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Synergistic Effect of Co-Gasification of Municipal Solid Waste and Coconut Shells with Natural Zeolite Catalyst

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ABSTRACT

This study investigates the co-gasification of municipal solid waste (MSW) and coconut shell (CS) using natural zeolite catalysts, with a focus on elucidating physicochemical properties, syngas composition, and potential synergistic effects to enhance energy production performance. Proximate and ultimate analyses of MSW and CS delineate distinctive properties, guiding optimized co-processing. Natural zeolite catalysts, identified as mordenite, clinoptilolite, and alpha quartz via XRD analysis, introduce a novel dimension with potential catalytic influences on gasification products. Experimental assessments reveal the nuanced impact of varying biomass ratios on syngas composition, showcasing significant shifts in CO, CH_4, and H_2 concentrations quantified through gas chromatography. Flame color visualizations, captured quantitatively in real-time, provide immediate indicators of flammable gas presence during co-gasification scenarios, offering insights into process dynamics. Residue analyses, quantified across different biomass ratios, delineate tar, char, and gas distributions, informing optimization strategies. XRD analysis of chars at 750°C quantitatively illustrates microcrystalline structures and potential catalytic implications of $CaCO_3$ in the presence of MSW. This study bridges theoretical and practical dimensions, providing quantitative insights into the gasification process, syngas composition, and residue management. Emphasizing the potential of co-gasification with natural zeolite catalysts, it contributes substantial quantitative data, positioning itself as a scientific reference for advancing waste-to-energy processes and optimizing biomass utilization. The study underscores the importance of synergistic effects in achieving enhanced performance and sustainability in waste-to-energy conversion.

1. INTRODUCTION

The escalating challenges posed by rapid urbanization, with an urban population projected to reach 5 billion by 2030 [1], emphasize the urgent necessity for efficient waste management strategies. To confront the mounting impact of urbanization on waste generation and disposal, advanced municipal solid waste-to-energy (MSWTE) technologies demand exploration. Gasification, a pivotal technology within the circular economy-MSWTE framework, holds promise. This eco-friendly method converts carbon-based substances into syngas, offering a sustainable alternative to conventional waste disposal practices. However, the heterogeneous nature of municipal solid waste (MSW), comprising diverse materials like plastics, paper, food waste, and metals, presents challenges in maintaining consistent gasification conditions and achieving optimal energy recovery. Notably, MSW gasification is plagued by significant tar emissions during the process, leading to environmental and operational concerns [2], [3], exacerbated by the high ash content inherent in MSW [4].

The co-gasification of municipal solid waste (MSW) with various feedstocks, such as coal char [5] and tire char [2], presents a viable approach to mitigate tar content and improve gasification efficiency. Investigation into biomass blends, including sawdust, rice husk, and bamboo dust [6], has highlighted notable synergies. For instance, a blend of rice husk and sawdust at a 0.35 ratio increased the lower heating value from 3.16 to 3.64 MJ/Nm³, while rice husk and bamboo dust reached 4.25 MJ/Nm³ [7]. Similarly, blending palm kernel shell (PKS) and coconut shell (CS) at ratios of 70:30 and 60:40 resulted in reduced activation energy and increased syngas production and calorific value [8]. Co-gasification of wood chips (WC) and CS at a 70:30 ratio demonstrated significant enhancements in syngas composition and heating value [9]. These findings

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underscore the potential of specific blending ratios in optimizing gasification performance. Moreover, the co-gasification of lignocellulosic biomasses, like wood and coconut shells, has shown substantial hydrogen yield, emphasizing the influence of feedstock proportions and catalyst selection [9], [10]. Consequently, further exploration into incorporating CS in co-gasification with MSW holds promise for sustainable energy production.

The paucity of research on the co-gasification of MSW and CS highlights a significant gap in current literature, despite promising findings from previous studies. For example, co-gasification of coconut shell and charcoal reduces tar content compared to sole coconut shell gasification, although complete elimination is not achieved [11]. Similarly, blending MSW with olive stone biochar enhances syngas yield and heating value due to differences in ash content and alkali metal concentrations [12]. The incorporation of materials like switchgrass in co-gasification alters syngas composition, reducing CO levels while increasing H_2 and hydrocarbons [13]. Challenges persist, particularly concerning MSW's characteristics, such as moisture and ash content, impacting gasification processes and leading to technical issues like slagging and fouling [12]. Optimization of temperature and equivalence ratio is vital for achieving optimal syngas output and carbon conversion [12]. However, the effectiveness of co-gasification is influenced by feedstock physical properties, necessitating tailored optimization for specific gasifier designs. Gasification under different atmospheres yields varied results, with steam enhancing H_2 and CO_2 concentrations, and CO_2 atmosphere boosting the reactivity and conversion rates of certain biochars [12]. Additionally, co-gasification of MSW and biomass can mitigate pollutants like tar and HCl, with efficiency dependent on ER and temperature [14]. Studies suggest that co-gasification of MSW and coconut shells holds significant potential for enhancing carbon conversion efficiency and syngas yield compared to sole MSW gasification.

Furthermore, the abundance of natural zeolites holds significant promise for enhancing the co-gasification of MSW. Zeolite catalysts, renowned for their ample availability and distinctive characteristics such as high surface area, porosity, and molecular adsorption capabilities, exert a substantial influence on reaction kinetics and the quality of syngas. Numerous studies have demonstrated the effectiveness of incorporating zeolites in biomass co-gasification setups, showcasing notable reductions in tar content and enhancements in hydrogen concentration [15,16]. For instance, in PKS gasification, zeolites achieved up to a 98% reduction in tar content, leading to an improved hydrogen concentration in the syngas ranging from 52% to 64%. This underscores the potential of zeolites in refining gas composition and increasing energy yields. Beyond traditional biomass, the application of natural zeolite catalysts in fine coal waste gasification introduces an innovative pathway, revealing a syngas composition with significant hydrogen and carbon monoxide content, emphasizing the prospect of fine coal waste as a viable energy source [17]. However, research on the utilization of natural zeolites in the co-gasification of MSW with CS remains scarce in existing literature.

Therefore, expanding research into the co-gasification of MSW and coconut shells with natural zeolite catalysts is imperative. This study aims to provide comprehensive assessments of MSW and CS composition and energy content, exploring co-gasification strategies and the catalytic potential of zeolites. By enhancing understanding and practical knowledge in MSWTE processes, this research seeks to address contemporary challenges in urban waste management and advance towards a more sustainable energy paradigm.

2. EXPERIMENTAL SETUP

2.1 Sample Preparation

The specimens employed in this investigation comprised municipal solid waste (MSW) and coconut shells (CS). The MSW utilized was identified as a composite of food remnants, paper, wood, fabric, rubber, and plastic. The preliminary processing of MSW involved desiccation at a temperature of 105°C for a duration of 3 hours using an oven. Subsequent to this, the MSW underwent preparation through fragmentation into dimensions of 5 mm x 5 mm. The waste composition during this preparation exhibited the following percentages: food remnants 50.875%, paper 8.14%, wood 4.07%, fabric 0.763%, rubber 0.509%, and plastic 35.613%.

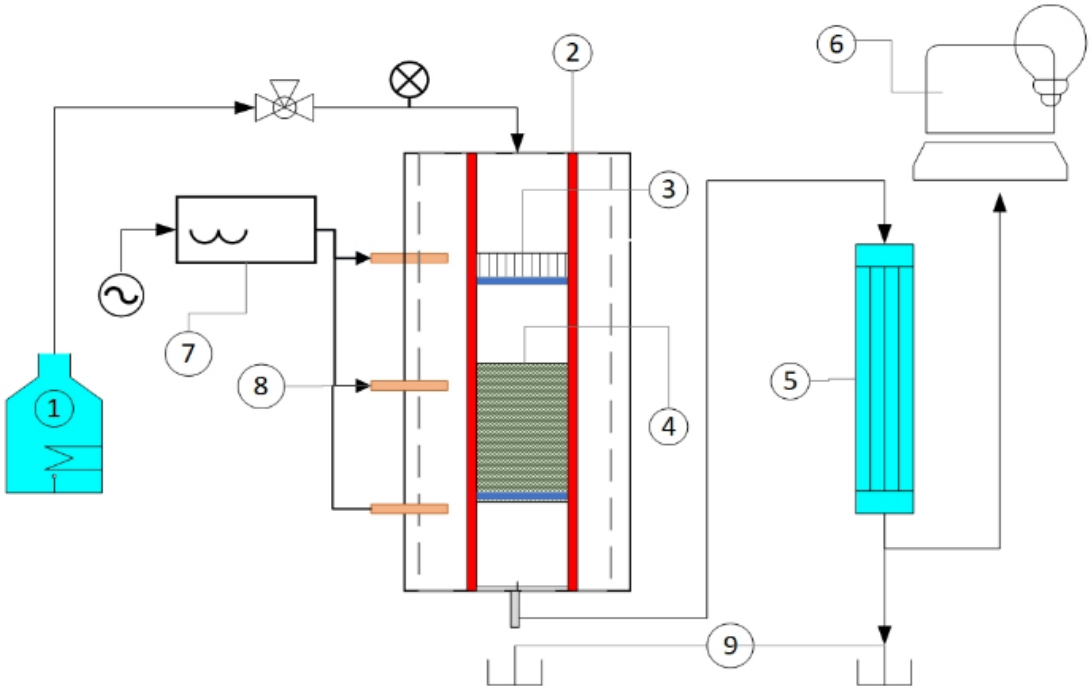
2.2 Characterization Techniques

In order to elucidate the characteristics of MSW and CS, proximate, ultimate, and calorific value analyses were conducted as preliminary data acquisition steps prior to the commencement of the research. Proximate analysis was employed to determine the moisture content, ash content, and volatile matter. Ultimate analysis was conducted to ascertain the carbon, hydrogen, and nitrogen content. The calorific value was determined using a bomb calorimeter.

X-Ray Diffraction (XRD) served as the methodology for examining nano-particle size as well as the crystalline and amorphous nature of the materials. The XRD analysis utilized the D2Phaser instrument from Bruker with the objective of delineating the structural characteristics of the active catalyst and nickel impregnation. The measurements were performed at 2θ, with intensity recorded in the range of 10° to 90°.

2.3 Experimental Procedure

The experimental protocol was executed within the confines of a fixed bed reactor, leveraging an induction heater complemented by a programmable temperature controller. The reactor tube, bifurcated into distinct tiers, featured a lower compartment hosting a composite of MSW and CS. Conversely, the upper section accommodated the natural zeolite catalyst, specifically sourced from Bayah, as delineated in Figure 1.



1. Evaporator
2. Reactor
3. Zeolite Catalyst
4. Biomass
5. Condenser
6. GC-MS
7. Control Panel
8. Thermocouple
9. Tar sampler

Fig. 1. Experimental setup diagram for co-gasification test.

Each experimental iteration involved the deposition of a 50 g sample of the MSW and coconut shell amalgam into the lower section. The zeolite catalyst was strategically positioned in the upper segment of the tube, bolstered by K wool ceramic fiber material, renowned for its high-temperature insulating attributes (up to 1260°C).

Throughout the experiment, the reactor underwent controlled electric heating, diligently monitored by three type K thermocouples. Each thermocouple meticulously gauged the furnace temperature and the real-time temperatures within the biomass and catalyst domains.

The analysis of co-gasification byproducts encompassed syngas constituents (H_2, CO, CH_4, CO_2), char, and tar. A gas chromatograph (GC) (Agilent GC 7820A), featuring an ultimetal HayesepQ T 80/100 mesh column, was deployed for the precise quantification of H_2, CH_4, CO_2, and CO concentrations within the syngas matrix. Helium, operating as the carrier gas, facilitated the injection of gas samples via an airtight syringe.

Upon attaining a consistent reaction temperature in the gasification zone, steam, in a Steam/(MSW+CS) ratio of 1.3, was introduced into the gasification milieu. The co-gasification temperature was rigorously maintained at 750°C. The schematic depiction of the experimental apparatus is elucidated in Figure 1, and the catalyst-to-biomass ratio remained steadfastly configured at 1:5 g/g.

3. RESULT AND DISCUSSION

3.1 Physicochemical Properties of Biomass

The composition of municipal solid waste (MSW) encompasses a diverse array of materials, including food remnants, paper, wood, fabric, rubber, and plastic, each with unique chemical properties that can influence gasification processes. Food remnants, rich in organic matter, contribute to the volatile content of MSW, enhancing gasification reactivity and promoting the production of syngas constituents. Paper, primarily composed of cellulose fibers, readily decomposes during gasification, releasing carbonaceous gases and influencing the calorific value of the waste stream. Wood, containing cellulose, hemicellulose, and lignin, contributes to both volatile matter and fixed carbon content, impacting char formation and syngas composition. Textile waste, such as fabric, undergoes thermal decomposition, releasing gases like carbon monoxide and hydrocarbons, which affect gasification kinetics and product yields. Rubber waste, characterized by hydrocarbons and sulfur compounds, undergoes pyrolysis to produce gases and can influence syngas quality through the formation of sulfur-containing compounds. Plastic waste, comprising diverse polymers and additives, exhibits varied gasification behaviors, with some plastics contributing to tar production or char formation. In this study, the comparison of the MSW with other MSW compositions was not conducted. Nevertheless, evaluating the representativeness of the MSW in relation to standard municipal solid waste compositions is crucial. Variations in waste composition,

influenced by geographic, demographic, and socio-economic factors, can yield different proximate and ultimate analyses, thereby impacting syngas quality.

Furthermore, the proximate and ultimate analyses of MSW and CS offer crucial insights into their potential for energy conversion. In terms of moisture content, MSW displays a lower percentage (6.27%) compared to coconut shell (8.62%), indicating a potential advantage in combustion efficiency. However, MSW exhibits a higher ash content (3.98%) in contrast to coconut shell (0.48%), suggesting that the latter may offer a cleaner gasification process with reduced ash-related operational challenges.

Table 1. Results of proximate and ultimate analyses conducted on MSW and CS.

Biomass	Specifications			
	Proximate			
	M (%)	Ash (%)	VM (%)	FC (%)
	6.27	3.98	77.33	12.42
	Ultimate			
MSW	C (%)	H (%)	O (%)	N (%)
	49.07	6.05	39.79	0.95
	Caloric Value (Cal/g)			
	4597			
	Proximate			
	M (%)	Ash (%)	VM (%)	FC (%)
CS	8.62	0.48	72.78	18.12
	Ultimate			
	C (%)	H (%)	O (%)	N (%)
	47.63	6.29	45.42	0.13
	Caloric Value (Cal/g)			
	4464			

Furthermore, the higher volatile matter in MSW (77.33%) enhances its reactivity during thermal conversion, contributing to efficient gasification. On the other hand, coconut shell's higher fixed carbon content (18.12%) implies superior energy potential, as fixed carbon directly influences calorific value and oxidation stability. The ultimate analysis reveals distinct elemental compositions, with variations in carbon, hydrogen, oxygen, and nitrogen content influencing the biomass combustion characteristics and overall energy yield.

Considering the calorific value, MSW demonstrates a slightly higher value (4597 cal/gram) compared to CS (4464 cal/gram). While this suggests favorable energy content in MSW, the marginal difference emphasizes the importance of considering multiple factors in assessing overall biomass suitability, including ash content and moisture. The presence of high ash content and moisture in feedstocks plays a pivotal role in shaping both the efficiency and environmental implications of gasification processes [12]. While moisture content has the potential to increase CH_4 levels in syngas due to steam reforming, maintaining optimal moisture levels is essential for efficient gasification, as excess moisture can result in energy loss in the form of steam and a decrease in calorific value [18]. Conversely, elevated ash content poses challenges, as each 1% increase in ash content correlates with a reduction in calorific value by 0.2 MJ/kg [19]. The variability in ash content among different biomass types, ranging from 0.37% to 10.44%, significantly impacts the gasification process and the quality of the resulting synthesis gas [19]. Furthermore, maintaining alkali index values within the range of 0.17 to 0.34 kg G/J is deemed necessary to prevent slagging and fouling, underscoring the criticality of controlling ash composition [20]. Ultimately, prioritizing lower ash content is preferred for achieving higher calorific value and mitigating operational challenges in gasifiers.

3.2 Characteristics of Bayah Natural Zeolite Catalyst

The XRD analysis of Bayah natural zeolite aimed to identify its zeolite type is presented in Figure 2. The XRD results revealed distinct peaks at angles 10, 11, 13.5, 22.5, 25.5, 27, and 30 degrees. These peaks corresponded to mordenite, clinoptilolite, and alpha quartz zeolite types. Specifically, mordenite exhibited peaks at angles 10, 13.5, 22.5, and 25.5 degrees, while clinoptilolite displayed peaks at angles 10, 11, 13.5, 22.5, 25.5, and 30 degrees. The observed peak similarities predominantly align with the clinoptilolite structure, followed by the mordenite structure.

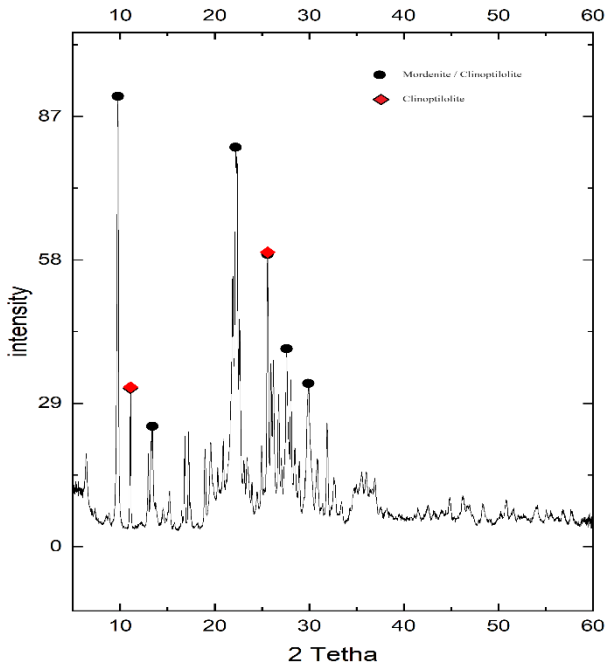


Fig. 2. XRD test results of Bayah natural zeolite catalyst.

However, mordenite, clinoptilolite, and alpha quartz zeolites showcase distinctive properties that amplify their catalytic prowess in various processes, including the co-gasification of municipal solid waste (MSW) and coconut shells. Mordenite's catalytic efficiency is boosted by its two-dimensional channel structure featuring six-ring pores, which promote molecular diffusion, while its acidic properties, determined by the Si/Al ratio and cation exchange capacity, significantly enhance its activity [21], [22]. Meanwhile, clinoptilolite's effectiveness in catalytic processes is further bolstered by its ion-exchange capabilities, often exploited in modifying the zeolite with metals like Fe, Cu, and Co to enhance its catalytic properties [23]. Moreover, mordenite's structural integrity and remarkable thermal stability, resisting amorphization up to 800°C, render it suitable for high-temperature catalytic processes [24]. Alpha quartz zeolite relies on its high surface area and the presence of potent acidic sites and redox centers crucial for catalytic activity, notably observed in the conversion of dihydroxyacetone [25]. Additionally, modifications involving metals such as Ni, Co, and their combinations with mordenite have demonstrated improved catalytic selectivity and efficiency, particularly in hydrocracking processes [26]. Therefore, the comprehensive characterization of Bayah natural zeolite provides valuable insights into its crystallographic structure, elemental composition, and physical properties, laying a foundation for potential applications, particularly in catalytic processes.

To further comprehend the characteristics of Bayah natural zeolite, SEM-EDS analysis was conducted to determine the Si/Al composition. The results are summarized in Table 2, presenting the elemental composition of the natural zeolite, including O, Mg, Al, Si, K, and Ca. Additionally, the surface area, micropore volume, and average pore radius were determined through BET analysis, yielding values of 28.62 m^2/g, 0.01 cm^3/g, and 6.35 Å, respectively. The obtained outcomes align with prior research, which reported a surface area within the range of 65.5 to 33.22 m^2/g [27]. The specific surface area mentioned in the previous study is 31.266 m^2/g.

Table 2. Characteristics of Bayah natural zeolite.

Natural zeolite element					
O	Mg	Al	Si	K	Ca
33.77	0.56	9.57	49.5	2.34	4.44
Surface area, volume and pore radius					
BET (m^2/g)		Micropore volume (cm^3/g)		Average pore radius (Å)	
28.62		0.01		6.35	

The investigation of Bayah Natural Zeolite reveals a Si/Al ratio of 5.71, which exceeds the 4.61 ratio reported in a prior study [28], suggesting a notable prevalence of silicon in the zeolite structure and significant thermal resistance.. This high Si/Al ratio is comparable to natural zeolites like clinoptilolite, which also exhibit Si/Al ratios ≥ 4. Leveraging such high Si/Al ratios, clinoptilolite-based catalysts demonstrate enhanced thermal and chemical stability, critical for high-temperature gasification processes [29]. Clinoptilolite's high silicon content contributes to its remarkable thermal stability up to 600°C, albeit with a loss of crystallinity and partial porosity observed at temperatures exceeding 450°C [30]. Therefore, the high Si/Al ratio observed in Bayah Natural Zeolite suggests its potential for developing catalysts with improved stability, comparable to clinoptilolite, which is

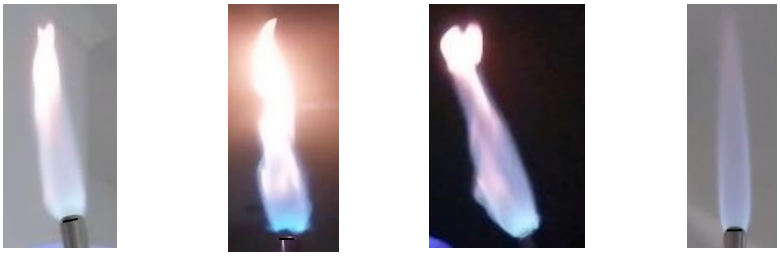
advantageous for high-temperature gasification applications.

3.3 Syngas Analysis

3.3.1 Flame color visualization

In the gasification process, the resulting syngas undergoes combustion, generating flames that serve as pivotal indicators of the gasification process [31]. Flame colors are distinguished into red and blue categories, with red denoting a lower composition of easily combustible gases (CO, H_2, CH_4), while a bluish hue indicates a higher presence of flammable gases (CO, H_2, CH_2). When utilizing 100% coconut shell with the natural zeolite catalyst from Bayah, the flame predominantly exhibits a blue color, suggesting a heightened composition of flammable gases (CO, H_2, CH_4).

Visual observations of flame colors in different composition ratios, such as 40:60 and 20:80, reveal predominantly reddish flames with slight bluish tints near the base as shown in Figure 3. These visual characteristics imply lower contents of flammable gases (CO, H_2, CH_4) compared to the 100% coconut shell scenario. In the context of 100% MSW, the resulting flame color is similarly predominantly reddish, indicating a diminished presence of flammable gases. Collectively, these flame color visualizations offer nuanced insights into the varying compositions of flammable gases during the gasification process under different biomass compositions and ratios.



(a) (b) (c) (d)

Fig. 3. Flame color of syngas from co-gasification using Bayah natural catalyst: (a) 100% CS, (b) CS:MSW = 40:60, (c) CS:MSW = 20:80, and (d) 100% MSW.

3.3.2 Gas chromatography analysis

In the gas chromatography analysis, examining different waste composition ratios provides valuable insights into the composition of syngas generated during co-gasification of MSW and CS. In the 0:100 ratio, where the composition is solely 100% CS, the syngas is characterized by a significant presence of CO at 26.80%, CH_4 at 20.56%, and detected hydrogen at 39.40% as shown in Figure 4. As the MSW content increases in the 80:20 ratio, with 40 grams of MSW and 10 grams of CS, the syngas composition shows a notable shift with CO at 26.70%, CH_4 at 12.19%, and a higher concentration of detected hydrogen at 45.37%.

Further variation is observed in the 60:40 ratio, where 60% MSW (30 grams) and 40% CS (20 grams) result in syngas with CO at 21.98%, CH_4 at 12.04%, and a significant increase in detected hydrogen at 49.70%. Finally, in the 100:0 ratio, focusing solely on MSW, the syngas composition reveals CO at 26.12%, CH_4 at 16.42%, and detected hydrogen at 41.79%. This comprehensive analysis underscores the impact of varying waste composition ratios on the gas composition during co-gasification of MSW and CS, offering crucial data for optimizing gasification processes and tailoring them to specific waste streams.

The analysis delves further into supporting data from proximate, ultimate, and calorific value testing. Notably, the volatile matter in MSW is higher compared to coconut shell, registering at 77.33%. Additionally, the highest hydrogen content is found in coconut shell, amounting to 6.29. The volatile matter content significantly influences the reactivity and efficiency of the gasification process, playing a crucial role in optimizing hydrogen production[32]. Combining these findings, it can be inferred that the blending of these biomass variations has the potential to yield high syngas values as fuel. The mixture of biomass ratios aims to explore whether the combination produces superior syngas results compared to using a single biomass as the gasification fuel. This is further supported by the observation of a blue flame in the 40:60 ratio, indicating a high composition of syngas components (CO, H_2, CH_4).

The observed synergistic effect in the co-gasification of MSW and CS is evident through the flame color visualization and gas chromatography analysis. Flame color, a visual indicator of the gasification process, displayed a significant shift when combining MSW and CS compared to using either biomass alone. In the 40:60 composition ratio of CS to MSW, the flame exhibited a nuanced reddish color with slight bluish tints, suggesting lower contents of flammable gases (CO, H_2, CH_4) compared to the 100% CS or MSW scenarios. This indicates a synergistic effect wherein the combined feedstocks alter the combustion characteristics, likely due to the interaction of their unique chemical compositions during gasification.

Gas chromatography analysis further supports this observation, revealing variations in syngas composition at different biomass ratios. As MSW content increased in the 80:20 ratio, the concentration of detected hydrogen notably rose to 45.37%, surpassing the hydrogen content in the 0:100 CS ratio. The 60:40 ratio showed a significant increase in detected hydrogen at 49.70%, reinforcing the idea that the combination of

MSW and CS in specific proportions enhances the production of hydrogen-rich syngas. These findings align with the flame color visualizations, indicating a synergistic influence on the gasification process.

The underlying mechanisms for this synergistic effect can be linked to the unique characteristics of MSW and CS. The higher volatile matter in MSW (77.33%) compared to coconut shell, coupled with the substantial hydrogen content in CS (6.29%), provides a basis for the observed synergy. The relationship between volatile matter and hydrogen content implies that blending these biomass variations has the potential to yield syngas with superior fuel properties. The combination of MSW and CS in specific ratios is envisioned to optimize gasification processes, resulting in a higher concentration of flammable gases, as indicated by the bluish tint in the flame color of the 40:60 ratio. This study contributes valuable insights into tailoring gasification processes for specific waste streams, emphasizing the potential for synergistic effects in co-gasification scenarios.

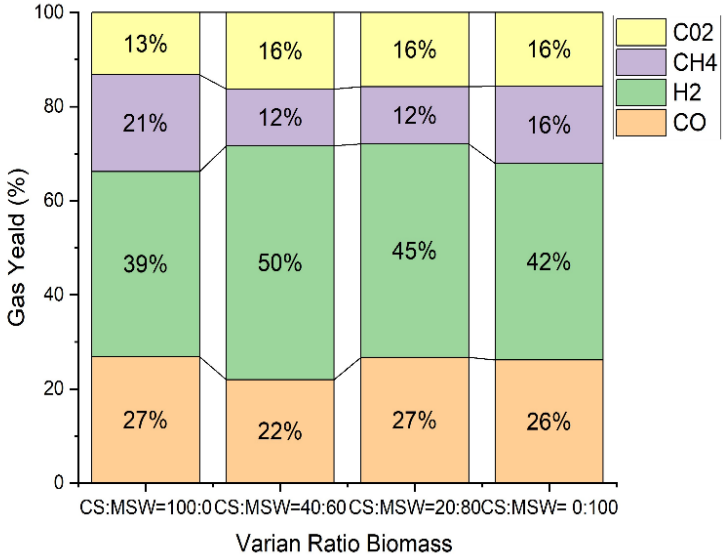


Fig 4. Gas composition in syngas from co-gasification of CS with MSW.

Table 3. Percentage distribution of tar, ash, and gas during co-gasification process.

Product	CS:MSW = 100:0	CS:MSW = 60:40	CS:MSW = 20:80	CS:MSW = 0:100
Tars	4.5%	7.1%	10.1%	8.9%
Chars	20.5%	15.2%	14.1%	13.7%
Gases	75.0%	77.7%	75.8%	77.4%

3.3.3 Co-gasification residue analysis

In the aftermath of gas sampling within the reactor, the subsequent phase involves the meticulous weighing of residues resulting from the gasification process. The residues encompass tars, chars, and residual zeolite remnants derived from the reaction. The outcomes of the residue products, expressed as percentages corresponding to each composition ratio, are elaborated in Table 3.

The observed variations in residue composition across different biomass ratios shed light on the efficiency of co-gasification. As the CS:MSW ratio shifts, the percentages of tars, chars, and gases exhibit discernible patterns. Notably, the percentage of tars increases with higher MSW content, reaching its peak at 10.1% in the 20:80 CS:MSW ratio. Conversely, chars content follows a decreasing trend as MSW content rises. The gas fraction remains relatively stable, emphasizing the potential impact of biomass composition on the co-gasification process. This comprehensive analysis aids in optimizing biomass ratios for enhanced gasification efficiency and residue management.

The identifiable trends in residue composition across various biomass ratios, as depicted in Table 3, are in accordance with existing literature and offer valuable insights into optimizing gasification efficiency beyond the confines of this study. These observed variations, such as the escalation in tar percentage with higher MSW content and the concurrent decline in chars content as MSW content increases, are consistent with prior research [33]. Achieving an optimal balance among all operational parameters simultaneously poses practical challenges; thus, attaining equilibrium between the optimal values of operational conditions becomes imperative [34]. Gasification processes have been extensively explored, with researchers endeavoring to optimize conditions through thermal and catalytic treatments to enhance gas quality by diminishing tar content in the syngas, augmenting hydrogen content, and streamlining processing steps [35]. Moving forward,

several avenues for future development exist, including the utilization of simulation models like Aspen Plus and computational fluid dynamics (CFD), which, when validated against experimental data, bolster the reliability of observed residue composition patterns. These tools can provide further insights into optimizing gasification efficiency beyond the specific conditions investigated in this study.

3.4 XRD Analysis of Chars

The gasification process conducted at 750°C with a steam-to-biomass ratio of 1.3, employing natural zeolite as a catalyst, yielded a char byproduct subjected to XRD analysis. The results, as depicted in Figure 4, unveiled a microcrystalline structure characterized by high disorder, signifying amorphous features of graphite microcrystals found in chars from gasification of 100% CS. Notably, when MSW was introduced into the biomass mix, XRD patterns revealed prominent crystalline calcite ($CaCO_3$) peaks at various compositions, hinting at a potential catalytic role of $CaCO_3$ in the gasification process.

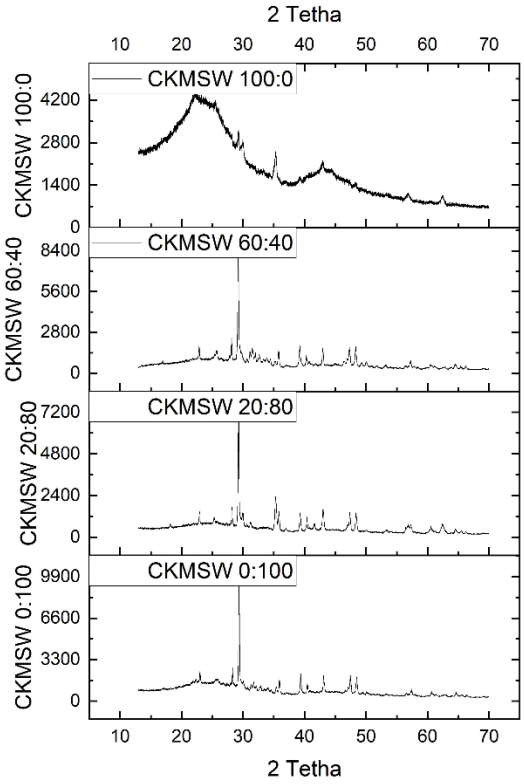


Fig 5. X-ray diffraction (XRD) analysis of ashes obtained from co-gasification employing natural zeolite catalyst.

The XRD analysis shown in Figure 4 revealing the presence of microcrystalline graphite and crystalline calcite in Bayah natural zeolite offers crucial insights into the gasification mechanism. These findings suggest that microcrystalline graphite plays a role in enhancing the gasification process by facilitating heat transfer within the gasifier, owing to its high thermal conductivity and stability [36]. Additionally, the presence of crystalline calcite, which decomposes into CaO and MgO during gasification, acts as a catalyst to enhance gas yield and promote chemical reactions [37]. CaO, derived from $CaCO_3$ decomposition, not only creates active sites for reactions but also aids in sulfur capture as CaS, contributing to the purification and efficiency of the gasification process [37]. Overall, the presence of microcrystalline graphite and crystalline calcite in Bayah natural zeolite plays significant roles in enhancing gasification efficiency and reactivity, with $CaCO_3$ acting as a catalyst to facilitate these processes.

In terms of mechanistic insights, the co-gasification process exhibits accelerated reactions due to the presence of amorphous carbons, facilitating higher gasification reactivity [38]. The addition of mineral catalysts, such as Ca, Fe, Mg, K, P, and Al oxides, enhances catalyst activity, leading to improved gasification performance [39], [40]. The activated carbon product from CS gasification undergoes improved porosity development influenced by chemical ratios and gasification temperature, further demonstrating the intricate mechanisms involved in achieving synergetic effects.

6. CONCLUSION

The co-gasification study of municipal solid waste (MSW) and coconut shell (CS) was conducted to examine their composition and energy content, assess their physicochemical properties relevant to gasification processes, and investigate the catalytic potential of Bayah natural zeolites. MSW, consisting of various

materials such as food remnants, paper, wood, fabric, rubber, and plastic, demonstrated higher volatile matter content, enhancing reactivity, while CS displayed superior energy potential due to its higher fixed carbon content. Analysis of co-gasification strategies between MSW and CS revealed nuanced variations in gas composition and residue distribution at different biomass ratios, indicating synergistic effects conducive to hydrogen-rich syngas production. Moreover, exploration of the catalytic potential of zeolites, notably Bayah natural zeolite, identified mordenite, clinoptilolite, and alpha quartz zeolites, each offering distinctive catalytic efficiencies. These findings contribute significantly to the quantitative understanding of biomass utilization for energy conversion and emphasize the potential for tailored gasification strategies optimized for specific waste streams, thereby advancing energy sustainability initiatives.

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