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Energy and exergy analysis of green hydrogen production

Yeşil hidrojen üretiminin enerji ve ekserji analizi

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Highlights

- *Biomass Gasification*
- *Equilibrium Model*
- *Pyrolysis*
- *Energy and Exergy Analysis*
- *Hydrogen Production*

Graphical Abstract

The study examines two *critical process conditions: pyrolysis at a low temperature of 500°C and gasification at a high temperature of 900°C. Using a method involving thermal equilibrium calculations and modeling, the analysis investigates hydrogen production and comprehensively evaluates energy and exergy efficiencies.*

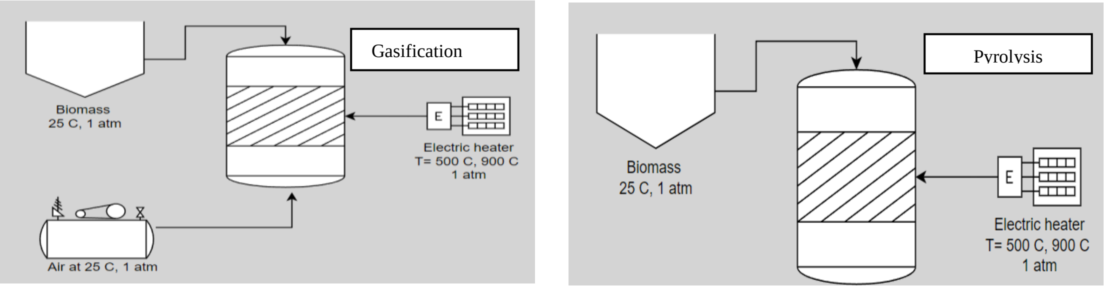

Figure. Analysis of Pyrolysis and Gasification Systems

Aim

This study aims to contribute by examining the performance of thermal conversion methods from biomass for green hydrogen production.

Design & Methodology

A pilot-scale pyrolysis and gasification reactor has been chemically and thermally compared.

Originality

The novel aspect of this study is the high-temperature analysis of the pyrolysis system for green hydrogen production.

Findings

The research identifies that pyrolysis at 900°C is the optimal model condition due to low energy consumption and absence of agent materials.

Conclusion

The model results indicate that the pyrolysis process achieves 60% energy efficiency at 500°C and 94% energy efficiency at 900°C.

Declaration of Ethical Standards

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Energy and Exergy Analysis of Green Hydrogen Production

Araştırma Makalesi / Research Article

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ABSTRACT

Biomass pyrolysis and gasification are recognized as effective thermal technologies for producing green hydrogen obtained through thermal conversion from biomass. This research paper presents a comparatmive analysis of the energy and exergy performance of pyrolysis and gasification systems. The study investigates two critical process conditions: low-temperature pyrolysis at 500°C and high-temperature gasification at 900°C. The analysis integrates thermodynamic equilibrium calculations and modeling to produce hydrogen and offers a comprehensive evaluation of energy and exergy efficiencies. The comparison is carried out between a downdraft gasifier and a pyrolysis process, both employing wood chips as the biomass feedstock. This paper delves into the energy and exergy yields of these distinct thermal conversion methods for energy production. The research identifies pyrolysis at 900°C as the optimal model condition due to its lower energy consumption and the absence of agent materials. Energy and exergy analyses are conducted at both 500°C and 900°C for all processes. The model results demonstrate that pyrolysis yields 60% energy at 500°C and 94% at 900°C. Furthermore, the study reports on the effects of temperature variations on energy and exergy yields. This study contributes to the examination of the performance of thermal conversion methods from biomass for green hydrogen production.

Keywords: Biomass Gasification, Equilibrium model, Pyrolysis, Energy and exergy analysis, Hydrogen Production.

Yeşil Hidrojen Üretiminin Enerji ve Ekserji Analizi

ÖZ

Biyokütleden termal dönüşüm yöntemi ile elde edilen yeşil hidrojen üretimi için biomass piroliz ve gazifikasyon, sürdürülebilir hidrojen üretimi için etkili termal teknolojiler olarak kabul edilmektedir. Bu araştırma makalesi, piroliz ve gazifikasyon sistemlerinin enerji ve ekserji performansını karşılaştırmalı bir analizini sunmaktadır. Çalışma, düşük sıcaklıkta 500°C'de piroliz ve yüksek sıcaklıkta 900°C'de gazifikasyon olmak üzere iki kritik işlem koşulunu incelemektedir. Analiz, termal denge hesaplamaları ve modellemelerini içeren bir yöntem kullanarak hidrojen üretimini gerçekleştirir ve enerji ve ekserji verimliliğini kapsamlı bir şekilde değerlendirir. Karşılaştırma, biyokütle malzemesi olarak odun yongalarını kullanan bir downdraft gazifikasyon ünitesi ile piroliz işlemi arasında gerçekleştirilir. Bu makale, enerji üretimi için bu farklı termal dönüşüm yöntemlerinin enerji ve ekserji verimini detaylı olarak incelemektedir. Araştırma, düşük enerji tüketimi ve ajan malzeme kullanımının olmaması nedeniyle 900°C'de pirolizin en iyi model koşul olduğunu belirler. Tüm işlemler için hem 500°C hem de 900°C'de enerji ve ekserji analizleri gerçekleştirilir. Model sonuçları, piroliz işleminin 500°C %60 enerji verimi sağladığını ve 900°C'de %94 enerji verimi sağladığını göstermektedir. Ayrıca, çalışma sıcaklığındaki değişikliklerin enerji ve ekserji verimine etkileri de raporlanmıştır. Bu çalışma, yeşil hidrojen üretimi için biyokütleden termal dönüşüm yöntemlerinin performansını inceleyen bir katkı sunmaktadır.

Anahtar Kelimeler: Biyokütle Gazlaştırma, Denge Modeli, Piroliz, Enerji ve Ekserji Analizi, Hidrojen Üretimi

1. INTRODUCTION

Energy demand is on the rise globally, propelled by increasing trends in energy consumption and the gradual depletion of fossil fuel reserves. Solid waste generation remains a significant issue worldwide, particularly with ongoing economic development [1].Inadequate treatment of solid waste poses a substantial environmental challenge [2]. Coal, a traditional solid fuel, continues to play a dominant role in global power generation, contributing approximately 40% of the total power generated worldwide [3].

However, the diminishing reserves of coal have underscored the urgent need to explore alternative energy sources [4]. Initiatives such as the Kyoto Protocol have emphasized the importance of reducing carbon dioxide emissions, making biomass a particularly attractive option due to its renewable nature [5]. As the importance of circular economy principles grows, hydrogen energy systems are emerging as alternative pathways for sustainable energy production from solid waste, aiming to reduce reliance on fossil fuels [6].

Biomass represents the largest sustainable feedstock globally, accounting for approximately 15% of the world's primary energy consumption [7]. Utilizing biomass sources offers the potential to produce carbon-neutral fuels, mitigating the impacts of greenhouse gas emissions [8]. Thermochemical conversion technologies, such as gasification and pyrolysis, have garnered significant attention as viable alternatives to fossil fuels,

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with organic wastes being converted into various products via highly endothermic processes [9]. Gasification and pyrolysis are widely studied methods for converting biomass into valuable products, including syngas, which consists of hydrogen, carbon monoxide, carbon dioxide, methane, higher hydrocarbons, char, and liquids (tars) [10]. The efficiency of syngas production depends on several operational parameters, including biomass source, gasification agent, retention time, and temperature. Numerous studies have explored energy and exergy analyses to enhance hydrogen production from biomass thermochemical methods [11-25]. Despite extensive research on thermodynamic equilibrium in gasification and pyrolysis processes, there remains a gap in comparing the energy and exergy analyses of these methods. Therefore, the primary objective of this study is to investigate and enhance a model for hydrogen production in a pilot-scale reactor under pyrolysis and gasification conditions, utilizing exergy and energy analyses. This research aims to contribute to the advancement of sustainable energy production methods from biomass. In addition to the existing literature, our study aims to fill this gap by conducting a comparative analysis of the exergy and energy efficiencies of pyrolysis and gasification methods. By investigating the performance of both processes in producing hydrogen from biomass, we seek to provide valuable insights into their respective advantages and limitations. Through a rigorous examination of operational parameters and thermodynamic principles, we aim to refine existing models and contribute to the advancement of sustainable energy production technologies. Numerous studies have contributed significantly to the understanding of biomass conversion processes. For instance, Balu et al. conducted research on the steam gasification of woody biomass, revealing that steam gasification supports higher energy quality compared to other systems [11]. Castello and Fiori conducted studies on downdraft gasification, focusing on exergy and energy analyses to enhance gas quality in the presence of supercritical water [1]. Lu et al. evaluated exergy losses occurring due to chemical reactions [12]. Furthermore, Sharma and Shet developed a gasification equilibrium model for air/steam gasification of biomass [13], while Mahishi and Goswami investigated various operational conditions such as temperature, biomass ratio, equivalence ratio, pressure, and temperature [14]. Pellegrini evaluated the energetic and energy analyses of sugarcane biomass gasification in the presence of air and steam agents [15].

Studies by Zhang et al. compared the effects of operational conditions on hydrogen production from water gasification [16], and Mehrpooya et al. modeled the efficiency of exergy in steam gasification with various biomass materials [17]. Additionally, Zhang et al. conducted a thermodynamic evaluation for autothermal biomass gasification [18], and Abuadala and Dincer evaluated the energy and exergy efficiencies of steam gasification [19]. Eri and coworkers developed a thermodynamic equilibrium model for air/steam biomass gasification [20], while Dong et al. investigated solid waste with increasing moisture content in their research [21]. Furthermore, Burhenne et al. reported the char yield of wood chips in the pyrolysis process [22], and Di Blasi studied the higher yield of gas production from pyrolysis at 800°C [23]. Kabalina et al. conducted exergy analysis on a polygeneration system [24], and Soto and Romanelli reported the percentage decrease in the moisture of biomass [25]. By synthesizing findings from these diverse studies and integrating them into our comparative analysis, we aim to offer comprehensive insights into the performance and potential of both gasification and pyrolysis methods for hydrogen production from biomass.

2. MATERIAL and METHOD

2.1. Thermal Conversion Model

A pilot-scale pyrolysis and gasification reactor has been chemically and thermally compared. Energy and exergy analyses have been conducted for hydrogen gas production, considering the principles of the first and second laws of thermodynamics [26]. Wood chips have been selected as the raw material for this study. Gasification and pyrolysis runs have been performed in a fixed-bed reactor, as illustrated in Figure 1, under various conditions.

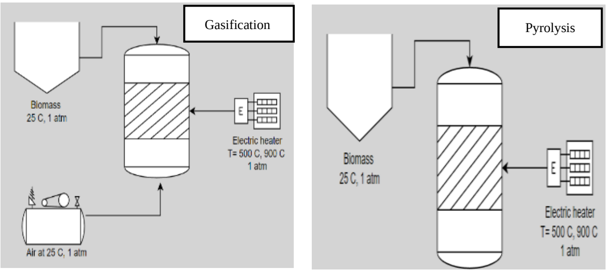

Figure 1. Stoichiometric chemical equilibrium model

The results of the calculations have been compared with experimental data based on Gibbs free energy. The gasification and pyrolysis reactor have been maintained isothermal, with 25 kg of wood chips introduced into the reactor and heated to temperatures of 500°C and 900°C under pyrolysis and gasification conditions, respectively. All gasification and pyrolysis reactions and assumptions have been established, including the stoichiometric balance of carbon, oxygen, hydrogen, sulfur, and nitrogen, formulated to achieve the operating temperature.

Gibbs free energy, also known as Gibbs function or free enthalpy, has been utilized to measure the maximum amount of work done in a thermodynamic system when temperature and pressure are held constant [27]. The thermal system reactor has been simulated using two different models: gasification and pyrolysis reactor. The thermal conversion stoichiometric reactor was employed to convert wood and manure waste into basic components such as CO2, H2, CH4, and ash, which were measured through ultimate and proximate analysis [28]. The mole numbers of compounds were estimated to minimize

Gibbs free energy. Energy efficiency, exergy efficiency, and carbon conversion have been defined as performance indicators of thermal conversion systems [15]. The stoichiometric model has taken into account the elemental composition and proximate analysis, as shown in Table 1. The gasification process is defined as the addition of partial oxygen to the system until all carbon content in biomass is converted to gaseous products. The thermal conversion process includes water gas reaction, boundary reaction, and methane reactions. Unknown impurities can be calculated from material balance equations. The main parameters of the gasifier are defined as the gasifying medium, pressure, and heat gain or loss of the gasifier. The amount of unconverted solid carbon is a parameter only in the first part of the model. When gasification occurs under the operating conditions, the amount of unconverted solid carbon equals zero.

Table 1. The ultimate and proximate analysis of woodchips

Parameter	Wood chips
C (%)	45
H (%)	5.88
N (%)	0.32
O (%)	47.94
HHV (kJ/kg)	19632
VOC (%)	88.92

Several assumptions are made in the model for the gasification and pyrolysis parts, as outlined below [29].

- •Steady-state conditions.
- •Negligibility of kinetic and potential energy.
- •Reference conditions: T0=298K and P0=1 atm.
- •Char is assumed to be solid carbon, and tar is ignored.
- •The biomass model only considers C, H, and O content.

2.1.1. Thermodynamic equilibrium of pyrolysis and gasification process

Biomass sources are converted into combustible gases consisting of H_2 and CO through thermal conversion technologies such as gasification and pyrolysis [15]. The gasification process involves several steps, as depicted in Figure 1, including drying, pyrolysis, combustion, and gasification. Air, steam, and oxygen are utilized as gasification agents in the process, with the gasification agent being injected into the system during the drying phase. The gasification process encompasses the following reactions:

Water-gas: C + H2O → CO + H2, ΔH = -131.4 kJ/mol

Boudouard: C + CO2 → 2CO, ΔH = -172.6 kJ/mol

Methane generation: C + 2H2 → CH4, ΔH = +75 kJ/mol

Water gas shift: CO + H2O → CO2 + H2, ΔH = -41.2 kJ/mol

A pilot-scale gasification and pyrolysis reactor has been examined both chemically and thermally. The energy and exergy analysis of the system have been calculated using the first and second laws of thermodynamics [16]. The second law of thermodynamics incorporates irreversible entropy increase to analyze the exergy of the systems, revealing exergy loss and energy saving potential. Energy and exergy analysis are widely utilized in thermal processes by numerous researchers [30]. The relationship between products and reactants is defined by a series of independent equilibrium reactions. Two equilibrium models, based on the laws of energy conversion, have been developed for biomass gasification and pyrolysis [31].

2.1.2. Mass balance calculation

In this study, a batch type gasification system is being modeled to calculate mass and energy balances based on the stoichiometric equation of the wood chips. Thermal decomposition occurring during the gasification step will be discussed separately in the following sections. The general mass balance equation can be written as follows:

$$\sum M_{in} = \sum M_{out}$$

$$\sum M_{in} = M_{water} + M_{woodchip} + M_{air}$$

$$\sum M_{out} = M_{gas} + M_{char} + M_{tar} + M_{other}$$

Wood chips have been utilized as the raw material for the thermal conversion process in this study. Analysis results indicate that the moisture content is calculated to be 16%. The feedstock enters the gasifier to initiate the drying and pyrolysis processes under environmental conditions and atmospheric pressure. Partial oxygen is introduced into the system for the gasification process. The mass balance of all components is determined at the conclusion of the thermal conversion [32].

2.1.3. Thermal energy conversion calculations

In this study, the biomass-air gasification and pyrolysis reactor have been modeled. The results of mass balance calculations have been utilized to determine the temperature profile using an analytical model approach. The system is assumed to operate under adiabatic conditions in complete isolation.

Experimental results have been compared with estimated model results to evaluate the temperature. The necessary information to calculate energy yield and temperature values is presented in Table 2.

Table 2. The required information to estimate energy yield

	T (K)	Cp (kj/kmolK)	LHVgas (KJ/kmol)
N_2	323,0	29,2	0,0
H_2	323,0	28,9	241,8
CO	323,0	33,5	282,0
CO_2	323,0	38,1	0,0
CH_4	323,0	36,9	801,3

2.1.4. Energy calculation

The energy balance for the gasifier has been provided based on the first law of thermodynamics under steady-state conditions, with physical and kinetic energies neglected. The energy equilibrium of the system has been established by isolating the gasifier [19]. The chemical structure of wood chips has been designed as $CH_{1.5}O_{0.7}$.

$$\sum_i Eni = \sum_e Enout + Qlost$$

$$En_{biomass} + En_{agent} + Q_{heat} = En_{syngas} + En_{Tar} + En_{biochar} + Q_{lost}$$

$$Eni = En^{ph} + En^{ch}$$

$$En^{ph} = \sum_i ni * hi$$

$$En^{ch} = \sum_i ni * LHVi$$

$$Q_{lost} = U_w A(T_w - T_0) = 0$$

En_{Tar} and $En_{biochar}$ are ignored at energy calculation

$Q_{heat} = En_{syngas} - En_{biomass} - En_{agent}$ at gasification

$Q_{heat} = En_{syngas} - En_{biomass}$ at pyrolysis

E_{ni} = energy entering the gasifier

E_{ne} =energy leaving from the gasifier

Q_{lost}= energy lost during the gasification reaction

h_i =specific enthalpy (kJ/kmol)

n_i= molar flow rate of components

HHV_i = higher heating value of materials

$En^{ph} = physical\ energy$

$En^{ch} = chemical\ energy$

U_w = overall heat transfer coefficient,

T_w=gasifier wall temperature

T_o=environmental temperature

T has called as the gasification temperature. The heat loss has neglected on the reactor Wall [33]. Two types of energy efficiencies that called cold gas efficiency and sensible efficiency respectively have calculated from below equations. The cold gas efficiency has defined as the ratio of chemical energy of the product gas to the total energy of feedstock including biomass and agent. While the sensible efficiency has described as the ratio of physical energy of the product gas to the total energy of feedstock [16].

$$\eta_{cold\ gas} = \frac{En_{gas}^{chem}}{En_{biomass} + En_{agent}}$$

$$\eta_{sensible} = \frac{En_{gas}^{ph}}{En_{biomass} + En_{agent}}$$

The identify the energy content for conversion technology of biomass feedstock has calculated using below equation.

$$HHV_{Feedstock} = 0.3491M_C + 1.1783M_H + 0.1005M_S - 0.1034M_O - 0.0151M_N \quad \text{MJ/kg}$$

$$LHV_{feedstock} = HHV_{feedstock} - hg\left(\frac{9H}{100} + \frac{MC}{100}\right) \quad \text{MJ/kg}$$

$M_C, M_H, M_S, M_O, M_N = molecular\ weight\ of\ carbon, hydrogen, sulfur, oxygen, nitrogen.$ H and MC are Hydrogen and moisture content percentage of feedstock, respectively; hg is the latent heat of steam (2.260 MJ/kg) [33].

2.1.5. Exergy calculation

The pyrolysis and gasification processes can be considered under steady-state conditions. Exergy analysis has been employed to evaluate the systems based on the second law of thermodynamics [34-35]. Exergy analysis is recognized as more effective and practical than energy analysis, providing deeper insights into efficiency assessment. It serves as a criterion for approaching ideal conditions and determines the types and values of irreversibilities [36]. Total exergy (Ex) is described as the sum of chemical exergy (Ex,ch) and physical exergy (Ex,ph). The exergy balance for the gasifier and pyrolysis can be written as follows, neglecting Ex,loss and Ex,UC [37]. The specific heat capacity coefficient has calculated as using a, b, c and d that shown as Table 3.

$$Ex_{biomass} + Ex_{agent} = Ex_{gas}$$

$$E_x = Ex_{ch} + Ex_{ph}$$

$$E_{x,ph}^{i} = (H_i - H_0) - T_0(S_i - S_0)$$

$$(H_i - H_0) = \int_{T0}^{T} CpdT$$

$$(S_i - S_0) = \int_{T0}^{T} \frac{Cp}{T} dT - RIn(\frac{P}{P0})$$

$$Cp = a + bT + CT^2 + dT^3$$

$$E_{x,ph} = \sum_i yi\, E_{x,ph}^{i}$$

$$E_{x,ch} = \sum_i yi\, \varepsilon_{0,i} + RT_0 \sum_i yi\, (\frac{InPo}{Poi})$$

$\varepsilon_{0,i}$= standard chemical potential of a pure chemical component [38].

n_i = molar flow rate of component

ex_i^{ph}= physical exergy of gases

ex_i^{ch}= chemical exergy of gases

The difference in specific enthalpy and entropy of gases and chemical exergy has been obtained from Table. The exergy analysis of biomass has been calculated using the following equations. The lower heating value of solid waste (biomass), moisture content (MC), chemical exergy (exg), evaporation enthalpy of water (hg), and correlation factor (β) have been used to calculate the biomass exergy.

Table 3. The thermodynamic properties of materials

Component	a	b 10^{-2}	c 10^{-5}	d 10^{-9}	LHV (kJ/kmol)
H_2	29.11	-0.19	0.40	-0.87	240420
N_2	28.90	-0.15	0.81	-2.87	-
CO	28.16	0.17	0.53	-2.22	282800
CO_2	22.26	5.98	-3.5	7.47	-
CH_4	18.89	5.02	1.27	-11	801280

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$$Ex_{biomass} = \beta LHV_{biomass} + MC(ex_g + \beta h_g)$$

Table 4. Thermodynamic properties of component [38].

Species	Cp (kJ.kmol/K)
H_2	$Cp = 29.11 - 0.1916x10^{-2}T + 0.4003x10^{-5}T^2 - 0.870x10^{-9}T^3$
N_2	$Cp = 39.060 - 512.79\left(\frac{T}{100}\right)^{-1.5}$
CO	$Cp = 28.16 + 0.1675x10^{-2}T + 0.5327x10^{-5}T^2 - 2.22x10^{-9}T^3$
CO_2	$Cp = 22.26 + 5.981x10^{-2}T - 3.501x10^{-5}T^2 + 7.469x10^{-9}T^3$
CH_4	$Cp = 18.89 + 5.024x10^{-2}T + 1.269x10^{-5}T^2 - 11.01x10^{-9}T^3$

3. RESULTS and DISCUSSION

The final mass balance results of the pyrolysis and gasification processes are presented in Table 5. Mass, enthalpy, temperatures, energy, and exergy values have been calculated for the composing materials at 0°C and 1 atm. Furthermore, the results have been presented via graphical representation, comparing differences in energy and exergy between pyrolysis and gasification. The stoichiometric model for wood chips' thermal conversion systems has been compared separately for gasification and pyrolysis conditions. The calorific values of syngas have been calculated based on the Lower Heating Value (LHV) of volatile components in the syngas. The LHV of components has been obtained using stoichiometric methods, and the composition of syngas, syngas calorific value, energy yield, exergy, and hydrogen yield have been compared between pyrolysis and gasification processes. According to Table 5, the gasification process is more effective than the pyrolysis process at 500°C but similar to the pyrolysis process at 900°C.

Table 5. The results of mass balance equation at pyrolysis and gasifier process to calculate energy and exergy analysis at 500°C and 900°C

	Pyrolysis products		Gasification products	
	500°C	**900°C**	**500°C**	**900°C**
Woodchips				
CO %	9	11	11	16
CO_2 %	14	7	15	0,01
CH_4 %	1	3	10	2
H_2O %	0,1	0,1	0,1	0
N_2 %	0	0	20	0,8
H_2 %	10	19	10	14
Char %	6.6	5.9	3.6	2.7
O_2 %	0	0	0.1	0.4
LHV_{syngas} (MJ/kg)	19.4	33.6	19.6	35.2

The input values calculated from proximate and ultimate analysis are shown in Table 6. These input values have been used in all calculations in this study. The results obtained from experiments have been evaluated with information from the literature, as presented in Table 7 [40].

Table 6. The input data calculated from proximate and ultimate analysis

Input Data	Values
Biomass Type	Woodchips
Biomass moisture (%)	16
LHVbiomass (kj/kg)	19128
Gasifier Type	Downdraft
Gasifier agent	Air
C	44,5
H	5,88
O	47,94
N	0,32
Ash	9,6

Table 7. Comparative results between stoichiometric model and literature (Gasification at=900°C)

Syngas composition	This work	Ref (1)	Ref (2)
CO (%)	16	13	16,10
CO2(%)	1	16,62	10,31
H2 (%)	14	13,32	13,63
CH4 (%)	2	11,91	12,37

According to the proximate and ultimate analysis presented in Table 8, wood chips have been chosen as the raw material over manure. The Lower Heating Value (LHV) is a crucial measure of the energy potential of the syngas and serves as an important parameter in selecting raw materials for high calorific value syngas.

Table 8. Proximate and ultimate analysis result of woodchips and manure

	Ultimate analysis (%)				**Proximate analysis (%)**		**HHV MJ/kg**
	C	H	N	O	Ash	Vol.	
Wood chips	45	5,8	0,3	47,9	9,6	88,92	19,63
Manure	41,4	5,8	2,6	50,0	13,4	86,89	18,6

The gasification and pyrolysis processes of the wood chips have been conducted at 500°C and 900°C, respectively. External heat has been provided to the unit by the heating element. Energy and exergy analyses of the pyrolysis/gasification reactor have been performed to calculate the change in energy fluxes of the control volume. The temperature ramps from 25°C to 500°C and 25°C to 900°C are illustrated in Figure 2 and 3, respectively.

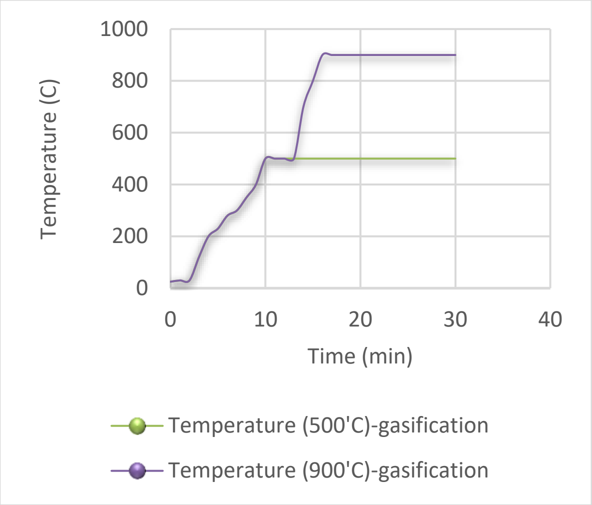

Figure 2. Temperature distributions the height of the reactor

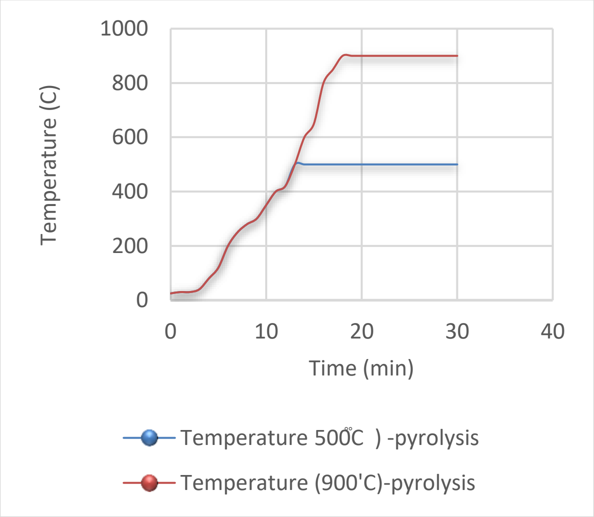

Figure 3. Temperature distributions the height of the reactor

The fluctuation in reactor temperature depends on the heat of reaction. This fluctuation can be understood through combustion mechanisms such as the Boudouard reaction, where the dissociation of carbon dioxide at higher temperatures alters the Gibbs free energy of the system, consequently influencing the heat of reaction. Due to the low quantity of oxygen in the pyrolysis process, carbon dioxide remains at low levels because carbon cannot fully convert it with enough oxygen. Instead, carbon monoxide and hydrogen production occur at higher rates at elevated temperatures. Carbonization occurs homogeneously in both thermal systems within the reactor. However, at 500°C, pyrolysis produces a higher level of char. Gas content starts to increase at higher temperatures. The effect of temperature differences on thermal efficiency in different processes is illustrated in Figure 4. The energy yield of the system changes positively with increasing temperature.

In this study, the energy content of wood chips is measured as 895 MJ/kg, while the exergy content is 343 MJ/kg. The energy and gas content of the pyrolysis and gasification reactors.

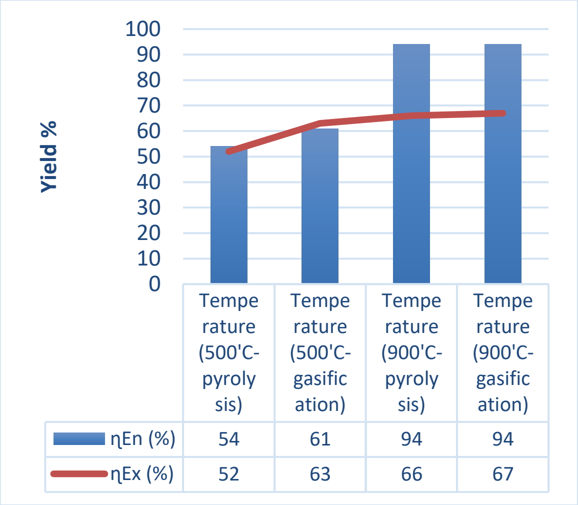

Figure 4. Thermal efficiency of system with respect to temperature

In the pyrolysis reactor, hydrogen content has accounted %10 much more than gasification system at 900̊C. Also, the CO_2 contentin the Gasification process at 500̊C has calculated as more than pyrolysis proses at 500 and 900̊C due to reaction between carbon and oxygen. The energy and exergy balances of the pyrolysis and gasification processes are summarised in this study based on 25 kg woodchips. The energy yield of pyrolysis process and gasification process has same results. This shows that the experiments have carried out with the pyrolysis process at high temperatures without the need for gasification process are more effective. The same energy output has obtained in simpler systems without the use of energy and gasification agent. In comparison of the pyrolysis and Gasification process at high temperature, the exergy yield of pyrolysis and Gasification has measured %66 and %68 respectively. The hydrogen content has evaluated as 19% and %15 respectively gasification and pyrolysis process at 900̊ C. In this work, difference of energy and exergy yield of pyrolysis and gasification process have investigated. The pyrolysis process at high temperature has the effective potential to significantly enhance the energy efficiency of wood chips.

4. CONCLUSIONS

There are many paper on gasification and pyrolysis process of woodchips at fixed bed reactor. But, comporision of system method has evaluated in this study and the following results have reached. When we compare pyrolysis process at 500̊C and 900̊C, the results have shown the exergy yield has increased due to temperature increases. The syngas quality and LHV have measured the highest at 900 ̊C in the gasification and pyrolysis process. For the pyrolysis process exergy and energy yield has the same with gasifier process at high temperature. The woodchips feedstock has higher volatile content can be compared with manure in the thermal systems due to its lower heating value (LHV). In summary, this paper studies the use of exergy analysis to evaluate the wood chips and manure at gasification and pryrolysis process at different temperature. In conclusion, this study offers a comprehensive examination of the gasification and pyrolysis processes applied to wood chips and manure in fixed-bed reactors. Through meticulous analysis and comparison, several key insights have emerged [41]. Firstly, it's evident that temperature plays a pivotal role in shaping the efficiency and output of both gasification and pyrolysis processes. Higher temperatures result in increased exergy yield and improved syngas quality, emphasizing the significance of temperature optimization for enhancing process performance. Moreover, the comparison between gasification and pyrolysis processes reveals notable similarities, particularly at elevated temperatures. The pyrolysis process demonstrates promising energy and exergy yields comparable to gasification, suggesting its viability as a viable alternative for biomass energy conversion. Furthermore, the superior performance of wood chips over manure underscores the importance of feedstock selection in achieving optimal process efficiency and energy production. Overall, the utilization of exergy analysis provides valuable insights into the efficiency and quality of thermal conversion processes. By leveraging these insights, stakeholders can make informed decisions to advance the development and implementation of sustainable biomass energy solutions. Thus, this study contributes to the broader understanding of biomass conversion technologies and their potential role in addressing energy challenges while promoting environmental sustainability.

DECLARATION of ETHICAL STANDARDS

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

REFERENCES

[1] Castello D., Fiori L., “Supercritical water gasification of biomass: a stoichiometric thermodynamic model”, ***Int J Hydrogen Energy***, 40:6771-81, (2015).

[2] Palomar A., Sundo M., Velasco P., Camus D., “End-of-pipe waste analysis and integrated solid waste management plan”, ***Civil Eng J.***, 5:1970-82, (2019).

[3] Adnan M.A. and Hossain M.M., “Co-gasification of Indonesian Coal and Microalgae – A Thermodynamic Study and Performance Evaluation”, ***Chem Eng Process – Process Intensif***, 128: 1-9, (2018).

[4] Husain Z., Ansari K.B., Chatake V.S., Urunkar Y., Pandit A.B. and Joshi J.B., “Valorisation of Biomass Pellets to Renewable Fuel and Chemicals Using Pyrolysis: Characterisation of Pyrolysis Products and Its Application”, ***Indian Chem. Eng***., 62: 78–91,(2020).

[5] https://unfccc.int, “The United Nation Framework Convention on Climate Change”, The Kyoto protocol New York: United Nations, (2009).

[6] Khademi M, Jahanmiri A, Rahimpour M., “A novel configuration for hydrogen production from coupling of methanol and benzene synthesis in a hydrogen permselective membrane reactor”, ***Int J Hydrogen Energy,*** 34:5091-107 (2009).

[7] Saxena R C, Seal D, Kumar S, Goyal H B., “Thermo-chemical routes for hydrogen rich gas from biomass: a review”, ***Renewable and Sustainable Energy Reviews***, 12:1909–1927, (2008).

[8] https://data.worldbank.org/indicator/,“WorldBank”, (2021).

[9] C.S. Park, P.S. Roy, S.H. Kim, “Current developments in thermochemical conversion of biomass to fuels and chemicals Gasification for Low-grade Feedstock”, ***Fuel,*** (2018).

[10] Turn SQ, Kinoshita D, Zhang Z, Ishimura D, Zhou J., “An experimental investigation of hydrogen production from biomass gasification” ***Int J Hydrogen Energy***, 23:641–8,(1998).

[11] Balu E, Lee U, Chung J., “High temperature steam gasification of woody biomassea combined experimental and mathematical modeling approach”, ***Int J Hydrogen Energy,*** 40:14104-15,(2015).

[12] Lu Y, Guo L, Zhang X, Yan Q., “Thermodynamic modeling and analysis of biomass gasification for hydrogen production in supercritical water”, ***Chem Eng J.***, 131: 233-44, (2007).

[13] Sharma S, Sheth PN., “Air steam biomass gasification: experiments, modeling and simulation”, ***Energy Convers Manage.,*** 110:307-18, (2016).

[14] Mahishi MR, Goswami D., “Thermodynamic optimization of biomass gasifier for hydrogen production”, ***Int J Hydrogen Energy***, 32, 3831-40, (2007).

[15] Pellegrini LF, de Oliveira Jr S., “Exergy analysis of sugarcane bagasse gasification”, ***Energy***, 32:314-27, (2007).

[16] Zhang Y, Li L, Xu P, Liu B, Shuai Y, Li B., “Hydrogen production through biomass gasification in supercritical water: a review from exergy aspect”, ***Int J Hydrogen Energy***, 44: 1572-36, (2019).

[17] Mehrpooya M, Khalili M, Sharifzadeh MMM.,“Model development and energy and exergy analysis of the biomass gasification process (Based on the various biomass sources)”, ***Renew Sustain Energy Rev.,*** 91: 869-87, (2018).

[18] Zhang Y, Li B, Li H, Liu H., “ Thermodynamic evaluation of biomass gasification with air in autothermal gasifiers”, ***Thermochim Acta***., 519: 65-71, (2011).

[19] Abuadala A, Dincer I, Naterer G., “Exergy analysis of hydrogen production from biomass gasification”, ***Int J Hydrogen Energy***, 35:4981-90, (2010).

[20] Eri Q, Wu W, Zhao X., “Numerical investigation of the airsteam biomass gasification process based on thermodynamic equilibrium model”, ***Energies,*** 10: 2163, (2017).

[21] Dong, J., Chi, Y., Tang, Y., Ni, M., Nzihou, A., Weiss-Hortala, E., Huang, Q., “Effect of operating parameters and moisture content on municipal solid waste pyrolysis and gasification”, ***Energy Fuel,*** 30: 3994-4001, (2016).

[22] Burhenne, L., Damiani, M., Aicher, T., "Effect of feedstock water content and pyrolysis temperature on the structure and reactivity of spruce wood char produced in fixed bed pyrolysis", ***Fuel***, 107:836-847,(2013).

[23] Di Blasi, C., "Combustion and gasification rates of lignocellulosic chars. Prog.," ***Energy Combust***, 35:121-140, (2009).

[24] Kabalina, N., Costa, M., Yang, W., Martin, A., "Santarelli, M., Exergy analysis of a polygeneration-enabled district heating and cooling system based on gasification of refuse derived fuel", ***J. Clean. Prod***., 141:760-773, (2017).

[25] Soto Veiga, J.P., Romanelli, T.L., "Mitigation of greenhouse gas emissions using exergy", ***J. Clean. Prod.***, 260:121092, (2017).

[26] Bejan, A., ***"Advanced Engineering Thermodynamics"***, 978-1-119-28104-7, 4th Edition. (2016).

[27] K. Tae, H. Cho, R. Luck, P.J. Mago., "Modeling of reciprocating internal combustion engines for power generation and heat recovery", ***Appl. Energy***., 102: 327-335, (2013).

[28] Xu P, Jin Y, Cheng Y., "Thermodynamic analysis of the gasification of municipal solid waste", ***Engineering***, 3:416-22, (2017).

[29] Prins MJ, Ptasinski KJ, Janssen FJJG., "Thermodynamics of gas-char reactions: first and second law analysis", ***Chemical Engineering Science***, 58:13– 16, (2003).

[30] Manatura K, Lu J-H, Wu K-T, Hsu H-T., "Exergy analysis on torrefied rice husk pellet in fluidized bed gasification", ***Appl Therm Eng***, 111:1016-24, (2017).

[31] N.S. Barman, S. Ghosh, S. De, "Gasification of biomass in a fixed bed downdraft gasifier - a realistic model including tar", ***Bioresour. Technol***., 107:505–511, (2012).

[32] Boateng AA, Mullen CA, Osgood-Jacobs L, Carlson P, Macken N., "Mass balance, energy, and exergy analysis of bio-oil production by fast pyrolysis", ***Trans Am Soc Mech Eng J ENERGY Resour Technol***, 134:04-2001, (2012).

[33] Souza-Santos ML., "Solid fuels combustion and gasification: modeling", ***Simulation, and Equipment Operation,*** New York, (2004).

[34] Basu, P., "Biomass Gasifcation and Pyrolysis: Practical Design and Theory", ***Academic Press***, Burlington, (2010).

[35] Dincer I, Rosen MA., "Exergy as a driver for achieving sustainability" , ***Int J Green Energy***, 1: 1-19, (2004).

[36] Szargut J., "Exergy Method: Technical and Ecological Applications", ***WIT Press***.,(2005).

[37] Wang J-J, Yang K, Xu Z-L, Fu C., "Energy and exergy analyses of an integrated CCHP system with biomass air gasification", ***Appl Energy***, 142:317-27, (2015).

[38] Y. A. Çengel, M. A. Boles, ***Thermodynamics: an engineering approach***, McGraw-Hill Higher Education, (2006).

[39] Szargut J, Morris DR, Steward FR., ***Exergy analysis of thermal, chemical and metallurgical processes***, Hemisphere Publishing, New York, (1988).

[40] K.G. Mansaray, A.E. Ghaly, A.M. Al-Taweel, F. Hamdullahpur, V.I. Ugursal, "Air gasification of rice husk in a dual distributor type fluidized bed gasifier", ***Biomass Bioenergy***, 17:315-332, (1999).

[41] Özbay, G., & Kökten, E. S. " Modeling of Bio-Oil Production by Pyrolysis of Woody Biomass: Artificial Neural Network Approach.", ***Politeknik Dergisi***, 23(4), 1255-1264.