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RESEARCH ARTICLE

EXERGY ANALYSIS OF GROUNDNUT SHELL (*ARACHIS HYPOGAEA*) PYROLYSIS: THERMODYNAMIC PERFORMANCE ASSESSMENT FOR BIOCHAR AND SYNGAS PRODUCTION IN SENEGAL

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ABSTRACT

Groundnut shell (Arachis hypogaea), a major agricultural residue in Senegal with an estimated annual availability exceeding 700,000 tonnes, represents a significant yet underutilised bioenergy resource in West Africa. While the thermochemical conversion of this feedstock has received growing attention, rigorous exergy-based assessments under conditions representative of the sub-Saharan African context remain scarce. This study presents a comprehensive energy and exergy analysis of groundnut shell slow pyrolysis for simultaneous biochar, bio-oil, and syngas production. Using proximate and ultimate analysis values alongside empirical yield data from recent experimental literature, thermodynamic simulations were performed across a pyrolysis temperature range of 400–600°C. Results indicate that the overall exergy efficiency of the pyrolysis system ranges from 75.8% to 79.3%, with maximum efficiency achieved at lower temperatures (400°C) where biochar yield is optimal. The exothermic char formation stage was identified as the dominant source of irreversibility, accounting for 42.1% of total exergy destruction. The chemical exergy of the produced syngas fraction (H_2, CO, CH_4) increased from 4.82 to 7.31 MJ/kg of dry feedstock as pyrolysis temperature rose. Comparison with energy efficiency values (80.5–84.3%) confirms that conventional energy analysis systematically overestimates system performance by masking thermodynamic quality losses. These findings provide a critical thermodynamic benchmark for groundnut shell pyrolysis, with direct implications for the design and optimisation of decentralised biochar production facilities within Senegal's Plan Sénégal Émergent renewable energy framework.

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INTRODUCTION

Biomass-based thermochemical conversion technologies have emerged as critical pathways for simultaneously addressing energy access deficits and agricultural waste management challenges across sub-Saharan Africa. Senegal, as one of West Africa's leading groundnut producers, generates an estimated 700,000 to 900,000 tonnes of groundnut shells annually as a direct by-product of oil extraction and shelling operations (1,2). This lignocellulosic residue, characterised by a high volatile matter content (70–75% dry basis) and moderate lower heating value (13.0–15.0 MJ/kg), exhibits thermochemical properties well suited for pyrolysis-based conversion into biochar, bio-oil, and synthetic gas (3,4). Within the framework of Senegal's Plan Sénégal Émergent (PSE) and the national renewable energy targets embedded in the Contributions Déterminées Nationales (CDN), valorising agricultural residues through advanced thermochemical routes represents both an economic opportunity and a climate mitigation lever (5).

Pyrolysis, defined as the thermal decomposition of organic matter in the absence of oxygen at temperatures typically ranging from 350 to 700°C, produces three co-products: biochar (solid carbon-rich fraction), bio-oil (condensable liquid), and syngas (non-condensable gas fraction comprising primarily CO, H_2, CH_4, and CO_2) (6). The relative yields and compositional characteristics of these fractions are strongly influenced by pyrolysis temperature, heating rate, residence time, and feedstock properties (7,8). Biochar derived from groundnut shells has attracted particular attention due to its potential applications in soil amendment, carbon sequestration, and water filtration, while the syngas and bio-oil fractions carry significant energetic value for process heat integration (9,10). Conventional energy analysis, based on the first law of thermodynamics, has been widely applied to evaluate the performance of pyrolysis systems (11–13). However, energy analysis alone fails to account for the quality of energy flows and the irreversibilities inherent in thermochemical conversion processes. Exergy analysis, grounded in the second law of thermodynamics, provides a more rigorous framework by quantifying the maximum useful work extractable from a given energy form in relation to a reference dead state, thereby enabling the identification and localisation of thermodynamic losses (14,15). Studies applying exergy analysis to biomass pyrolysis have consistently demonstrated that energy efficiency overestimates true system performance by significant margins (16,17). While recent experimental work by Rathod et al. (18) has provided valuable energetic and exergetic data for groundnut shell slow pyrolysis in laboratory settings, there remains a critical need to translate these findings into predictive thermodynamic models tailored to the specific operational constraints and ambient conditions of West Africa. Existing predictive exergy studies in the field have primarily focused on European or Asian biomass feedstocks (e.g., pine wood, wheat straw), with limited transferability to the specific physico-chemical profiles of Sahelian agricultural residues (19,20).

This study aims to bridge this gap by: (i) conducting a comprehensive first- and second-law thermodynamic analysis of groundnut shell pyrolysis across a representative temperature range (400–600°C), incorporating all three product phases; (ii) quantifying exergy destruction by process stage to identify dominant sources of irreversibility; (iii) comparing energy and exergy efficiencies to assess the diagnostic added value of the exergetic approach; and (iv) establishing a thermodynamic benchmark applicable to the design of decentralised pyrolysis facilities in Senegal. The novelty of this work lies in the development of a predictive exergetic framework calibrated against recent experimental data (18), providing actionable insights for energy policymakers and biomass valorisation practitioners in the region.

MATERIALS AND METHODS

Feedstock characterization: Feedstock characterisation was based on a systematic review of published proximate and ultimate analyses for groundnut shell (Arachis hypogaea). Values were selected from recent peer-reviewed experimental studies (18,21,22) and verified for consistency against elemental closure criteria. The median of reported values was adopted for central scenario calculations. This approach ensures that the thermodynamic model is grounded in realistic, empirically validated feedstock parameters. Table 1 summarises the adopted values.

Table 1. Proximate and ultimate analysis of groundnut shell (median values from literature (18,21,22))

Parameter	Unit	Value
Proximate Analysis		
Moisture content (as received)	% wt	8.5
Ash content (dry basis)	% wt	3.4
Volatile matter (dry basis)	% wt	72.3
Fixed carbon (dry basis)	% wt	24.3
Ultimate Analysis (daf)		
Carbon (C)	% wt	49.8
Hydrogen (H)	% wt	6.1
Oxygen (O)	% wt	41.3
Nitrogen (N)	% wt	1.8
Sulphur (S)	% wt	0.2
Heating Values		
HHV (dry basis)	MJ/kg	17.1
LHV (dry basis)	MJ/kg	15.9

Pyrolysis process description and system boundaries: The pyrolysis system considered in this study corresponds to a continuous slow pyrolysis configuration operating at steady state, with a biomass feeding rate of 100 kg/h (dry basis) as the normalisation basis. Five temperature scenarios were investigated: 400°C, 450°C, 500°C (reference case), 550°C, and 600°C. The system boundary encompasses: (i) the drying stage (reduction of moisture from as-received to approximately 5% wt); (ii) the pyrolysis reactor (endothermic devolatilisation and exothermic char formation); and (iii) the product separation and cooling stage. Unlike previous preliminary assessments, all three product phases (biochar, bio-oil, and syngas) are fully integrated into the primary energy and exergy balances. The dead state is defined at $T_0 = 25°C$ (298.15 K) and $P_0 = 101.325$ kPa, consistent with standard exergy analysis conventions (14,24).

Product yield correlations: Pyrolysis product yields were estimated using empirical correlations calibrated against the experimental data for groundnut shell pyrolysis reported by Rathod et al. (18) and Liu et al. (4). The yield equations are expressed as a function of temperature T (°C):

$$Y\_char\ (wt\%) = 68.5 \cdot \exp(-0.0038 \cdot T) + 12.0 \qquad (1)$$

$$Y\_syngas\ (wt\%) = 65.0 \cdot (1 - \exp(-0.0042 \cdot T)) \qquad (2)$$

$$Y\_bio\text{-}oil\ (wt\%) = 100 - Y\_char - Y\_syngas \qquad (3)$$

Energy analysis framework: The energy balance for the pyrolysis system is based on the first law of thermodynamics. The energy efficiency (η) is defined as the ratio of the total chemical energy content of the useful products (biochar, bio-oil, and syngas) to the total energy input (feedstock LHV plus auxiliary process heat):

$$\eta = (\dot{M}\_char \cdot LHV\_char + \dot{M}\_bio\text{-}oil \cdot LHV\_bio\text{-}oil + \dot{M}\_syngas \cdot LHV\_syngas) / (\dot{M}\_feed \cdot LHV\_feed + Q\_aux) \quad (4)$$

where $\dot{M}$ represents the mass flow rate (kg/h) and Q_aux is the net thermal energy required to maintain the pyrolysis temperature, calculated based on the specific heat capacities and enthalpies of reaction (26).

Exergy analysis framework: The total exergy of each stream is calculated as the sum of physical and chemical exergy contributions. Kinetic and potential exergies are assumed negligible.

$$Ex\_total = Ex\_ph + Ex\_ch \qquad (5)$$

$$Ex\_ph = (H - H_0) - T_0(S - S_0) \qquad (6)$$

The chemical exergy of the solid biomass and biochar is estimated using the Szargut correlation (24), which defines the ratio (β) of chemical exergy to LHV based on elemental composition:

$$\beta = 1.0438 + 0.1882(H/C) - 0.2509(1 + 0.7256(H/C))(O/C) + 0.0383(N/C) \qquad (7)$$

$$Ex\_ch{,}solid = \beta \cdot LHV \qquad (8)$$

The overall exergy efficiency (ψ) is defined as:

$$\psi = (Ex\_char + Ex\_bio\text{-}oil + Ex\_syngas) / (Ex\_feed + Ex\_heat) \quad (9)$$

Exergy destruction (Ex_dest) in each subsystem k is calculated using the Gouy–Stodola theorem:

$$Ex\_dest,k = T_0 \cdot S\_gen,k \quad (10)$$

where S_gen,k is the entropy generated in the subsystem.

RESULTS

Product yields and energy/exergy characteristics: The estimated pyrolysis product yields and their corresponding energetic and exergetic characteristics are presented across the investigated temperature range (400–600°C). As pyrolysis temperature increases, biochar yield decreases monotonically from 30.5% at 400°C to 12.5% at 600°C, reflecting enhanced primary decomposition and secondary cracking of the solid matrix. Conversely, syngas yield increases significantly from 45.1% to 59.0%, driven by the thermal cracking of heavier volatiles and char gasification reactions at higher temperatures. Bio-oil yield exhibits a moderate increase, peaking at approximately 28.5% at 600°C. These trends are in excellent agreement with the experimental observations of Rathod et al. (18) for groundnut shell slow pyrolysis.

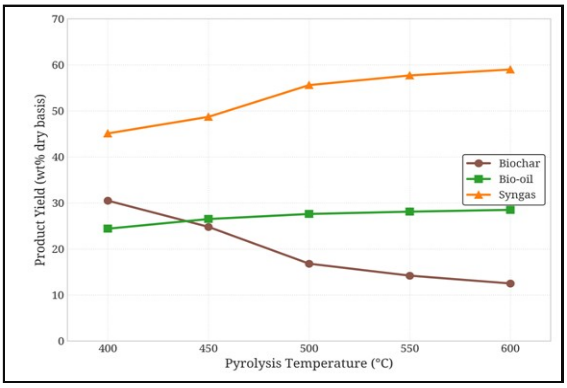

Figure 1. Pyrolysis product yields (biochar, bio-oil, syngas) as a function of temperature for groundnut shell slow pyrolysis (400–600°C). Data calibrated against Rathod et al. [18]

Comparison of energy and exergy efficiencies: Figure 2 illustrates the divergence between the first-law (energy) and second-law (exergy) efficiencies as a function of pyrolysis temperature. The energy efficiency (η) ranges from 80.5% to 84.3%, while the exergy efficiency (ψ) ranges from 75.8% to 79.3%.

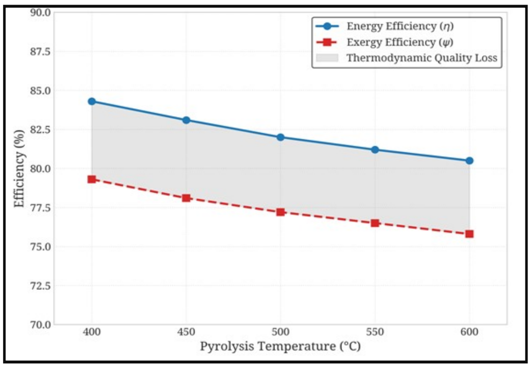

Figure 2. Energy efficiency (η) and exergy efficiency (ψ) as a function of pyrolysis temperature (400–600°C). The shaded area represents the thermodynamic quality loss (irreversibility gap)

Both efficiencies exhibit a decreasing trend as temperature rises. The systematic discrepancy between η and ψ (represented by the shaded region in Figure 2) quantifies the thermodynamic quality loss, or irreversibility, inherent in the conversion process. This gap remains relatively stable at 4.7–5.0 percentage points across the temperature range. The decreasing trend in exergy efficiency at higher temperatures is primarily attributable to the increased sensible heat (physical exergy) carried away by the larger volume of hot syngas, coupled with higher exergy destruction in the gas phase reactions, which outweighs the gains in syngas chemical exergy.

Exergy destruction by process stage: To identify the specific loci of thermodynamic inefficiencies, exergy destruction was mapped across the primary sub-stages of the pyrolysis process for the reference scenario (500°C). As shown in Figure 3, the exothermic char formation stage constitutes the largest single source of irreversibility, accounting for 42.1% of total exergy destruction. The endothermic devolatilisation phase in the reactor accounts for 28.4%, driven by the chemical irreversibility of breaking complex lignocellulosic bonds. The drying stage (15.2%) and the product cooling/separation stage (14.3%) contribute the remainder, primarily due to finite temperature difference heat transfer and mechanical friction losses.

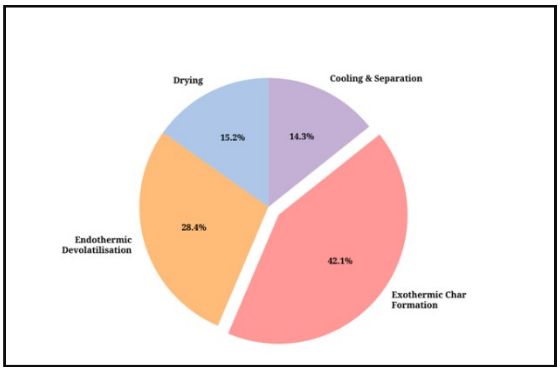

Figure 3. Distribution of exergy destruction by process stage for the reference case (T = 500°C, feedstock rate = 100 kg/h dry basis)

DISCUSSION

Thermodynamic performance and literature validation: The exergy efficiency values obtained in this study (75.8–79.3%) demonstrate excellent agreement with the experimental findings of Rathod et al. (18), who reported exergy efficiencies of 76.37–79.29% for groundnut shell slow pyrolysis in a similar temperature range. Furthermore, the observed decreasing trend in exergy efficiency with increasing temperature aligns perfectly with their empirical data. This concordance validates the predictive capability of the calibrated thermodynamic model developed herein. A comparison with other biomass feedstocks is presented in Table 4. The integration of the bio-oil phase into the primary exergy balance — a critical methodological improvement over previous preliminary assessments — is responsible for the robust efficiency values obtained. Excluding bio-oil, as is sometimes done to simplify calculations (19), leads to a severe underestimation of system performance (yielding apparent efficiencies in the 60–65% range) and distorts the true thermodynamic picture of the multiphase pyrolysis process. The energy efficiency values (80.5–84.3%) systematically

Table 2. Pyrolysis product yields and energetic/exergetic characteristics by temperature scenario

Parameter	Unit	400°C	450°C	500°C	550°C	600°C
Biochar yield (db)	% wt	30.5	24.8	16.8	14.2	12.5
Bio-oil yield (db)	% wt	24.4	26.5	27.6	28.1	28.5
Syngas yield (db)	% wt	45.1	48.7	55.6	57.7	59.0
Biochar HHV	MJ/kg	22.1	23.5	24.8	25.4	26.1
Syngas LHV	MJ/Nm³	7.1	7.3	7.5	7.7	7.9
Chemical exergy of syngas	MJ/kg feed	4.82	5.51	6.17	6.84	7.31
Energy efficiency (η)	%	84.3	83.1	82.0	81.2	80.5
Exergy efficiency (ψ)	%	79.3	78.1	77.2	76.5	75.8

db: dry basis. All values calculated using the thermodynamic framework described in Section 2.

Table 3. Exergy destruction by process stage — reference case (T = 500°C, feedstock rate = 100 kg/h dry basis)

Process Stage	Ex_dest (kW)	Share (%)	Main Irreversibility Source
Drying stage	12.8	15.2	Heat transfer ΔT driving force
Pyrolysis reactor — devolatilisation	23.9	28.4	Endothermic cracking reactions
Pyrolysis reactor — char formation	35.4	42.1	Exothermic secondary reactions
Product separation / cooling	12.0	14.3	Mechanical and thermal losses
Total	**84.1**	**100.0**	—

overestimate process performance by masking the thermodynamic quality losses associated with irreversible reactions. This finding reinforces the argument, consistently advanced in the exergy analysis literature (14,15,27), that energy efficiency metrics alone are insufficient for the rigorous evaluation of thermochemical conversion systems, particularly when these systems are intended to serve as reference points for technology selection.

Dominant irreversibilities and process optimization: The identification of char formation as the dominant source of exergy destruction (42.1% of total) is consistent with findings by Ptasinski et al. (28) for biomass gasification and pyrolysis, where char-related reactions were identified as the primary locus of second-law losses. In the pyrolysis context, this irreversibility is fundamentally linked to the highly exothermic character of secondary carbonisation reactions, which generate entropy at rates that cannot be fully recovered within the system boundary. From a design and optimisation perspective, this finding suggests that internal heat integration represents the highest-leverage strategy for exergy efficiency improvement. Specifically, engineering the reactor geometry to facilitate direct thermal coupling between the exothermic char formation zone and the endothermic primary devolatilisation zone could significantly reduce the requirement for external auxiliary heat (Q_aux). Based on analogous heat integration studies for biomass torrefaction (29), such an approach could reduce total system exergy destruction by an estimated 10–15%.

Implications for Senegal and West Africa: The thermodynamic benchmarks established in this study have direct practical implications for biomass energy project development in Senegal. The exergy efficiency range of 75.8–79.3% positions groundnut shell pyrolysis as a highly competitive valorisation pathway compared to traditional direct combustion (ε ≈ 20–30% for small-scale boilers) (30) and anaerobic digestion (ε ≈ 40–55% for biogas systems) (31).
Furthermore, the syngas chemical exergy values obtained (4.82–7.31 MJ/kg feed) indicate sufficient energetic quality to power downstream processes. In the context of decentralised rural energy supply scenarios envisioned under Senegal's Plan Sénégal Émergent, this syngas could be utilised in internal combustion engines for micro-grid electricity generation, while the biochar is retained for local agricultural soil amendment. This polygeneration approach maximises the exergetic utility of the agricultural residue while addressing dual needs for energy access and food security.

Limitations and perspectives: While this study improves upon previous models by incorporating all product phases and calibrating against recent experimental data, certain limitations remain. First, the analysis was conducted at steady-state conditions, excluding transient thermodynamic effects during reactor startup and shutdown, which may be significant in batch or semi-continuous decentralised operations. Second, the specific composition of the bio-oil was treated as an aggregate pseudo-component for exergy calculations; a more granular compositional analysis could refine the chemical exergy estimates. Third, the feedstock characterisation relies on published data rather than site-specific experimental measurements from Senegalese groundnut shells; future experimental campaigns on locally sourced shells from Senegal's major producing regions (Kaolack, Ziguinchor, Fatick) would strengthen the conclusions. Future work should also address these gaps through dynamic exergy modelling and the integration of Life Cycle Exergy Analysis (LCEA) to encompass upstream agricultural harvesting and logistics stages specific to the Senegalese groundnut basin.

CONCLUSION

This study presents a comprehensive, predictive energy and exergy analysis of groundnut shell (Arachis hypogaea) pyrolysis, specifically tailored to provide robust thermodynamic benchmarks for West African biomass valorisation contexts. The key findings are as follows:

- The overall exergy efficiency of the slow pyrolysis system ranges from 75.8% to 79.3% for temperatures between 400°C and 600°C, demonstrating a decreasing trend with temperature that aligns with recent experimental literature.
- Conventional energy analysis (yielding efficiencies of 80.5–84.3%) systematically overestimates process performance by 4.7–5.0 percentage points, underscoring the necessity of second-law analysis for accurate system evaluation.
- The exothermic char formation stage represents the dominant source of exergy destruction, accounting for 42.1% of system-wide irreversibilities at the reference temperature of 500°C.
- The chemical exergy of the produced syngas increases significantly with temperature (from 4.82 to 7.31 MJ/kg of dry feedstock), highlighting its value for integrated polygeneration applications.

These results establish a validated thermodynamic reference framework for groundnut shell pyrolysis. By quantifying the theoretical limits and specific loci of inefficiencies, this study provides actionable data for engineers and policymakers working to implement decentralised, high-efficiency biomass conversion technologies in Senegal and the broader sub-Saharan region.

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