rate. Higher airflow led to significantly higher reactor temperatures and burner flame temperatures, as well as shorter syngas ignition delays and shorter syngas burn durations. In the utilized batch gasifier, the highest tested flow (389 L/min) achieved a peak of ~801 °C in the reactor and ~1256 °C at the burner, with the syngas igniting in ~165 s and burning for approximately 26 minutes. The produced syngas under these conditions was nearly pure methane (~99% CH_4 by the conducted measurements), yielding a cold-gas efficiency of ~27.7% and an energy output of ~1.4 MJ per batch (for 3.2 kg of peel).

These results demonstrate that tamarind peel is a viable biomass feedstock for updraft gasification. The process can generate a high-temperature flame and useful heat from an otherwise discarded agricultural residue. Utilizing this biomass waste for syngas production could contribute to renewable energy generation in rural or remote areas and help reduce environmental problems associated with open burning of biomass.

Importantly, these findings suggest that tamarind peel gasification has practical potential as a decentralized, small-scale bioenergy solution—particularly for off-grid or underserved communities where conventional energy access is limited. The simplicity of the reactor design, combined with the locally available feedstock and adequate energy yield, supports its relevance for distributed energy systems in dryland agricultural regions.

Future research should aim to further optimize the gasifier design and operating parameters (such as airflow rate, air distribution, and perhaps catalysts for tar cracking) to improve the gas yield and energy efficiency. It will also be important to fully characterize the syngas composition (including hydrogen, carbon monoxide, carbon dioxide, tar, and particulates) and to assess emission controls, in order to ensure clean and efficient utilization of the gas. With these improvements, small-scale gasification of tamarind peel and similar agricultural wastes could become a practical and scalable solution for sustainable energy and waste management in developing regions.

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