



Experimental Study on Refuse-Derived Fuel Moisture Content and Gasification Efficiency for Sustainable Energy

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Received: 04/06/2026

Revised: 23/06/2026

Accepted: 25/06/2026

Abstract: This study investigates the effect of moisture content in Refuse-Derived Fuel on gasification efficiency at a Waste-to-Energy Power Plant in Surakarta. Using a fixed-bed downdraft gasifier, the research experimentally tests two MC levels of 20% and 50%. High moisture content can absorb significant thermal energy during evaporation, potentially lowering reaction temperatures and syngas quality. The primary objective is to determine the optimal moisture content that maximizes Cold Gas Efficiency and syngas heating value. Results indicate that high feedstock moisture content triggers severe thermal damping within the gasifier core. Parasitic energy consumption for water vaporization significantly suppressed internal bed temperatures (Reactor and Belly zones), thereby chemically quenching primary endothermic carbon-cracking pathways. The mean Cold Gas Efficiency plummeted from an optimized peak of 42.86% in April down to a compromised level of 28.30% in June. These findings provide critical quantitative data and demonstrate that enforcing strict mechanical pre-treatment drying to lock the input moisture threshold near 20% is thermodynamically mandatory to avoid reaction quenching and ensure commercial power-generation viability in tropical climates.

Keywords: gasification; Waste-to-Energy; RDF; efficiency; syngas



SDGs Problem Solving

This research directly addresses SDGs Chapter #7 by bridging experimental analysis with real world problem solving. Optimizing gasification efficiency by managing RDF moisture content offers a scalable, scientifically proven solution to maximize Waste-to-Energy output. This technical problem-solving provides the empirical framework necessary to replace fossil fuels with reliable, sustainable alternatives from municipal waste.

Conflict of Interest Statement: The author(s) declares that the research was conducted in the absence of any commercial or financial relationship that could be construed as a potential conflict of interest.

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1. INTRODUCTION

The exponential growth of the global population and rapid urbanization have directly accelerated Municipal Solid Waste (MSW) production, posing significant environmental and public health challenges. Globally, conventional waste management pathways, such as open dumping and unsanitary landfilling, are rapidly depleting spatial capacities and triggering severe greenhouse gas emissions. In response to these crises, global energy paradigms are shifting toward sustainable waste valorization. In Indonesia, the national strategy for municipal solid waste management is progressively transitioning from primitive landfilling to advanced energy recovery technologies, commonly integrated within utility scale Waste-to-Energy (WtE) facilities (Coelho *et al.*, 2019; Qonitan, Wayan Koko Suryawan and Rahman, 2021; Rosi and Sandria, 2025). This transition is highly critical not only for municipal environmental remediation but also for advancing the national renewable energy mix through high-performance energy conversion frameworks.

Among various thermochemical conversion methodologies, gasification stands out as a highly efficient, sustainable, and environmentally benign technology for green power architecture. Unlike direct mass incineration, which often suffers from low thermal conversion efficiency and severe particulate emissions, gasification converts heterogeneous carbonaceous materials into a high-energy combustible syngas primarily composed of hydrogen (H₂), carbon monoxide (CO), and methane (CH₄) via partial oxidation under controlled sub-stoichiometric conditions (Ahmed *et al.*, 2021; Porshnov, 2022). This thermochemical conversion pathway stands out for its high fuel flexibility, yielding syngas that can cleanly power internal combustion engines and gas turbines. Furthermore, this gas product can serve as a chemical precursor for synthesizing drop in biofuels, cementing the technology's role in modern renewable energy research (Jahromi *et al.*, 2021).

However, achieving high efficiency energy conversion in commercial WtE plants heavily depends on the physical and chemical homogeneity of the input feedstock, specifically Refuse-Derived Fuel (RDF). RDF processed from Indonesian municipal streams is notoriously heterogeneous, characterized by high fractions of food waste and organic materials that retain excessive moisture due to the humid tropical climate (AlNouss *et al.*, 2024; Quan *et al.*, 2026). High moisture content (MC) in RDF presents a formidable thermodynamic barrier to effective energy conversion. Thermodynamically, water ballast within the fuel matrix acts as a critical parasitic heat sink, requiring significant latent heat for evaporation and superheating in the reactor's drying zone (Nguyen-Thi, Bui and Bui, 2023). Consequently, this massive endothermic energy drain drastically reduces the sensible heat available for downstream zones, causing a sharp drop in the gasifier's core reaction temperatures.

From an energy conversion perspective, this moisture-induced temperature drop severely inhibits thermal tar cracking mechanisms and penalizes the kinetic rates of endothermic reduction reactions, such as the water-gas and Boudouard pathways (Culsum *et al.*, 2026). As a result, the chemical energy of the solid carbon is poorly transferred to the gas phase, leading to heavy tar formation, lower syngas Lower Heating Value (LHV), and a substantial decrease in the system's global Cold Gas Efficiency (CGE) (Setioputro *et al.*, 2025). While laboratory-scale and computational equilibrium models suggest that optimal gasification conversion strictly requires fuel moisture thresholds below 20% (Etutu, Laohalidanond and Kerdswan, 2016), real-world WtE operations in tropical developing

nations are continually forced to handle high-moisture fuels due to limited drying infrastructure and monsoon seasons ([Sahda, Sentosa and Adhani, 2026](#)).

Despite its critical importance to the renewable energy sector, there is a clear research gap in comprehensive empirical data on how extreme, real-world variations in feedstock moisture directly affect the internal macro-thermal dynamics and mass balances of utility-scale, fixed-bed downdraft gasifiers. Most existing literature relies heavily on idealized, steady-state equilibrium simulations that fail to capture the chaotic physical dynamics, fluid-bed channeling, and localized reaction quenching that occur during high-moisture operations in industrial settings, such as the Waste-to-Energy facility in Surakarta. Therefore, mapping the quantitative degradation thresholds of energy conversion parameters under realistic moisture shocks is a mandatory scientific prerequisite to ensuring the commercial and operational viability of tropical Waste-to-Energy schemes.

This experimental study addresses these primary technical barriers by tracking the real time consequences of fluctuating fuel moisture inside the reactor core. By analyzing two distinct operational thresholds at 20% and 50% moisture content (MC), purposely designated to evaluate the gasifier's performance under two thermodynamic and practical extremes, the research quantifies the resulting degradation or optimization of global RDF gasification and energy efficiency. Here, the 20% MC threshold serves as the optimized baseline, representing the maximum limit for stable autothermal downdraft gasification to sustain endothermic reactions without auxiliary heating ([Setioputro et al., 2025](#)). Conversely, the 50% MC threshold reflects the real-world operational challenges at the Waste-to-Energy Plant in Surakarta during the tropical rainy season, where high organic fractions induce to extreme moisture spikes ([Qonitan, Wayan Koko Suryawan and Rahman, 2021](#)). By evaluating these two practical extremes, this research maps the dynamic temperature shifts across the oxidation and reduction beds, alongside high resolution syngas yields. Ultimately, the findings of this study provide critical quantitative baselines and robust operational guidelines needed to prevent thermal reaction quenching, maximize power generation stability, and support sustainable expansion of renewable energy in tropical regions.

2. METHODOLOGY

The study was conducted at the Waste-to-Energy Power Plant in Surakarta, Indonesia, using Gasifier Unit D. This system is designed for large scale Municipal Solid Waste (MSW) processing. The operational data analysis covered a period from March 2025 to July 2025 and compared results derived from two distinct operating conditions: Moisture Content of 20% and Moisture Content of 50%. The experimental setup and technical specifications of the gasifier unit are detailed in [Figure 1](#).

The experimental design is grounded in the thermochemical gasification principle. As detailed in the theoretical framework in [Figure 1](#), the process in a fixed-bed downdraft gasifier involves the partial oxidation of RDF to produce syngas. The reactor is conceptually divided into four distinct operational zones: drying zone with a temperature of 373K - 423K (100°C - 150°C), pyrolysis zone with a temperature of 423K - 973K (150°C - 700°C), oxidation (combustion) zone with a temperature of 973K - 1773K (700°C - 1500°C), and reduction zone with a temperature of 1073K - 1373K (800°C - 1100°C) ([Sharma et al., 2022](#); [Cvetinović et al., 2024](#)). To ensure low tar content in the final syngas, this research utilizes a downdraft configuration. The mechanical layout forces any volatiles emerging

from the pyrolysis stage to pass straight through the high temperature oxidation zone, maximizing the thermal cracking of heavy hydrocarbons.

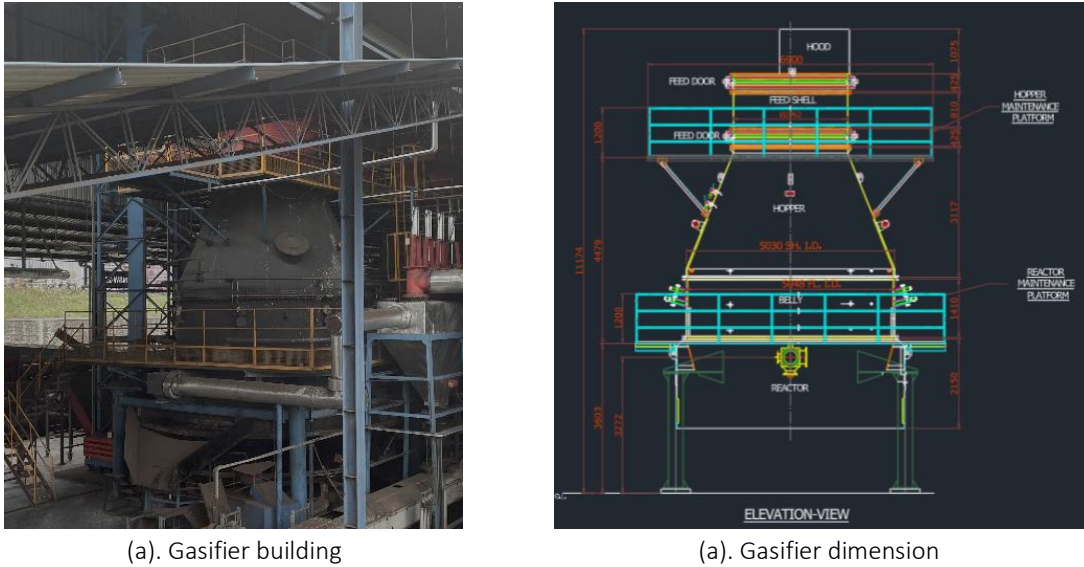


Figure 1. Gasifier in Waste-to-Energy Power Plant in Surakarta

The experimental design is grounded in the thermochemical conversion principle of gasification, a process that differs significantly from conventional incineration in its chemical pathway and environmental impact, as shown in Figure 2. Unlike incineration, which operates with excess air at temperatures typically below 800°C to produce inert exhaust (CO₂ and H₂O and hazardous ash, gasification occurs in an oxygen deprived (O₂ deprived) environment at temperatures often exceeding 1,200°C. This sub-stoichiometric condition allows the carbonaceous elements in the RDF to be converted into a high-value combustible fuel, syngas (CO and H₂), rather than being fully oxidized. Furthermore, the reducing atmosphere in gasification minimizes the formation of toxic pollutants such as NO_x, SO_x, and dioxins, which are common in incineration, while transforming inert materials into stable slag rather than hazardous fly ash.

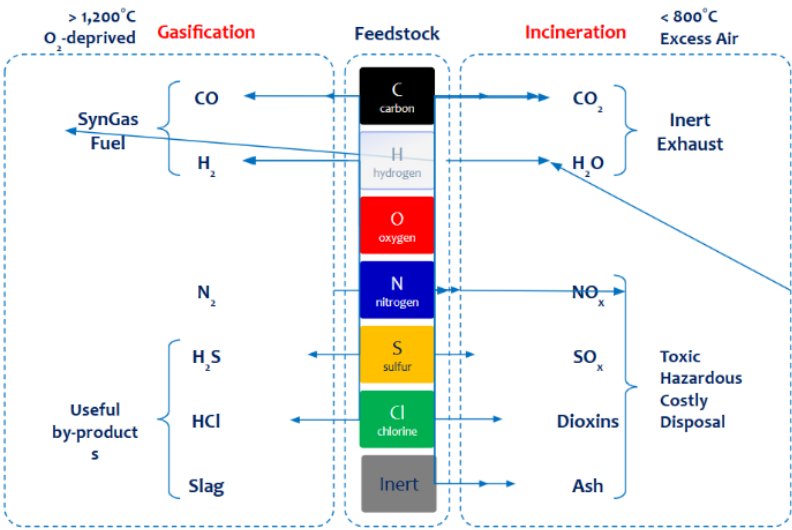


Figure 2. Gasification vs Incineration Framework (Waste-to-Energy Surakarta)

In the Waste-to-Energy Power Plant Gasifier in Surakarta, this conversion is achieved through four distinct operational zones that facilitate the progressive transformation of RDF. The process begins in the drying zone (100°C - 150°C), where moisture is removed from the feedstock, a stage that is highly sensitive to the initial moisture levels (20% and 50%) investigated in this study. As the material descends, it enters the pyrolysis zone (150° - 700°C), where the organic compounds decompose into charcoal and volatile gases in the absence of oxygen. The downdraft configuration then forces these volatiles through the oxidation (combustion) zone (700°C - 1500°C), where partial oxidation provides the thermal energy required for the entire process. Finally, in the reduction zone (800°C - 1100°C), the char reacts with the combustion products through endothermic reactions to produce the final syngas.

2.1. Prediction Model Performance

This study utilizes Refuse Derived Fuel (RDF) as its primary feedstock, produced directly from Municipal Solid Waste (MSW). To ensure the stability of the autothermal gasification process and high quality syngas output, a comprehensive multi stage preparation and sampling procedure was implemented. The process begins with mechanical screening using a trommel screen to remove fine particles smaller than 20 mm. This stage is critical because laboratory analysis indicated that these smaller fractions contain excessively high levels of moisture and ash, which can impede thermal efficiency and lead to clinker formation (Tihin *et al.*, 2023). Following the initial screening, the material undergoes a rigorous separation phase to remove non-combustible inert components. Manual sorting is conducted on a designated sorting table to extract glass, stones, ceramics, and remove ferrous metal contaminants that could damage the gasifier's internal mechanical components. Sampling was performed following a systematic quartering method to ensure that each sample used for proximate and ultimate analysis was representative of the bulk material. Approximately 100 kg of conditioned RDF was collected for each variation, from which smaller working samples were derived for laboratory testing. These samples were analyzed to determine their chemical composition (C, H, O, N, S) and energy content, providing the baseline data needed to calculate the Lower Heating Value (LHV) and assess the impact of moisture variation on the system's.

2.2. Statistical Test

To guarantee the validity and reproducibility of the results, all experimental and derived data were analyzed through a structured workflow. The statistical procedure began by converting standardized reports into a dry basis. Following this, the dataset was refined by addressing missing values, eliminating duplicates, and managing outliers. Once the data were refined, normality tests were conducted to verify the distribution. These analytical tasks were performed using IBM SPSS, Microsoft Excel, and Tecplot360.

The results of the Shapiro-Wilk normality test indicated a difference in the data's distributional behavior between the two moisture levels Table 1. At 20% MC (April), a high level of thermodynamic steady-state condition. This is verified by the p-values for Flow Rate ($p = 0.708$), Reactor A ($p = 0.387$), and Reactor B ($p = 0.687$), which comfortably exceeded the critical alpha threshold of $p > 0.05$, thereby confirming that the data follows a standard normal distribution. However, at 50% MC (June), it exhibited significant non-linear deviations, with p-values for Flow Rate, Reactor A, and Reactor B

dropping sharply below the alpha level ($p = 0.004$, $p = 0.038$, and $p = 0.014$, respectively). In thermal engineering systems, this widespread rejection of normality implies that the excessive feedstock moisture content of 50% acted as an unpredictable thermal ballast. The system was forced to undergo repeated internal temperature shocks as a large fraction of thermal energy was randomly diverted solely to evaporate the water trapped in the incoming Refuse-Derived Fuel (RDF), inducing severe turbulence and chaotic fluid dynamics over the days of operation (Dejtrakulwong and Patumsawad, 2014).

Table 1. Test of Normality

PARAMETER	P-VALUE	
	MC 20%	MC 50%
Flow Rate	0.708	0.004
Reactor A	0.387	0.038
Reactor B	0.687	0.014
Outlet Gas A	0.115	0.028
Outlet Gas B	0.040	0.331

Table 2. Test of Homogeneity

PARAMETER	P-VALUE
Flow Rate	0.3531
Reactor A	0.000025
Reactor B	0.000011
Outlet Gas A	0.2853
Outlet Gas B	0.5529

Furthermore, the Levene's test for homogeneity revealed that the variance was not uniform across the two groups. The fluidic parameter, Flow Rate ($p = 0.353$), and the water-side thermal parameters, Outlet Gas A ($p = 0.285$) and Outlet Gas B ($p = 0.055$), successfully met the assumption of homogeneity, meaning their variance spread remained statistically uniform across the periods. However, a critical thermodynamic disruption was discovered in the gas-side parameters. Reactor A ($p = 0.000025$) and Reactor B ($p = 0.000011$) failed the homogeneity test, resulting in highly significant heterogeneity in variances Table 2. This distinct heterogeneity provides robust evidence that shifting the feedstock moisture content from 20% to 50% does not merely shift the absolute temperature values but fundamentally alters the variance structure of the syngas stream. The constant shifting of the drying zone inside the downdraft gasifier under the 50% moisture load caused the gas leaving the reactor to carry inconsistent energy density, resulting in a highly volatile and non-uniform thermal spread compared to the tightly controlled, homogeneous variance profile observed during the dry baseline operation.

This study focused primarily on evaluating how feedstock moisture dictates overall system efficiency. Statistical validation from hypothesis testing (both ANOVA and T-Tests) confirmed this relationship, returning a p-value below 0.001 across all key operational variables including gas flow rate and outlet temperatures. This mathematical output confirms that the operational shifts between the 20% moisture content (April) and the 50% moisture content (June) are highly significant and cannot be attributed to random daily variations. The significant differences in the mean values demonstrate that high moisture content forces the system to operate under a completely different thermodynamic balance Table 3.

The energy penalty caused by water vaporization under the 50% MC condition limits the peak cracking temperature in the oxidation zone, which directly alters the chemical composition, density, and flow characteristics of the syngas, thereby impacting the heat transfer rates and temperature profiles across both the gas pass and the cooling water loop of the heat exchanger unit. This statistical evidence confirms that moisture content is a primary critical constraint on the operation of the Waste-to-Energy gasification system in Surakarta.

Table 3. Test of Hypothesis

PARAMETER	P-VALUE
Flow Rate	< 0.001
Reactor A	< 0.001
Reactor B	< 0.001
Outlet Gas A	< 0.001
Outlet Gas B	< 0.001

2.3. Mathematics

To assess the macro-thermal performance and thermochemical conversion efficiency of the gasifier at the Waste-to-Energy facility in Surakarta, a series of steady-state thermodynamic equations was applied. The mathematical modelling framework is organized into three sequential stages, which are determining the thermal power input, calculating the syngas energy output, and evaluating the global system efficiency. The first stage of the framework defines the baseline thermal power introduced by the solid Refuse-Derived Fuel (RDF) matrix into the system boundary, expressed as follows:

$$LHV_{MSW} = \frac{E_{in}}{M_s} \quad (1)$$

$$P_{in} = \frac{M_s \times LHV_{MSW}}{3600 \times 1000} \quad (2)$$

The second stage of the framework focuses on quantifying the useful energy rate produced by the producer gas phase using physical data extracted from the log sheets:

$$V_g = \frac{F_{end} - F_{start}}{\Delta t} \quad (3)$$

This step involves blending the recorded volumetric throughput data directly with the average lower heating value obtained from the producer gas (LHV_{PG}) tracking, the net syngas chemical power output (P_{out}) available to drive the industrial gas-engine generators is formulated as:

$$P_{out} = \frac{V_g \times LHV_{PG}}{3600} \quad (4)$$

The final stage of the mathematical modeling framework evaluates the thermodynamic degradation and net energy recovery ratio of the commercial system under varying moisture stresses. To identify the total rate of thermal dissipation, radiation, and parasitic drying enthalpy absorbed during the

feedstock evaporation phase, the Global System Power Loss (P_{loss}) is computed via energy balance difference:

$$P_{loss} = P_{in} - P_{out} \quad (5)$$

Ultimately, the Cold Gas Efficiency (η_{CGE}) of the gasifier, which indicates the percentage of solid fuel chemical energy successfully retained within the cold producer gas matrix, is defined as:

$$\eta_{CGE} = \left(\frac{P_{out}}{P_{in}} \right) \times 100\% \quad (6)$$

To provide a direct structural correlation with the primary raw field measurements, substituting the individual power equations yields the comprehensive system efficiency formula:

$$\eta_{CGE} = \left(\frac{V_g \times LHV_{PG}}{M_s \times LHV_{MSW}} \right) \times 100\% \quad (7)$$

3. RESULTS AND DISCUSSION

3.1. Feedstock Analysis

The thermodynamic and chemical performance of a twin-fire gasifier is intrinsically governed by the baseline physicochemical properties of its operational feedstock. In the Waste-to-Energy (WtE) plant configuration in Surakarta, municipal solid waste (MSW) undergoes sorting and a specialized structural transformation via wet pyrolysis, yielding a relatively homogeneous biomass matrix known as Refuse-Derived Fuel (RDF). The ultimate and proximate analyses of the foundational waste categories constituting the RDF are presented in Table 4 and Table 5.

Table 4. Ultimate analysis of MSW categories (wt%)

Waste Category	Ultimate Analysis (%)						Total
	Carbon (C)	Hydrogen (G)	Nitrogen (N)	Sulfur (S)	Oxygen (O)	Ash	
Organic	34,63	4,73	1,25	0,22	36,43	22,73	100
Paper	38,57	5,85	0,17	0,23	43,76	11,44	100
Cardboard	38,57	5,85	0,17	0,23	43,76	11,44	100
Complex Waste	59,00	8,71	0,22	0,23	17,57	14,28	100
Textile	51,00	5,38	0,59	0,24	37,13	5,66	100
Plastic	68,56	10,38	0,27	0,18	10,16	10,50	100
Other	71,16	7,57	0,45	0,21	5,03	15,59	100
Combustibles							
Fine/Small	18,84	2,78	0,94	0,44	16,65	60,34	100
Waste							

Source: Municipal Solid Waste Analysis Results, Waste-to-Energy Power Plant Surakarta

Table 5. Proximate analysis of MSW categories (wt% on Dry Basis)

Waste Category	Proximate Analysis (%)				
	Moisture Content (MC)	Volatile Matter (VM)	Ash Content	Fixed Carbon (FC)	Base Calorific Value (kcal/kg)
Organic	5,15	49,60	22,73	22,52	3244,31
Paper	6,49	67,91	11,44	14,15	4000,95
Cardboard	6,49	67,91	11,44	14,15	4000,95
Complex Waste	2,84	77,43	14,28	5,46	7802,79
Textile	3,32	77,90	5,66	13,12	5070,20
Plastic	1,99	84,96	10,50	2,55	7210,57
Other Combustibles	4,88	81,25	15,59	1,25	6724,36
Fine/Small Waste	2,65	29,61	60,34	7,41	1534,00

Source: Municipal Solid Waste Analysis Results, Waste-to-Energy Power Plant Surakarta

3.2. Producer Gas (Syngas) Quality

The fundamental thermodynamic equilibrium shifts within the twin fire gasifier pathways directly dictate both the volumetric composition and energetic stability of the resulting producer gas (PG). To monitor the composition of the of the product gas, this study utilized a Gasboard-3100P series Portable Infrared Syngas Analyzer for continuous tracking of the specific volumetric concentrations of Carbon Monoxide (CO), Carbon Dioxide (CO₂), Methane (CH₄), Hydrogen (H₂), and Oxygen (O), alongside the Lower Heating Value (LHVPG) of the gas output A stark contrast in syngas distribution emerges when comparing the dry climate operation in April (MC 20%) with the operation in June (MC 50%), as summarized in Figure 3 and Figure 4.

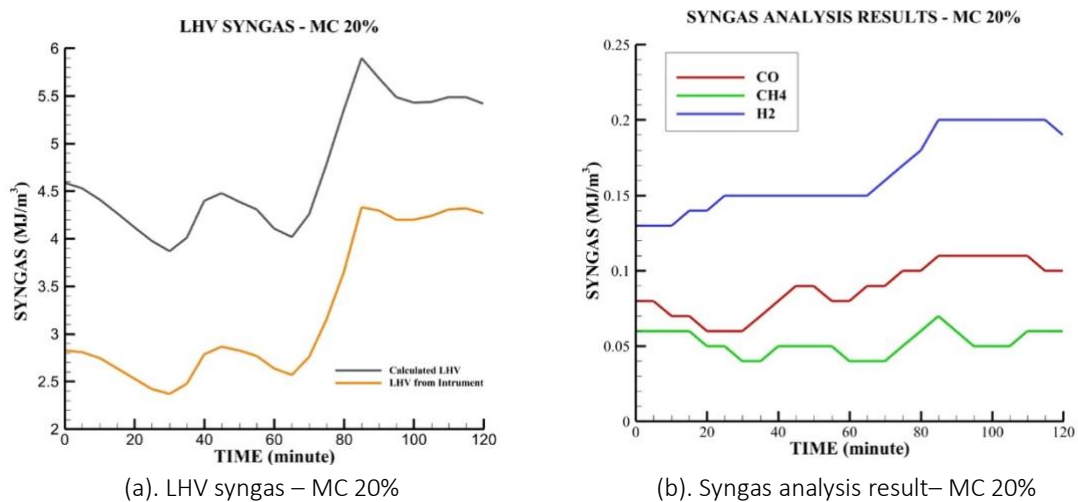


Figure 3. Producer gas quality of Moisture Content 20%

Interestingly, the behavior of hydrogen (H₂) displayed a divergent trend. In April, H₂ composition remained steady at around 1.70%-2.10%. However, in June, the water-rich environment increased H₂ production, raising the baseline to 13.00%-20.00% (Chauhan *et al.*, 2023; Ungureanu *et al.*, 2025). While an increase in hydrogen is typically desirable, the catastrophic depletion of CO, alongside a marginal drop in methane (CH₄) (averaging 0.04% in April versus 5.36% in June), severely

penalized the global energetic density of the fuel gas (Atnaw, Sulaiman and Yusup, 2013; Inayat et al., 2025). Consequently, the calculated and instrument-measured LHV profiles reflect this chemical degradation. The dry, optimal syngas from April yielded a stable calculated LHV profile averaging 5.83 MJ/m³ (4.19 MJ/m³ via instrument measurement). Conversely, the moisture quenched June syngas experienced a net energy drop, with a calculated average LHV of 4.84 MJ/m³ and a recorded value as low as 2.37 MJ/m³.

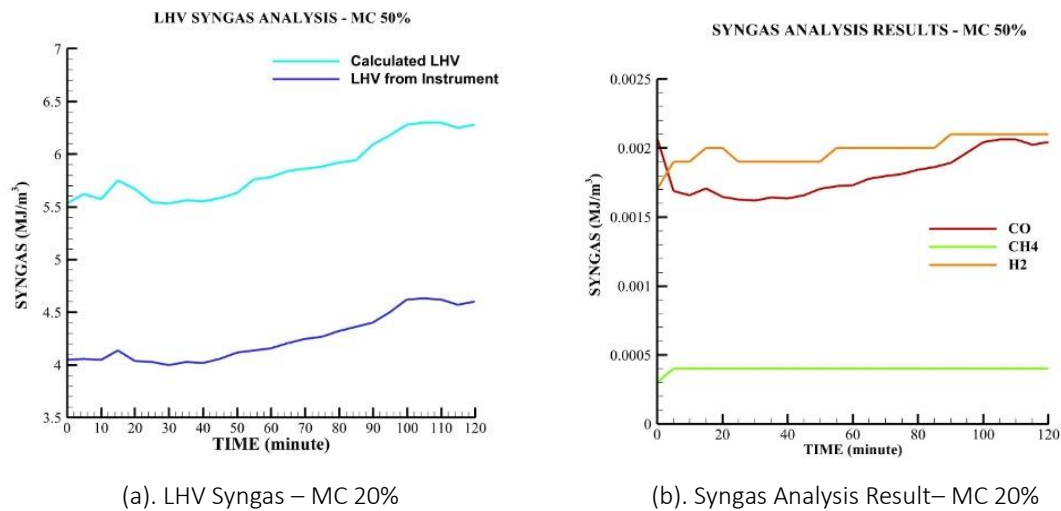


Figure 4. Producer gas quality of Moisture Content 50%

3.3. Cold Gas Efficiency

To evaluate the energy conversion performance of a Waste-to-Energy system, this study relies on Cold Gas Efficiency (CGE) as the definitive thermodynamic metric. This value maps the ratio between the chemical energy retained in the generated syngas and the latent chemical energy bound within the solid generated refuse derived fuel (RDF) input. To evaluate the overall energy performance of Gasifier D under different moisture levels, the Cold Gas Efficiency (η_{CGE}) was calculated (see Table 6).

Table 6. Cold gas efficiency calculates

Parameter	April (MC 20%)	June (MC 50%)	Unit
Feedstock Input Rate	1800	1800	kg/h
Syngas Volumetric Yield	2003.84	971.88	m ³ /h
Average Net LHV Syngas	4.12	5.61	MJ/m ³
Calculated Thermal Input	5.35	5.35	MW
Calculated Thermal Output	2.293	1.514	MW
Global System Power Loss	3.057	3.836	MW
Mean Cold Gas Efficiency	42.86	28.30	%

The overall viability of a Waste-to-Energy system is directly reflected in its η_{CGE} . This parameter measures the efficiency energy bound within the raw MSW is successfully captured in the dry syngas. The data from the 120 minute gasification trials show a clear drop in thermal efficiency as the feedstock moisture content increased from 20% in April to 50% in June. With low moisture (April), Gasifier D achieved an average η_{CGE} of 42.86%. However, during high-moisture conditions (June),

efficiency dropped significantly to 28.30%, resulting in a net efficiency loss of 14.56%. This sharp drop in CGE from 42.86% to 28.30% highlights a common operational hurdle for Waste-to-Energy plants across the tropics. Developing countries with similar climates and waste profiles, such as Thailand, Malaysia, and Brazil, face the same issue: municipal waste heavily dominated by wet organic matter and high seasonal humidity. In Malaysia, comprehensive reviews confirm that the high moisture content in municipal solid waste significantly reduces its net calorific value and limits its economic feasibility, making advanced thermal options such as gasification critical yet highly challenging to deploy economically without addressing this high moisture barrier (Fazeli *et al.*, 2016). Similarly, operational studies in Thailand confirm that running wet refuse-derived fuel (RDF) severely penalizes the system's net energy potential, necessitating energy-intensive pre-treatments such as bio-drying to prevent severe core thermal dampening (Bhatsada *et al.*, 2023). This aligns with broader thermodynamic assessments in Brazil, which demonstrate that processing high-moisture tropical feedstocks under high ambient humidity severely degrades the efficiency parameters of thermal WtE facilities (Dadario *et al.*, 2021). These regional comparisons demonstrate that the efficiency loss observed at the Surakarta plant is part of a broader thermodynamic reality, reinforcing the case for strict predrying in tropical Waste-to-Energy operations.

A notable paradox arises when comparing syngas quality to its total volume. Legally, the average net Lower Heating Value (LHV) of the syngas in June was higher (5.61 MJ/m³) than in April (4.12 MJ/m³). This happened because the excess steam in June stimulated the chemical pathways that produce high-energy hydrogen (H₂) and methane (CH₄). However, this higher energy concentration per cubic meter did not result in higher overall system efficiency (Nguyen-Thi, Bui and Bui, 2023). This is because the total volume of syngas produced in June collapsed drastically, falling from 2003.84 m³/h in April to just 971.88 m³/h in June, a drop of about 51.5%. Because the syngas volume was halved, the total power captured in the gas phase decreased from 2.293 MW in April to 1.514 MW in June. This proves that the total volume of gas produced has a much greater impact on global efficiency than the gas composition alone.

From a thermochemical perspective, this drop in gas volume, and efficiency is caused by the large amount of energy wasted on water evaporation. Even though both test periods used the same feedstock input rate of 1800 kg/h and had a constant thermal input of 5.35 MW, the system power loss rose from 3.057 MW in April to 3.836 MW in June. When waste with 50% moisture enters the reactor, a large portion of the heat generated by combustion is wasted just to convert the moisture into steam. This steam barrier cools the reactor's internal bed, lowering the temperature below the level required for effective gasification. Consequently, the key carbon cracking reaction (the Boudouard reaction) is halted, preventing the waste from forming carbon monoxide (CO) (Zainal *et al.*, 2002; Setioputro *et al.*, 2025; Culsum *et al.*, 2026). The unreacted carbon remains trapped as leftover char, lowering the carbon conversion efficiency. These indicators demonstrate that drying municipal waste to a 20% moisture threshold is mandatory for the Waste-to-Energy gasifiers in Surakarta to prevent thermal quenching and ensure commercial viability (Sahda, Sentosa and Adhani, 2026).

3.4. Reactor Temperature Distribution

The transient temperature distribution across the distinct thermochemical zones within the fixed-bed gasifier serves as a primary indicator of operational stability, heat-transfer mechanisms, and thermochemical reaction kinetics (see Figure 5). The temperature data extracted from the core reactor beds (REACTOR-A and REACTOR-B) confirms a substantial thermal suppression under high-moisture conditions. In April (MC 20%), the combustion and primary reduction zones successfully sustained high, stable temperatures required to drive charcoal reduction. However, during the June operation (MC 50%), a substantial amount of the sensible heat released during the oxidation stage was parasitically consumed as the latent heat of vaporization to convert the feedstock's structural water into steam. This thermodynamic penalty is further evidenced by the volatile behavior observed in the reactor's upper zones. The pyrolytic throat temperatures (BELLY-1A/B and BELLY-2A/B), which act as the thermal bridge for initial volatile release, exhibited restricted profiles in June due to the continuous energy sink from upstream drying. Because the core reactor temperature was heavily suppressed, the kinetics of the primary endothermic gasification reactions were severely restricted.

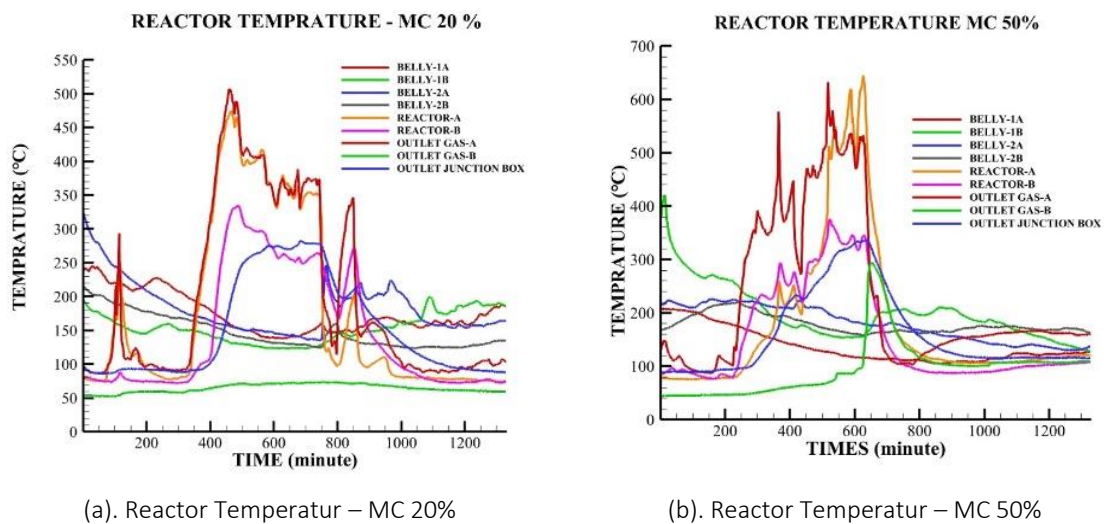


Figure 5. Reactor temperature distribution

4. CONCLUSION

This experimental study evaluated and demonstrated the critical influence of feedstock moisture content (MC) in Refuse-Derived Fuel (RDF) on the macro and microscopic gasification performance of a commercial scale downdraft reactor at the Waste-to-Energy in Surakarta facility. The empirical findings reveal that reducing the fuel moisture threshold from 50% (June) to 20% (April) is the primary thermodynamic bottleneck to achieving efficient and sustainable Waste-to-Energy conversion. The investigation highlights a significant thermochemical trade off within the reactor bed. Although the high-moisture feedstock (50% MC) initially stimulated steam-reforming pathways, inflating hydrogen (H₂) concentrations up to a range of 13.00%–20.00% and raising the volumetric Lower Heating Value (LHV) to 5.61 MJ/m³ it induced severe thermal damping inside the gasifier core. The parasitic diversion of combustion heat to supply the latent heat of water vaporization heavily quenched the localized thermal fields. This thermodynamic penalty restricted the endothermic carbon-cracking kinetics (the Boudouard reaction), causing the total syngas volumetric yield to

collapse by 51.5% (from 2003.84 m³/h to 971.88 m³/h and leaving a high fraction of unreacted residual char in the solid phase. On a macroscopic scale, this localized energy drain increased the global system power loss from 3.057 MW to 3.836 MW, ultimately reducing the net Cold Gas Efficiency (η_{CGE}) from an optimized peak of 42.86% to a compromised level of only 28.30%. Consequently, these explicit thermodynamic and operational penalties demonstrate that enforcing strict mechanical pre-treatment drying to lock the input moisture threshold near 20% is a mandatory operational requirement to secure stable chemical kinetics, maximize volumetric gas yields, and ensure the economic and commercial viability of RDF downdraft gasification at this facility.

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