CHEMICAL ENGINEERING TRANSACTIONS
VOL. 127, 2026

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Laura Capelli, Marzio Invernizzi, Selena Sironi

ISBN 979-12-81206-28-1; **ISSN** 2283-9216

DOI: 10.3303/CET26127046

Optimal RDF Gasification Medium Selection for Hydrogen-Rich Syngas Production via the Best-Worst Method

Isaac Mensah[a,*], Satyanarayana Narra[a], Julius Cudjoe Ahiekpor[b], Nana Yaw Asiedu[c]

[a]University of Rostock, Germany
[b]Kumasi Technical University, Ghana
[c]Kwame Nkrumah University of Science and Technology, Ghana
isaac.mensah@uni-rostock.de

The choice of gasification medium plays a critical role in determining syngas composition and hydrogen yield during refuse-derived fuel (RDF) gasification. Although numerous studies have examined the behaviour of individual gasifying agents, few have provided a systematic, multi-criteria comparison to identify the optimum medium for hydrogen-rich syngas production. This study evaluates four gasification media—steam, carbon dioxide (CO_2), oxygen (O_2) and air—using the best-worst method (BWM). Twelve technical, economic and environmental criteria were selected from scientific literature and assessed by experts to determine their relative importance. The resulting global weights were used to rank the gasification media. Steam gasification achieved the highest overall score (6.7109), followed by O_2 (5.2133), CO_2 (4.4608) and air (4.1295). Calorific value, hydrogen to carbon monoxide (H_2/CO) ratio and cost were identified as the most influential criteria. The proposed framework provides a transparent decision-support tool for selecting gasification media and can be applied to RDF and other waste-biomass feedstocks in waste-to-energy applications.

1. Introduction

Refuse-derived fuel (RDF), produced from the combustible fraction of municipal solid waste (MSW) such as plastics, paper, wood waste and textiles, has gained increasing attention as an alternative fuel for energy-intensive industries. Its utilisation in cement kilns, for example, has demonstrated significant reductions in fuel costs and carbon dioxide (CO_2) emissions (Morfopoulos et al., 2025).
However, direct RDF combustion presents operational challenges, including high chlorine content, corrosion, unstable combustion profiles and elevated pollutant emissions (Sharma et al., 2022). These limitations have motivated the exploration of thermochemical conversion routes that can convert RDF into cleaner, more controllable energy carriers.
Among thermochemical technologies, gasification is particularly attractive for producing hydrogen-rich (H_2-rich) syngas suitable for power generation, chemical synthesis and advanced energy systems. Compared to pyrolysis, gasification offers higher H_2 yields and improved syngas quality due to controlled oxidation conditions (Nguyen et al., 2024). The performance of gasification, however, is strongly dependent on the gasification medium. Steam, CO_2, oxygen (O_2), and air are commonly used gasifying agents, each influencing syngas composition, calorific value, conversion efficiency and environmental performance in different ways.
Steam gasification enhances H_2 production and eliminates nitrogen dilution but requires substantial heat input. CO_2 gasification improves process efficiency and contributes to CO_2 utilisation but is endothermic. O_2 gasification increases syngas energy density but is limited by O_2 production costs. Air gasification is inexpensive and widely available but produces syngas with low calorific value due to nitrogen dilution (Salem and Elsherbiny, 2022).
A substantial body of experimental and modelling research has investigated the effects of individual gasification media on syngas composition, conversion efficiency and process behaviour. Islam (2020) provided one of the most detailed modelling analyses by evaluating five gasifying agents in a fluidised bed system using ASPEN

Paper Received: 11 May 2026; Revised: 8 July 2026; Accepted: 18 July 2026
Please cite this article as: Mensah I., Narra S., Cudjoe Ahiekpor J., Asiedu N.Y., 2026, Optimal RDF Gasification Medium Selection for Hydrogen-Rich Syngas Production via the Best-Worst Method, Chemical Engineering Transactions, 127, 271-276 DOI:10.3303/CET26127046

Plus, demonstrating that steam consistently maximises H_2 content and H_2/CO ratio, while CO_2 favours carbon monoxide (CO) and methane (CH_4) formation under varying equivalence ratios.

Xiang et al. (2020) investigated the effects of equivalence ratio and gasifying agent to biomass ratio in an integrated gasification combined cycle, revealing that steam enhances H_2 production while CO_2 increases CO yield and O_2 reduces CO and CH_4 concentrations. While these investigations provide valuable insights into the behaviour of specific gasifying agents, they do not offer a systematic comparison that identifies the optimum medium for H_2-rich syngas production.

Most studies evaluate gasifying agents independently or under narrow operating conditions, making it difficult to draw generalisable conclusions. Moreover, the selection of an optimal gasification medium requires consideration of multiple, often conflicting criteria—including technical performance, economic feasibility and environmental impact—which cannot be captured through single-parameter experimental comparisons (Torkayesh et al., 2021).

This gap highlights the need for a structured, multi-criteria evaluation framework capable of integrating diverse indicators into a transparent decision-making process.

Multi-criteria decision-making (MCDM) methods have been increasingly applied in waste-to-energy (WtE) research to support technology selection (van de Kaa et al., 2017), site evaluation (Luo et al., 2020), risk assessment (Luo et al., 2021) and process optimisation (Hashemi-Amiri et al., 2023). Methods such as Analytic Hierarchy Process (AHP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), Preference Ranking Organization METHod for Enrichment Evaluations (PROMETHEE), Analytic Network Process (ANP), etc. have been used to incorporate technical, economic, environmental and social criteria into decision frameworks (Vlachokostas et al., 2021).

Among these, the best-worst method (BWM) has emerged as a robust and efficient tool for determining criteria weights using pairwise comparisons. BWM requires fewer comparisons than traditional methods such as AHP, reduces inconsistency and provides more reliable weight estimations, making it suitable for engineering decision problems involving multiple criteria (Rezaei, 2016).

In this context, the present study applies the BWM to evaluate four gasification media—steam, CO_2, O_2 and air—for H_2-rich syngas production from RDF. Twelve criteria were identified from scientific literature and grouped into technical, economic and environmental categories. Expert assessments were used to determine the relative importance of each criterion, and global weights were calculated to rank the gasification media. The study contributes to the scientific literature by:

- Identifying and structuring key criteria relevant to RDF gasification medium selection,
- Applying a holistic MCDM framework to compare gasification media, and
- Providing a systematic ranking of gasifying agents, addressing the current lack of comparative optimisation studies in the field.

This work offers a transparent decision-support tool for selecting gasification media and provides insights that can be applied to various waste biomass systems and real-world WtE applications.

2. Methodology

The methodological framework applied in this study follows the structure proposed by Rezaei (2016) for the BWM, with adaptations for gasification medium selection (van de Kaa et al., 2017).

2.1 Selection of criteria

Twelve decision criteria were identified through a targeted review of recent peer-reviewed studies (2019–2024) on H_2-rich syngas production from biomass and RDF gasification. The criteria were grouped into three categories—technical, economic and environmental—and the technical category was further divided into syngas fuel quality and syngas fuel yield. Table 1 lists the criteria and their corresponding goals (maximisation or minimisation).

2.2 Expert evaluation and ranking

Four experts with 5–20 years of experience in gasification, WtE systems and thermochemical conversion were selected using purposive sampling. Each expert independently assessed the relative importance of the criteria within each category using a 1–9 significance scale. Experts also identified the best and worst criteria in each category, as required by the BWM procedure.

Table 1: List of selected criteria in this study

Category	Criteria	Code	Goal	Reference
Technical-syngas fuel quality	Calorific value	C_1	Max	Singh and Tirkey, 2022
	H_2/CO ratio	C_2	Max	Singh and Tirkey, 2022
	Carbon conversion efficiency	C_3	Max	Nemmour et al., 2023
	Cold gas efficiency	C_4	Max	Singh and Tirkey, 2022
Technical-syngas fuel yield	H_2 percent	C_5	Max	Nemmour et al., 2023
	CO percent	C_6	Min	Nemmour et al., 2023
	Nitrogen	C_7	Min	Rey et al., 2024
	Sulphur	C_8	Min	Rey et al., 2024
Economic	Cost	C_9	Min	Pandey et al., 2019
	Availability	C_{10}	Max	Mishra et al., 2021
Environmental	CO_2	C_{11}	Min	Kaneesamkandi et al., 2023
	CH_4	C_{12}	Min	Kaneesamkandi et al., 2023

2.3 Best-worst method (BWM)

The BWM was applied in five steps:
Step 1: Define the criteria set. The twelve criteria identified from scientific literature formed the basis for evaluation.
Step 2: Select best and worst criteria. Experts specified the most and least important criteria within each category.
Step 3: Obtain best-to-others (BO) comparisons. Each expert rated the importance of the best criterion relative to all others on a 1–9 scale.
Step 4: Obtain others-to-worst (OW) comparisons. Each expert rated the importance of all criteria relative to the worst criterion on a 1–9 scale.
Step 5: Compute optimal weights and consistency ratio (CR).
The optimal weights were obtained by solving the BWM optimisation model in Eq(1). The CR was calculated from ξ* (i.e., the result of the objective function of the optimisation model) and the consistency index (CI) in Eq(2). Lower CR values indicate higher consistency. Table 2 shows the CI values. The optimal category weights were determined using the BWM solver v2.0, and CI was chosen as 5.23.

$$\left|\frac{w_B}{w_j} - a_{Bj}\right| \le \xi, for\ all\ j;\ \left|\frac{w_j}{w_w} - a_{jW}\right| \le \xi, for\ all\ j;\ \sum_j w_j = 1; \tag{1}$$

$$CR = \frac{\xi*}{CI} \tag{2}$$

Table 2: CI values (Rezaei, 2016)

a_{BW}	1	2	3	4	5	6	7	8	9
CI (max ξ)	0.00	0.44	1.00	1.63	2.30	3.00	3.73	4.47	5.23

2.4 Determination of global weights

Category weights were multiplied by the corresponding local weights of each criterion to obtain global weights. This step integrates expert judgement across all categories and ensures that criteria with higher strategic relevance exert greater influence on the final ranking.

2.5 Ranking of gasification media

The four gasification media—steam, CO_2, O_2 and air—were evaluated using the global weights. Each medium was assigned a performance score based on its reported behaviour in scientific literature with respect to the twelve criteria. The final ranking was obtained by multiplying the performance scores by the global weights and summing across all criteria

3. Results and discussion

3.1 Consistency of expert judgement

Table 3 shows the consistency results of the category scores by the four experts. The CRs calculated for all four experts fall well below 0.40, indicating reliable pairwise comparisons. Expert CR values ranged from 0.1084 to 0.3594, confirming that the best-to-others and others-to-worst judgements were coherent and suitable for deriving stable criteria weights (Rezaei, 2016).

Table 3: Calculated CR results

Category	Expert 1	Expert 2	Expert 3	Expert 4
Technical-syngas fuel quality (w_1^*)	0.5963	0.6974	0.7405	0.6496
Technical-syngas fuel quality (w_2^*)	0.0550	0.1022	0.0949	0.1648
Economic (w_3^*)	0.1743	0.1363	0.0696	0.1177
Environmental (w_4^*)	0.1743	0.0641	0.0949	0.0679
ξ*	1.8418	1.8799	1.6394	0.5670
CR	0.3522	0.3594	0.3135	0.1084

3.2 Criteria weights and their implications

Figure 1 gives the twelve selected criteria weights. The results show clear differentiation in the importance of the twelve criteria. Calorific value (C_1) received the highest global weight, reflecting its central role in determining syngas energy quality (del Alamo et al., 2012). The H_2/CO ratio (C_2) and cost (C_9) followed, indicating that both syngas suitability for downstream applications and economic feasibility strongly influence gasification medium selection. Technical performance indicators such as carbon conversion efficiency (C_3) and cold gas efficiency (C_4) also ranked highly, confirming their relevance in assessing overall process efficiency. Environmental criteria (CO_2 and CH_4 emissions) received moderate weights, suggesting that while emissions are important, experts prioritised syngas quality and process efficiency when selecting a gasification medium for H_2-rich syngas production. Sulphur and nitrogen compounds (C_7, C_8) received the lowest weights, consistent with their relatively minor influence on H_2 yield compared to other parameters.

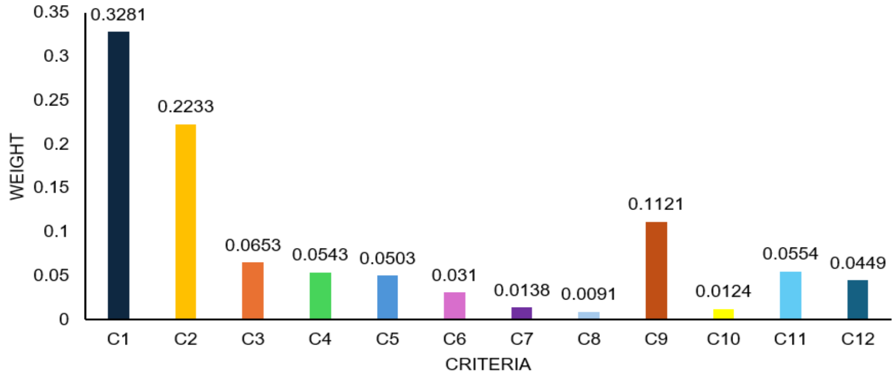

Figure 1: Overall criteria ranking

3.3 Ranking the gasification media

The gasification media were ranked as given in Figure 2. The final ranking derived from the global weights shows a clear preference for steam gasification, which achieved the highest total weighted score (6.7109). This result aligns with extensive experimental and modelling evidence demonstrating steam's ability to enhance H_2 yield, increase syngas energy density and eliminate nitrogen dilution. O_2 gasification ranked second (5.2133), driven by its ability to produce high-calorific-value syngas despite higher operational costs. CO_2 gasification ranked third (4.4608). Although it improves CO formation and contributes to CO_2 utilisation, its endothermic nature and lower H_2 yield reduced its overall performance. Air gasification obtained the lowest score (4.1295), primarily due to nitrogen dilution, which lowers syngas calorific value and reduces H_2 concentration. These trends are consistent with the experimental findings of Samad (2024), who investigated air, steam and O_2 gasification in a fluidised bed reactor using raw and torrefied wood sawdust. Their results showed that steam gasification produced the highest H_2 concentrations at 850 °C, followed by oxygen and then air, providing external validation for the ranking obtained in this study. The numerical scores also offer direct guidance for selecting gasification media in practical WtE applications. The high weighted score for steam highlights its suitability for systems prioritising H_2-rich syngas with elevated calorific value, such as integrated gasification–fuel cell configurations or H_2-driven chemical synthesis routes. Conversely, the lower score for air gasification reflects its relevance mainly in cost-constrained industrial settings where syngas quality is less critical, and fuel substitution is the primary objective.

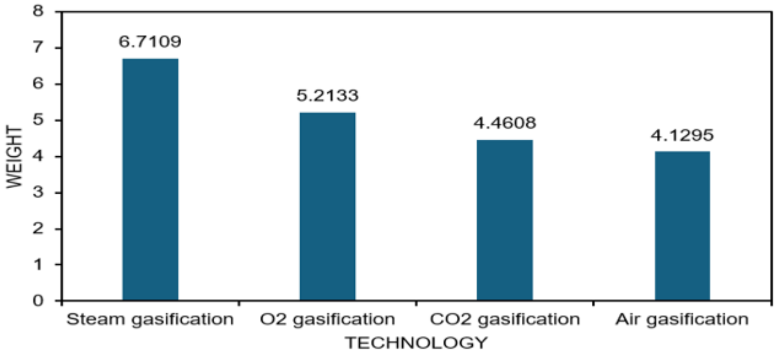

Figure 2: Gasification media ranking

3.4 Interpretation and practical relevance

The ranking confirms that steam is the most favourable medium for producing H_2-rich syngas from RDF when technical, economic and environmental criteria are considered simultaneously. The strong influence of calorific value and H_2/CO ratio on the final ranking highlights the importance of syngas quality for downstream applications such as heat production, electricity generation and synthesis processes. The results also demonstrate the value of a multi-criteria approach. While air is the cheapest and most accessible medium, its low syngas quality significantly reduces its overall score. Conversely, O_2 performs well technically but is penalised economically. Steam offers the best balance across all criteria, explaining its top ranking.

3.5 Applicability to WtE systems

The framework developed in this study provides a transparent decision-support tool for selecting gasification media for RDF and other heterogeneous waste biomass feedstocks. Because the criteria and weights are derived from expert judgement and scientific literature evidence, the approach can be adapted to different feedstocks, reactor configurations and operational objectives. The results also highlight the need for future work on the economic feasibility of steam gasification, particularly in comparison with air-based systems commonly used in industry.

4. Conclusions

This study applied the BWM framework to evaluate four gasification media for H_2-rich syngas production from RDF. Twelve technical, economic and environmental criteria were weighted to determine their relative influence on medium selection. The results show that calorific value, H_2/CO ratio and cost are the most influential criteria, together accounting for the highest global weights in the decision hierarchy. Based on the aggregated scores, steam gasification achieved the highest overall performance (6.7109), followed by O_2 (5.2133), CO_2 (4.4608) and air (4.1295). These findings demonstrate that steam provides the most favourable balance between syngas quality and process efficiency, while air remains limited by nitrogen dilution and low energy density. The proposed multi-criteria framework offers a transparent decision-support tool for selecting gasification media and can be adapted to other waste-biomass feedstocks. Future work should examine the economic feasibility of steam gasification to support its wider industrial adoption.

Acknowledgments

The authors would like to thank Dr.-Ing. Qahtan Thabit at the Institute for Renewable Energy Systems, Stralsund University of Applied Sciences, Germany, for his invaluable contributions towards the improvement of this manuscript. The meticulous attention dedicated by the experts in ranking the criteria contributed to the success of this study and is gratefully acknowledged. The authors gratefully acknowledge the financial support from the Open Access Publication Fund of the University of Rostock, Germany.

References

del Alamo G., Hart A., Grimshaw A., Lundstrøm P., 2012, Characterization of syngas produced from MSW gasification at commercial-scale ENERGOS Plants, Waste Management, 32, 1835–1842.

Hashemi-Amiri O., Mohammadi M., Rahmanifar G., Hajiaghaei-Keshteli M., Fusco G., Colombaroni C., 2023, An allocation-routing optimization model for integrated solid waste management, Expert Systems With Applications, 227, 1–23.
Islam M.W., 2020, Effect of different gasifying agents (steam, H2O2, oxygen, CO2, and air) on gasification parameters, International Journal of Hydrogen Energy, 45, 31760–31774.
Kaneesamkandi Z., Rehman A.U., Usmani Y.S., Sayeed A., Alabi H.S., 2023, Methodology for Selecting an Ideal Thermal Gasification Technique for Municipal Solid Waste Using Multi-Criteria Decision Analysis," Applied Sciences, 13, 1–19.
Luo C., Ju Y., Gonzalez E.D.R.S., Dong P., Wang A., 2020, The waste-to-energy incineration plant site selection based on hesitant fuzzy linguistic Best-Worst method ANP and double parameters TOPSIS approach: A case study in China, Energy, 211, 1–15.
Luo C., Ju Y., Dong P., Gonzalez, E.D.R.S., Wang A., 2021, Risk assessment for PPP waste-to-energy incineration plant projects in China based on hybrid weight methods and weighted multigranulation fuzzy rough sets, Sustainable Cities and Society, 74, 1–15.
Mishra S., Upadhyay R.K., 2021, Review on biomass gasification: Gasifiers, gasifying mediums, and operational parameters, Material Science for Energy Technologies, 4, 329–340.
Morfopoulos N., Samolada M.C., 2025, Effect of Waste-Derived Fuels (SRF/RDF) Composition on the Cement Industry's Environmental Footprint, Waste Biomass Valorization, 16, 4027–4040.
Nemmour A., Inayat A., Janajreh I., Ghenai C., 2023, Syngas production from municipal solid waste plasma gasification: A simulation and optimization study, Fuel, 349, 1–18.
Nguyen V.G., Nguyen-Thi T.X., Nguyen P.Q.P., Tran V.D., Agbulut U., Nguyen L.H., Balasubramanian D., Tarelko W., Bandh S.A., Pham N.D.A., 2024, Recent advances in hydrogen production from biomass waste with a focus on pyrolysis and gasification, International Journal of Hydrogen Energy, 54, 127–160.
Pandey B., Prajapati Y.K., Sheth P.N., 2019, Recent progress in thermochemical techniques to produce hydrogen gas from biomass: A state of the art review, International Journal of Hydrogen Energy, 44, 25384–25415.
Rey J.R.C., Longo A., Rijo B., Pedrero C.M., Tarelho L.A.C., Brito P.S.D., Nobre C., 2024, A review of cleaning technologies for biomass-derived syngas, Fuel, 377, 1–28.
Rezaei J., 2016, Best-worst multi-criteria decision-making method: Some properties and a linear model, Omega, 64, 126–130.
Samad N.A.F.A., 2024, Effects of different gasifying agents on synthesis gas composition from fluidized bed gasification using raw and torrefied wood sawdust, Chemical Engineering Transactions, 114, 1111–1116.
Salem A.M., Elsherbiny K., 2022, Innovative concept for the effect of changing gasifying medium and injection points on syngas quality: Towards higher H2 production, and Free-CO2 emissions, Energy, 261, 1–10.
Sharma P., Sheth P.N., Mohapatra B.N., 2022, Recent Progress in Refuse Derived Fuel (RDF) Co-processing in Cement Production: Direct Firing in Kiln/Calciner vs Process Integration of RDF Gasification, Waste Biomass Valorization, 13, 4347–4374.
Singh D.K., Tirkey J.V., 2022, Process modelling and thermodynamic performance optimization of biomass air gasification fuelled with waste poultry litter pellet by integrating Aspen plus with RSM, Biomass and Bioenergy, 158, 1–12.
Torkayesh A.E., Malmir B., Asadabadi M.R., 2021, Sustainable waste disposal technology selection: The stratified best-worst multi-criteria decision-making method, Waste Management, 122, 100–112.
van de Kaa G., Kamp L., Rezaei J., 2017, Selection of biomass thermochemical conversion technology in the Netherlands: A best worst method approach, Journal of Cleaner Production, 166, 32–39.
Vlachokostas C., Michailidou A.V., Achillas C., 2021, Multi-Criteria Decision Analysis towards promoting Waste-to-Energy Management Strategies: A critical review, Renewable and Sustainable Energy Reviews, 138, 1–19.
Xiang Y., Cai L., Guan Y., Liu W., Cheng Z., Liu Z., 2020, Study on the effect of gasification agents on the integrated system of biomass gasification combined cycle and oxy-fuel combustion, Energy, 206, 131–118.