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RESEARCH PAPER

Materials characterization for Refuse Derived Fuel (RDF) production as renewable energy resources

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Abstract. This study offers a comprehensive analysis of key parameters—volatile matter, carbon content, ash content, and gross energy—across various material samples intended for Refused Derived Fuel (RDF) briquette production. Through meticulous examination, promising trends emerge, highlighting optimal material combinations for efficient combustion and heat generation. Samples rich in volatile matter and carbon content, notably those incorporating wood powder, demonstrate elevated calorific values, indicating their potential for effective energy production. Conversely, material combinations with low ash content suggest cleaner combustion and reduced environmental impact. The gross energy analysis further validates the substantial heat generation potential of specific sample combinations, rendering them suitable for diverse heating applications. These findings emphasize the critical role of precise raw material selection and meticulous manufacturing process optimization in producing RDF briquettes with desirable properties. Such briquettes not only offer economic viability but also contribute to environmental sustainability by providing an alternative fuel source with reduced emissions. This research underscores the importance of continued exploration and refinement in the development of RDF briquettes, aiming to meet growing energy demands while mitigating environmental concerns.

Keywords: RDF; biomass; renewable energy; briquettes; characteristic

1. Introduction

Bali island is renowned for its vibrant cultural and religious traditions, which are deeply rooted in Hinduism. These traditions often involve elaborate ceremonies and offerings, resulting in the generation of substantial amounts of organic waste (Rajendra, 2012; Martana, 2019). While these offerings serve as expressions of gratitude to the gods, their disposal poses significant environmental challenges. Proper management of temple waste is imperative to mitigate adverse environmental impacts, aligning with sustainable development goals and the principles of environmental stewardship (Wijaya et al., 2021; Yadav et al., 2015). Hindu religious ceremonies in Bali involve the offering of various natural materials, such as flowers, leaves, straw, and fruits to the gods. These offerings, while symbolic of devotion, result in the generation of waste, which poses challenges for waste management (Jain, 2016; Singh et al. 2013; Singh et al., 2017). Notably,

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not all organic waste degrades rapidly, leading to environmental concerns such as odor, aesthetic disruption, and limited land capacity for disposal (Balachander, 2015).

The characterization of temple waste is essential to understand its composition and devise effective waste management strategies (Gargiulo et al., 2023; Makwana et al., 2023). Previous studies have indicated that organic waste constitutes a significant portion of temple waste, with compositions varying based on the types of offerings and ceremonies conducted. Biodegradable waste, including leaves, flowers, fruit, and food scraps, constitutes most of the temple waste (Yadav et al., 2015; Das & Baishya, 2017; Samadhiya et al., 2017; Yadav et al., 2018). Additionally, non-biodegradable components, such as bamboo, hard leaves, and coconut shells, contribute to the waste stream. The improper disposal of temple waste not only impacts terrestrial environments but also poses risks to aquatic ecosystems when waste is discarded in rivers or coastal areas (Singh, 2013; Suantara et al., 2020).

Traditionally, the management of organic temple waste in Bali has involved collection by sanitation personnel and transport to landfills. While composting has been employed to manage organic waste, its effectiveness in waste reduction remains limited (Wiyono et al., 2021). To address this challenge, alternative methods for waste management and resource recovery are being explored. These methods aim to convert organic waste into valuable products, thereby reducing environmental impacts and promoting resource efficiency (Khammee et al., 2019; Schritt & Pleissner, 2022; Wijaya et al., 2021). One promising approach is the conversion of organic waste into biomass-based energy resources, such as Refuse-Derived Fuel (RDF) (Brás et al., 2017; Shehata et al., 2022; Wijaya, Wiratama, Putra, & Atmaja, 2023; Wijaya, Wiratama, Putra, & Aris, 2023). RDF is produced by shredding and drying organic waste to remove moisture content, resulting in a fuel source with high calorific value.

The utilization of RDF offers several advantages, including reduced greenhouse gas (GHG) emissions, decreased reliance on fossil fuels, and opportunities for decentralized energy production (Nobre et al., 2019). The characterization of diverse materials from daily production activities as potential RDF material is crucial for assessing its suitability for energy production. This involves analyzing the chemical composition, calorific value, moisture content, and ash content of the several materials. Additionally, physical properties such as particle size distribution and bulk density play a role in determining the handling and combustion characteristics of RDF (Alsulaili et al., 2024; Călin et al., 2021; Paolo & Paola, 2015; Zhou et al., 2016).

Research studies have demonstrated the feasibility of utilizing some materials such as dried coffee husks, corn husks, corn cobs, eggshells, sawdust, and rice husks as RDF material for energy production. These studies have highlighted the calorific value of these materials, making them suitable feedstocks for RDF production. Moreover, come materials exhibit favorable combustion properties and can be effectively utilized as RDF material. The utilization of RDF for sustainable energy production offers a viable solution to the management of organic waste. RDF can be utilized in various applications, including steam generation, brick manufacturing, and power generation (Edo et al., 2016; Sieradzka et al., 2020).

The combustion of RDF produces heat energy, which can be used for steam production in industrial processes or electricity generation in power plants. Furthermore, RDF can serve as a substitute for fossil fuels such as coal, thereby reducing GHG emissions and mitigating climate change impacts. By harnessing RDF as a renewable energy resource, we can achieve energy security, reduce environmental pollution, and promote sustainable development. Additionally, the decentralized production of RDF offers opportunities for community-based energy projects, empowering local communities and enhancing economic resilience.

2. Material and method

The RDF was engineered from a unique blend of six materials: dried coffee husks, corn husks, corn cobs, eggshells, sawdust, and rice husks as fundamental constituents. There were 16 samples, including the six materials alone and 10 mixed compositions with 50%:50% ratio. Previous investigations, including the study by Wijaya and Putra (2021); Wijaya et al., 2021; Patent No. IDS000006518, 2023; Wijaya, Wiratama, Putra, & Atmaja, 2023) highlight that such waste typically accumulates in the vicinity of temples following ceremonial activities or most domestic activities. The samples are labeled as follow: temple waste and wood dust (S1), corn husk with wood dust (S2), dried coffee husk (S3), corn cobs and corn husk (S4), wood dust (S5), corn cobs and wood dust (S6), temple waste and corn cobs (S7), dried coffee husk and temple waste (S8), temple waste and corn husk (S9), dried coffee husk and wood dust (S10), dried coffee husk and corn husk (S11), corn cobs (S12), corn husk (S13), rice husk (S14), dried coffee husk and corn cobs (S15) and eggshells (S16). Samples are showed on Figure 1.

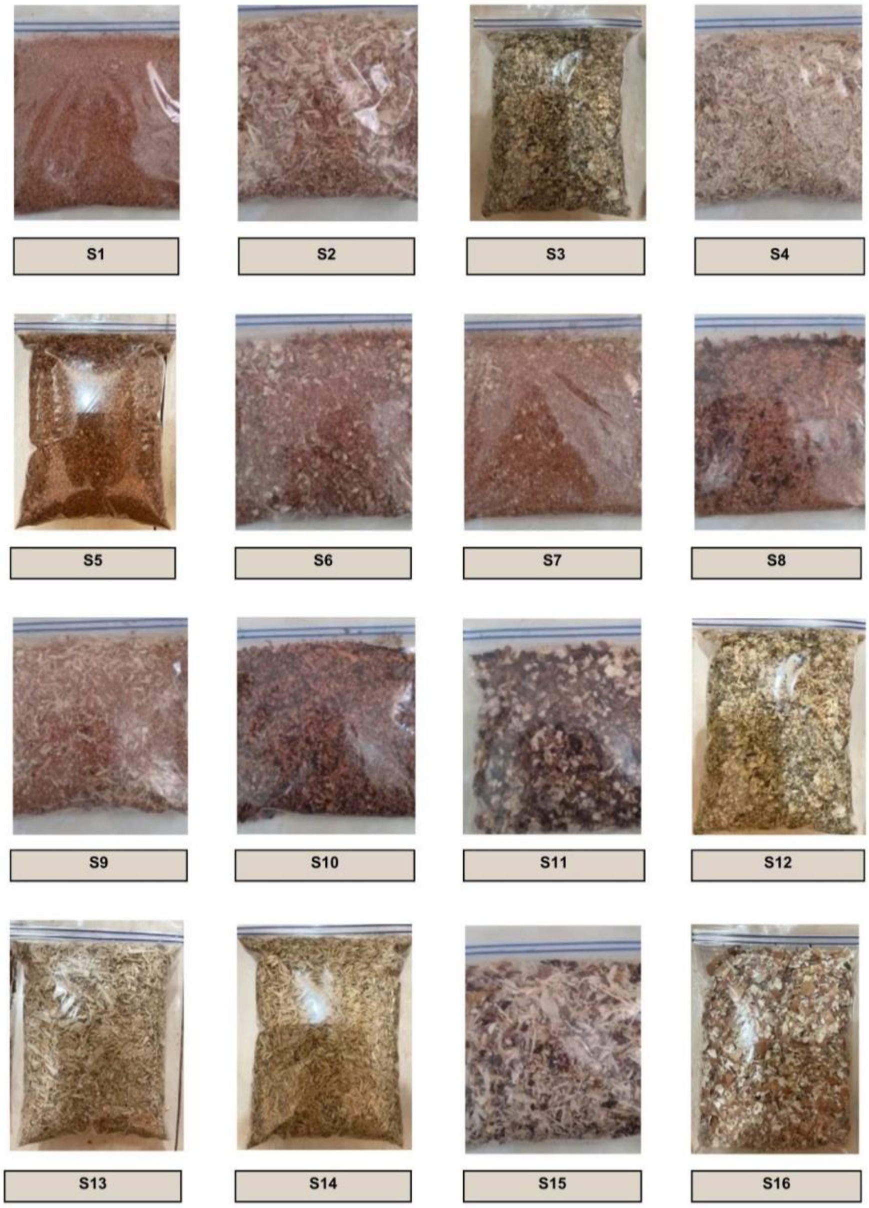

Figure 1. Raw material for RDF production material

2.1. RDF briquette production

The fabrication of biomass briquettes was meticulously executed through the compression of biomass into cylindrical pellets, each measuring between 5-10 cm in length and 1 cm in diameter. The process commenced with the initial size reduction of the dried temple waste using a MCC series 6-200 chaft cutter machine, powered by a GC-200 engine of 6.5 horsepower. This was followed by a finer milling stage, employing a FFC 23 machine integrated with a GX 270 engine of 9 horsepower. The resultant temple waste powder was subsequently compressed into pellets utilizing a vertical pellet press machine, SLD 150 MPK, equipped with a JF 180 engine. Additional materials, chosen for their relevance and availability, included dried coffee husks, corn husks, corn cobs, eggshells, sawdust, and rice husks. Each of these organic samples was subjected to the same rigorous analysis criteria as the initial materials, encompassing moisture content, ash content, organic matter, and calorific value, among others. This expansive selection of materials was intended to broaden the study's scope in identifying viable sources of biomass for RDF production, thereby contributing to the diversification of renewable energy resources.

2.2. Preparation of crab shell for chitosan extraction

2.3. Characteristic analysis of RDF

The analytical phase for RDF was expansive, embracing both the primary temple waste-derived fuels and the sixteen additional organic materials identified in the study's second year. The physical and chemical properties of RDF's and other organic were meticulously examined, focusing on moisture, ash, and organic content, and caloric potential. Moisture content was determined by oven drying at 103 ± 5°C until a constant mass was achieved, a critical step in ensuring the accuracy of subsequent analyses. Gravimetric methods were employed to quantify ash and organic matter, following protocols established by the Association of Official Agricultural Chemists (AOAC). Nutrient content, specifically nitrogen, was quantified using the semi-micro Kjeldahl technique, whereas phosphorus and calcium concentrations were measured through spectrophotometry and atomic absorption spectroscopy (AAS), respectively. The calorific value was evaluated using a Gallenkamp Ballistic Bomb Calorimeter, with combustion in an oxygen-rich atmosphere to measure energy content (Gałko et al., 2023; Rezaei et al., 2020; Widyatmoko et al., 2021). This comprehensive approach aimed to provide a robust dataset on the potential energy contributions of various organic materials when processed into RDF, offering valuable insights for the development of renewable energy solutions.

3. Result and discussion

The study's exploration of the moisture content of various RDF briquette samples unveils critical insights into the suitability and efficiency of these materials for fuel applications. Moisture content, representing the percentage of water mass within the briquettes, significantly influences the combustion process, energy yield, and overall feasibility of RDF briquettes as a renewable energy source.

3.1. Moisture content analysis

The analysis revealed a wide range of moisture contents across the different materials tested, as depicted in the accompanying graph (Figure 2). The moisture content varied significantly, from as low as 1.6% in eggshell samples to as high as 23.01% in corn stalk samples. Most materials maintained a moisture content below 15%, aligning with the optimal range for the efficient combustion of RDF briquettes. Eggshells exhibited the lowest moisture content at approximately 1.6%, indicating their potential as an excellent material for RDF briquette production due to minimal drying requirements and higher calorific value retention. In contrast, corn stalks, with a moisture content of 23.01%, highlighted the challenges in using high-moisture materials, necessitating extensive drying to prevent energy loss during combustion. The majority of the materials tested fell below the recommended 15% moisture content threshold, suggesting their general suitability for RDF briquette production without extensive pre-drying.

High moisture content hampers combustion efficiency as a substantial portion of the generated energy is consumed to evaporate the water content before the material can ignite. This results in lower heat output and potentially incomplete combustion, contributing to higher emissions and lower energy efficiency (Li et al., 2023; Nobre et al., 2019). Materials with higher moisture content weigh more and occupy greater volume, which can adversely affect transportation costs and storage requirements. In contrast, dryer materials are more cost-effective to transport and store due to their reduced weight and density. The combustion of high-moisture content materials tends to produce higher exhaust emissions because the energy used to evaporate the water reduces the efficiency of combustion, leading to incomplete burning and the release of uncombusted gases (Rania et al., 2019). The energy value or calorific value of RDF briquettes decreases with increasing moisture content. Dry materials combust more completely and efficiently, releasing more energy and thus providing a higher calorific value (Nowak, 2023).

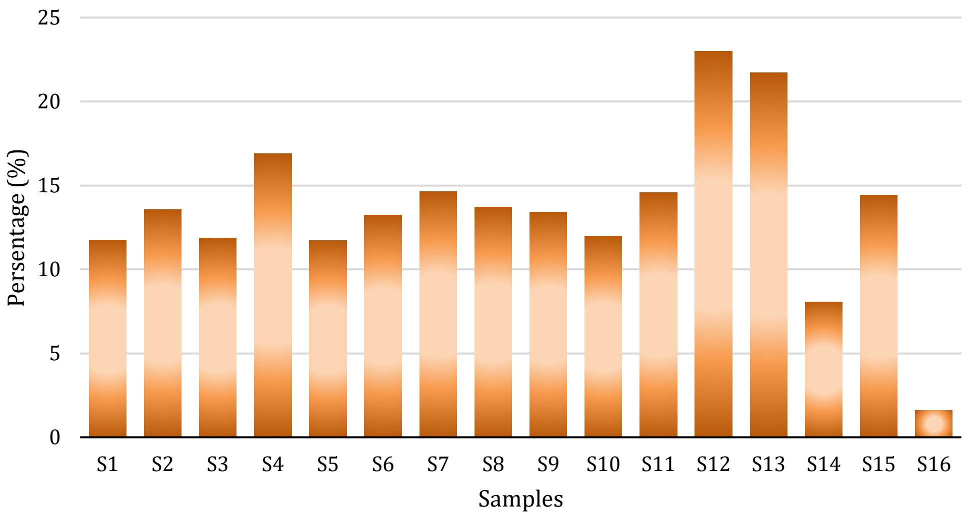

Figure 2. Moisture content percentage

The study underscores the pivotal role of moisture content in determining the quality and combustion efficiency of RDF briquettes. Materials such as eggshells, with inherently low moisture content, are highly favorable for briquette production, offering higher calorific values and requiring less energy for drying (Shumal et al., 2020). In contrast, materials like corn stalks require significant drying, highlighting the need for efficient moisture management strategies in RDF production to ensure high-quality fuel output (Schwarzböck et al., 2018).

The findings advocate for a meticulous selection of raw materials based on moisture content to optimize the RDF briquette manufacturing process. Implementing effective drying techniques prior to briquetting can enhance fuel quality, combustion efficiency, and environmental performance of RDF briquettes, contributing to the broader adoption of this renewable energy source.

3.2. Organic content analysis

The analysis of organic content highlighted the potential of various biomass materials in contribute to the high calorific value of RDF briquettes (Figure 3). Wood sawdust emerged as the material with the highest organic content (99.08%), underscoring its viability as a primary or supplementary material in briquette formulation due to its high energy content and combustion efficiency. Most samples demonstrated organic content above 90%, suggesting a broad suitability of these materials for RDF production based on their inherent energy potential. The notable exception was eggshells, with had a significantly lower organic content, indicating their limited contribution to the briquette's calorific value but potential benefits for other properties, like structural integrity.

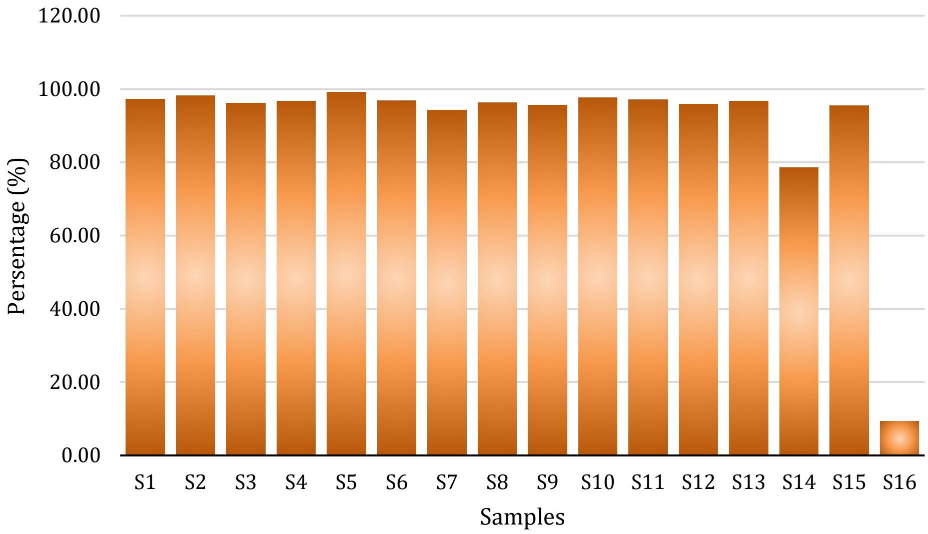

Figure 3. Organic content percentage

High moisture content in briquettes necessitates greater energy expenditure to evaporate the water before combustion can occur, thereby reducing the overall energy output. In contrast, high organic content correlates with a higher calorific value, enhancing the briquette's energy efficiency and combustion quality (Rajca et al., 2020; Sarc & Lorber, 2013). While organic materials generally contribute positively to the calorific value, the type of organic matter is crucial. For example, materials like plastics, despite their high energy content, can produce toxic emissions when burned. The selection of organic materials must balance energy output with environmental impact.

The moisture content directly impacts the briquette's transportation and storage costs. Lower moisture content materials require less drying, reducing production costs and potentially lowering the environmental footprint of the manufacturing process. Our findings emphasize the importance of careful material selection and preparation in RDF briquette production. By optimizing moisture and organic content, manufacturers can improve the efficiency, environmental sustainability, and economic viability of RDF briquettes (Brás et al., 2017).

In conclusion, the successful production of high-quality RDF briquettes hinges on a nuanced understanding and control of both moisture and organic content within the raw materials. Strategies to reduce moisture content to within the optimal range and maximize organic content without compromising environmental standards are essential for the development of efficient, sustainable, and economically viable RDF briquettes.

3.3. Volatile content analysis

Volatile content, expressed as a mass percentage, represents the portion of a material that readily evaporates at low to medium temperatures, encompassing compounds like water vapor and light organic compounds. Achieving the optimal volatile content is crucial for ensuring efficient combustion processes. While high volatile content can facilitate faster ignition, excessively volatile materials may lead to unstable combustion and excessive emissions (Brás et al., 2017; Porshnov et al., 2018). Precise control over the briquette manufacturing process temperature is instrumental in regulating volatile content. High volatile content facilitates prompt ignition, as volatile compounds readily evaporate at low temperatures, supporting the initial combustion process. This contributes to combustion efficiency and helps maintain stable burning. Proper volatile content levels aid in sustaining consistent combustion. Excessive volatile compounds may induce fluctuations, while insufficient volatiles can disrupt ignition and stability (Maj et al., 2022; Mlonka-Mędrala et al., 2021).Volatile compounds released during combustion can generate exhaust gases such as carbon dioxide (CO_2), water vapor, and other compounds. These emissions can impact environmental quality and air pollution levels, necessitating careful consideration of volatile compound composition during briquette manufacturing (Liedmann at al., 2017). Optimal volatile content enhances combustion efficiency by ensuring that most of the energy generated during combustion is utilized effectively. However, excessively high volatile content may result in unstable combustion and increased emissions. Materials with high volatile content may require careful handling and management, particularly concerning safety and fire prevention protocols (Jiang et al., 2024; Tihin et al., 2023).

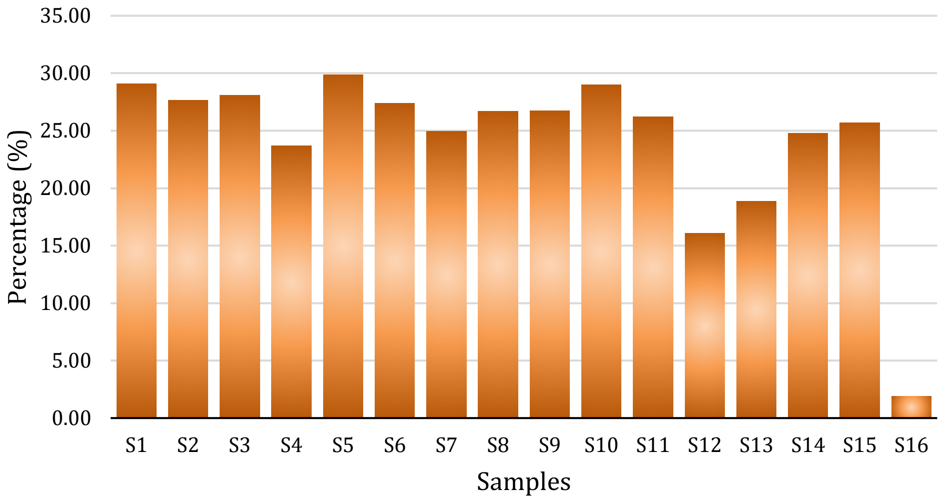

Figure 4. Volatile content percentage

Samples such as dry coffee husks and the combination of pure waste with wood sawdust exhibit notably high volatile contents, ranging from 28.07% to 29.09% (Figure 4). This indicates their potential for rapid ignition and substantial contribution to the combustion process of RDF briquettes. The presence of these highly volatile materials enhances the ignition phase, promoting efficient combustion. Conversely, materials with lower volatile content, such as eggshells with only 1.9% volatile content, have limited potential for evaporation and combustion at lower temperatures. This characteristic may be attributed to their denser composition and structural complexity, which impedes rapid evaporation and combustion.

Certain combinations of raw materials, such as coffee husks with wood sawdust and pure waste with wood sawdust, exhibit increased volatile contents compared to individual materials. This suggests a synergistic effect in volatile content enhancement, potentially leading to improved combustibility and energy release during RDF briquette combustion (Hayashi & Ohsawa, 2015; Kaniowski et al., 2022). The volatile content analysis reveals variability across different types of raw materials, when can significantly influence combustion behavior, heat generation, and the substitutability of RDF briquettes for conventional fuels. Understanding this variability is crucial for optimizing the composition of raw materials in RDF briquette production to achieve desired combustion characteristics and energy output.

Information derived from volatile content analysis is instrumental in designing optimal raw material compositions for RDF briquette production. By balancing volatile content, manufacturers can enhance combustion efficiency, reduce emissions, and ensure the overall quality and performance of RDF briquettes (García et al., 2021; Nasiri et al., 2023; Smoliński et al., 2022).

Optimization efforts may involve adjusting production parameters such as temperature, pressure, and processing time to achieve desired volatile content levels tailored to specific applications of RDF briquettes. Analyzing volatile content provides valuable insights into the combustion behavior and efficiency of RDF briquettes, guiding production strategies towards improved performance, environmental sustainability, and energy utilization (Alsulaili et al., 2024).

3.4. Carbon content analysis

Carbon content measurement quantifies the percentage of carbon mass present in briquettes (Figure 5). Carbon is a primary component in fuels that generates energy upon combustion. Therefore, high carbon content enhances the calorific value of briquettes. However, excessively high carbon content may also elevate carbon dioxide (CO_2) emissions during combustion. Thus, a balance between calorific value and GHG emissions is essential.

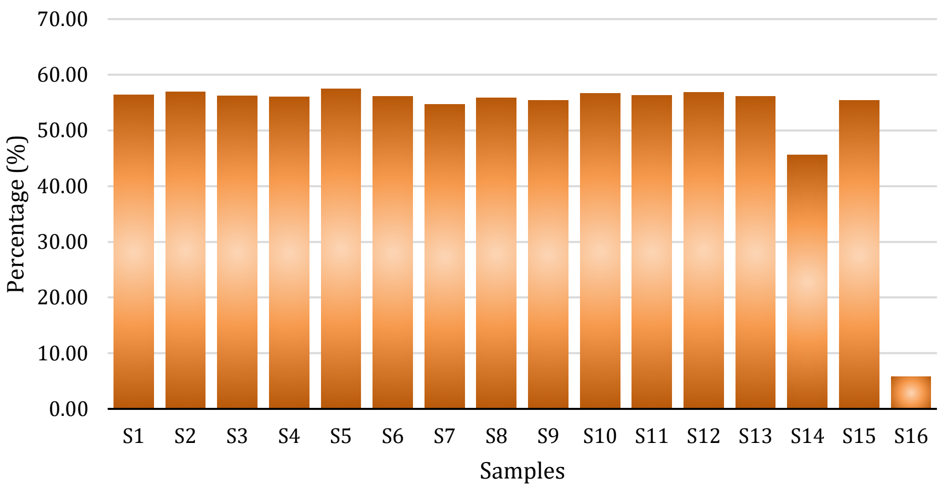

Figure 5. Carbon content percentage

The influence of carbon content on briquette quality includes: **Calorific value**: The carbon content directly correlates with the calorific value, or energy produced, upon complete combustion. Higher carbon content results in a greater calorific value, meaning briquettes with higher carbon yield more heat when used as fuel. **Combustion efficiency**: High carbon content contributes to better combustion efficiency. Since carbon is readily combustible, high carbon content fosters stable and consistent combustion processes. **Greenhouse gas emission**: Although carbon is a primary component of combustion, it is also producing exhaust gases like CO_2. Therefore, high carbon content in briquettes can escalate GHS emissions if not effectively controlled. **Reduction in fossil fuel use**: Utilizing briquettes with high carbon content can reduce the reliance on fossil fuels, thereby mitigating GHG emissions and air pollution. **Sustainability**: High carbon content in organic waste raw materials supports sustainability by utilizing waste as an alternative energy source (Egan et al., 2022; Materazzi et al., 2016; Paolo & Paola, 2015).

The analysis of carbon content in various raw material samples for RDF briquette production indicates the percentage of carbon components in each sample. This carbon content significantly affects the calorific value and combustion efficiency of RDF briquettes, influencing their overall energy contribution. For example, wood sawdust samples exhibit high carbon content percentages, ranging from 56.08% to 57.47%, indicating a high potential for energy generation during combustion, as carbon is the primary heat-producing component.

Conversely, materials with lower carbon content, such as eggshells with 5.79% carbon content, contribute less energy during combustion. This lower energy output may be due proportions of non-carbon organic components in these samples. Combinations of raw materials, such as coffee husks with wood sawdust and corn husks with wood sawdust, demonstrate sufficiently high carbon content, ranging from 56.12% to 56.91%. These combinations integrate the desirable characteristics of materials with good energy potential, enhancing the efficiency of RDF briquette combustion.

The carbon content in RDF briquettes is a vital indicator of their energy potential through combustion. Briquettes with higher carbon content generally possess higher calorific values, which significantly contributes to energy applications and heating. Understanding carbon content helps in selecting appropriate raw materials to produce RDF briquettes with optimal quality concerning calorific value and combustion performance. However, utilizing fuels with high carbon content can also increase CO_2 emissions, which is a critical factor in climate change (Chalermcharoenrat et al., 2015). Therefore, the use of RDF briquettes with high carbon content must be balanced with environmental considerations and GHG emission management.

Selecting the appropriate types and compositions of raw material and precise production processes are key to optimizing carbon content in RDF briquettes (Suryawan et al., 2024). By considering both environmental impacts and economic value, briquette manufacturers can achieve an optimal balance between calorific value, combustion efficiency, and exhaust gas emissions.

3.5. Ash content analysis

Ash content measurement quantifies the percentage of mineral and residual mass remaining after briquettes are burned. Ash can affect combustion in several ways. High ash content can disrupt the combustion process and form deposits on combustion equipment, reducing efficiency and causing increased wear. Therefore, briquettes with low ash content are preferred. Reduction ash content can be achieved through selective raw material selection and proper manufacturing process control (Isaac & Bada, 2020; Zaini et al., 2021).

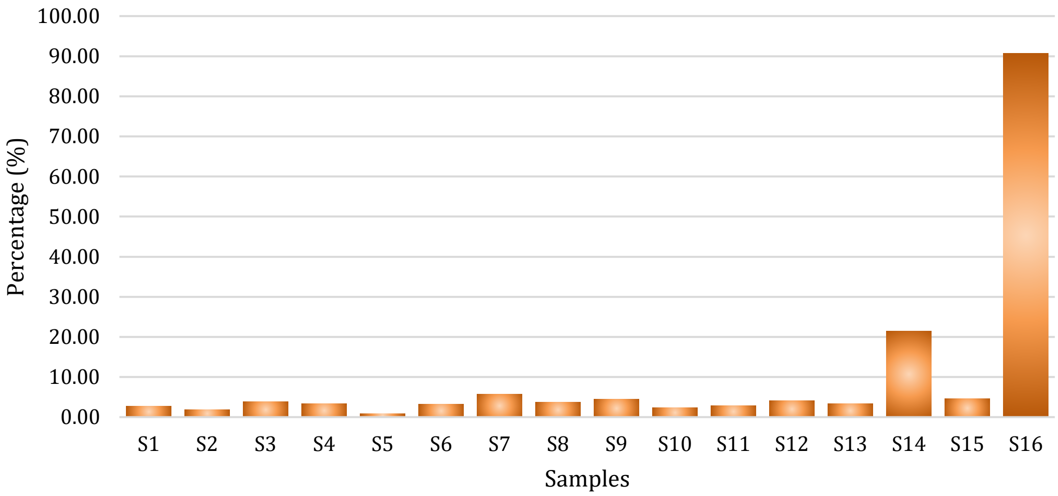

Figure 6. Ash content percentage

Low ash content in briquettes is desirable because ash does not burn and can disrupt efficient combustion. Accumulated ash can form deposits inside combustion equipment, reducing efficiency and causing increased wear. Low ash content helps create cleaner and more stable combustion, as minimal ash production during combustion results in fewer harmful particles and pollutant emissions. Briquettes with low ash content also tend to produce less residual ash after combustion, making combustion equipment use and maintenance easier and reducing the frequency of required maintenance activities.

In contrast, high ash content in briquettes can contribute to increased particle emissions into the air during combustion, which can negatively impact air quality and human health (Jamradloedluk & Lertsatitthanakorn, 2015; Siddiqi et al., 2021). Additionally, briquettes with low ash content produce less ash waste, reducing the cost and environmental impact of ash waste handling.

The analysis of ash content in various briquette material samples indicates the percentage of ash components present in each sample (Figure 6). Ash content is a crucial indicator when evaluating the quality of RDF briquettes, as it affects both the calorific value and combustion performance. Samples like wood sawdust exhibit low ash content, with only 0.92% ash. This low ash content suggests that wood sawdust has the potential to produce briquettes with higher calorific values and cleaner combustion, as ash contributes little to calorific value and can increase impurities during combustion.

Conversely, materials with high ash content, such as eggshells with 90.71% ash content, indicate that ash components are dominant in the sample. High ash content tends to reduce the calorific value of briquettes and negatively affects combustion performance by increasing ash production during the combustion process. Raw material combinations containing wood sawdust, such as coffee husks with wood sawdust and corn husks with wood sawdust, demonstrate relatively low ash content, ranging from 1.88% to 2.36%. This indicates the potential for briquettes with good calorific values and more efficient combustion.

Ash content in RDF briquettes significantly affects combustion cleanliness and environmental impact. Briquettes with low ash content tend to produce fewer ash emissions during combustion, supporting efforts to reduce environmental impact. Analyzing ash content is eesential for selecting suitable raw materials to produce RDF briquettes of desired quality, especially in terms of calorific value, combustion performance, and environmental impact.

To improve RDF briquette quality, manufacturers should strive to reduce ash content in raw materials and optimize their composition (Jiang et al., 2024; Sikarwar et al., 2022). The use of cleaner, more selective raw materials, along with precise temperature control and manufacturing processes, can help minimize ash content in briquettes. However, it is essential to note that a minimum level of ash content is unavoidable, as some mineral components will always remain as residues after combustion. Overall, RDF briquettes with low ash content provide higher combustion efficiency, lower emissions, and better overall quality.

3.6. Calorific value analysis

Calorific value represents the amount of heat energy produced when briquettes are completely burned. It is directly related to the chemical composition of the briquettes, especially the carbon and organic content. The higher the carbon and organic content, the higher the calorific value of the briquettes (Kijo-Kleczkowska et al., 2022). A high calorific value indicates greater efficiency in generating heat energy, meaning the briquettes will produce more heat when burned. This indicates that the briquettes can provide higher combustion efficiency, as more energy is generated from each unit of briquette (Munshi et al., 2024; Pardo et al., 2023).

Briquettes with high calorific value offer more effective and robust heating, making them suitable for various applications, such as industrial heating, household heating, or as an alternative energy source. Additionally, high calorific-value briquettes can reduce fuel requirements over time, which can lower energy costs and increase resource utilization efficiency (Bassey et al., 2022; Papastefanatos et al., 2022; Zhang et al., 2023). These briquettes tend to produce fewer unburned fuel residues and emit fewer toxic or hazardous gases when burned. Moreover, briquettes with high calorific value generate more energy per unit mass, requiring less space for storage and transportation, thereby reducing logistical costs (Tihin et al., 2023; Zajemska et al., 2022).

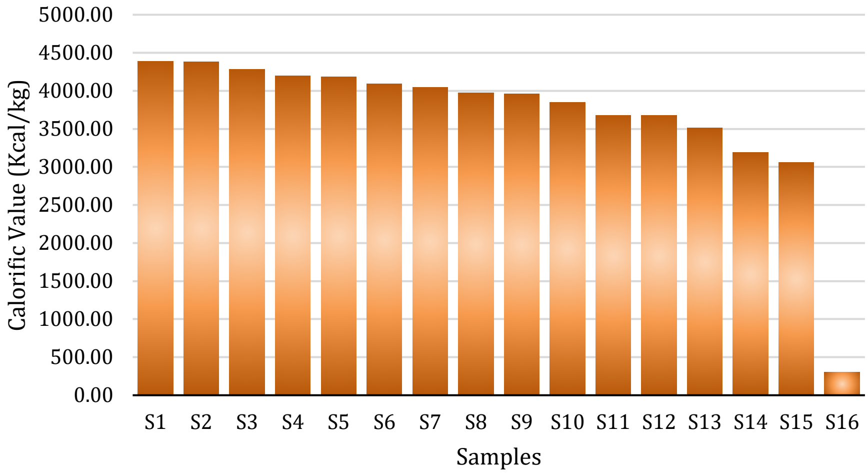

Figure 7. Calorific value analysis

The analysis of gross energy on various briquette material samples measures the energy value produced when each sample is completely burned. This value is crucial for evaluating fuel efficiency and the potential of briquettes to generate heat during combustion. Here is an overview of the gross energy analysis results for these samples. Samples with high gross energy values, such as dry coffee husks with a value of 4280.9 kJ/kg and wastepaper combined with wood powder (1:1) with a value of 4390.7 kJ/kg, indicate a strong potential to produce heat when burned (Figure 7). This suggests that briquettes made from these materials can serve as an efficient energy source. Corn stalks, with a gross energy value of 3675 kJ/kg, also have reasonable energy potential, although this value is lower compared to some other samples. Nevertheless, corn stalks can still be considered a useful energy source.

Briquettes made from materials with low gross energy values, such as eggshells (300.8 kJ/kg) and coffee husks and corn cob (1:1) (3060.9 kJ/kg), may have lower heat efficiency when burned. This suggest that these materials may not be suitable as primary fuels but could have potential when combined with other materials. Raw material combinations containing wood powder, such as corn husks mixed with wood powder (1:1) with a value of 4379.1 kJ/kg and corn cob mixed with wood powder (1:1) with a value of 4094 kJ/kg, demonstrate good energy potential. The wood powder content contributes positively to the energy value of the briquettes.

The gross energy analysis provides insights into the potential of raw materials to produce heat energy. High energy values indicate that briquettes from these materials have good calorific values and can be used as efficient alternative fuels. Compared to the SNI standards for RDF briquettes (Brunner et al., 2021), the analysis results show that the calorific values of the tested briquette samples vary in meeting the criteria for the designated classes. For Class 1, which has the highest calorific value requirement above 4777 kcal/kg, no briquette sample successfully reached this threshold. Some samples meet the criteria for Class 2, which requires a calorific value above 3583 kcal/kg, while fall below this threshold. However, all briquette samples in this analysis meet the standard for Class 3, which has a calorific value limit above 2389 kcal/kg. Overall, the analysis results indicate that these briquettes are generally suitable for use in Class 3, where the lower calorific value still meets the established requirements. Although a high calorific value is desirable, it is important to note that calorific value is not the only factor affecting briquette quality.

Other parameters such as moisture content, organic content, volatile matter content, carbon content, and ash content, should also be considered together. The selection of raw material types, manufacturing process control, and environmental considerations are important aspects in achieving high calorific value while maintaining overall briquette quality (Deshannavar et al., 2018; Makwana et al., 2023; ÖzyuğUran & Yaman, 2017). In conclusion, high calorific value in RDF briquettes contributes to better combustion efficiency, improved heating performance, and greater economic benefits. However, optimization of other parameters must also be done to achieve optimal briquette quality.

4. Conclusion

In conclusion, the comprehensive analysis of volatile matter, carbon content, ash content, and gross energy across various material samples for RDF briquettes provides valuable insights into their combustion characteristics and energy potential. Certain material combinations exhibit promising volatile matter percentages conducive to efficient combustion and heat generation, while samples rich in carbon content, particularly those incorporating wood powder, demonstrate potential for high calorific values and effective energy production. Conversely, low ash content in select material combinations indicates clean combustion and reduced environmental impact. Gross energy analysis further underscores the heat generation potential of different samples, with specific combinations showing favorable energy values suitable for efficient heating applications. These findings highlight the importance of meticulous raw material selection and manufacturing process optimization in producing RDF briquettes with desirable properties, thus contributing to both economic viability and environmental sustainability in the realm of alternative fuel sources.

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References

Alsulaili, A., Ali, O., Alenezi, N., & Al-Dabbous, A. N. (2024). Selection of municipal solid waste disposal technology using the Analytic Hierarchy Process and Genetic Algorithm for Gulf Cooperation Council Countries. *Journal of Engineering Research*. https://doi.org/10.1016/j.jer.2024.03.015

Balachander, J. (2015). *An Environmental Guide for Hindu Temples and Ashrams*.

Bassey, E. J., Cheng, J. H., & Sun, D. W. (2022). Thermoultrasound and microwave-assisted freeze-thaw pretreatments for improving infrared drying and quality characteristics of red dragon fruit slices. *Ultrasonics Sonochemistry*, *91*, 106225. https://doi.org/10.1016/j.ultsonch.2022.106225

Brás, I., Silva, M. E., Lobo, G., Cordeiro, A., Faria, M., & De Lemos, L. T. (2017). Refuse Derived Fuel from Municipal Solid Waste rejected fractions- a Case Study. *Energy Procedia*, *120*, 349–356. Elsevier Ltd. https://doi.org/10.1016/j.egypro.2017.07.227

Brunner, I Made Indradjaja M., Norhidayat, A., & Brunner, Satria M. (2021). Pengolahan Sampah Organik dan Limbah Biomassa dengan Teknologi Olah Sampah di Sumbernya. *Serambi Engineering*, *6*(3), 285-295. https://doi.org/10.32672/jse.v6i3.3120

Călin, C., Ion, I. V., Rusu, E., & Frătiţa, M. (2021). Performance analysis of a RDF gasification and solar thermal energy based CCHP system. *Energy Reports*, *7*(3), 186–192. https://doi.org/10.1016/j.egyr.2021.06.032

Chalermcharoenrat, S., Laohalidanond, K., & Kerdsuwan, S. (2015). Optimization of Combustion Behavior and Producer Gas Quality from Reclaimed Landfill Through Highly Densify RDF-Gasification. *Energy Procedia*, *79*, 321–326. https://doi.org/10.1016/j.egypro.2015.11.496

Das, D. Kumar & Baishya, P. (2017). Municipal Solid Waste Management: A Case Study of Kamakhya Devi Temple, Assam, India. *International Research Journal of Engineering and Technology*. *4*(9), 794-798.

Deshannavar, U. B., Hegde, P. G., Dhalayat, Z., Patil, V., & Gavas, S. (2018). Production and characterization of agro-based briquettes and estimation of calorific value by regression analysis: An energy application. *Materials Science for Energy Technologies*, *1*(2), 175–181. https://doi.org/10.1016/j.mset.2018.07.003

Edo, M., Budarin, V., Aracil, I., Persson, P. E., & Jansson, S. (2016). The combined effect of plastics and food waste accelerates the thermal decomposition of refuse-derived fuels and fuel blends. *Fuel*, *180*, 424–432. https://doi.org/10.1016/j.fuel.2016.04.062

Egan, A., Saju, A., Sigurnjak, I., Meers, E., & Power, N. (2022). What are the desired properties of recycling-derived fertilisers from an end-user perspective? *Cleaner and Responsible Consumption*, *5*, 100057. https://doi.org/10.1016/j.clrc.2022.100057

Gałko, G., Mazur, I., Rejdak, M., Jagustyn, B., Hrabak, J., Ouadi, M., Jahangiri, H., & Sajdak, M. (2023). Evaluation of alternative refuse-derived fuel use as a valuable resource in various valorised applications. *Energy*, 263(D), 125920. https://doi.org/10.1016/j.energy.2022.125920

García, R., González-Vázquez, M. P., Rubiera, F., Pevida, C., & Gil, M. V. (2021). Co-pelletization of pine sawdust and refused derived fuel (RDF) to high-quality waste-derived pellets. *Journal of Cleaner Production*, *328*, 129635. https://doi.org/10.1016/j.jclepro.2021.129635

Gargiulo, V., Alfe, M., Ruoppolo, G., Cammarota, F., Rossi, C.O., Loise, V., Porto, M., Calandra, P., Pochylski, M., Gapinski, J., & Caputo, P. (2023). How char from waste pyrolysis can improve bitumen characteristics and induce anti-aging effects. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, *676(A)*. 132199. https://doi.org/10.1016/j.colsurfa.2023.132199

Rajendra, I Gst. Ngr. Anom (2012). How a Belinese traditional home creates a comfortable internal environment without resorting to energy usage. *Jurnal Kajian Bali, 2*(1), 41-56.

Hayashi, T., & Ohsawa, Y. (2015). Knowledge structuring and reuse system using RDF for supporting scenario generation. *Procedia Computer Science*, *60*(1), 1281–1288. https://doi.org/10.1016/j.procs.2015.08.233

Isaac, K., & Bada, S. O. (2020). The co-combustion performance and reaction kinetics of refuse derived fuels with South African high ash coal. *Heliyon*, *6*(1), e03309. https://doi.org/10.1016/j.heliyon.2020.e03309

Jain, N. (2016). Waste management of temple floral offerings by vermicomposting and its effect on soil and plant growth. *International Journal of Environmental & Agriculture Research*, *2*(7), 89-94.

Jamradloedluk, J., & Lertsatitthanakorn, C. (2015). Properties of densified-refuse derived fuel using glycerin as a binder. *Procedia Engineering*, *100*, 505–510. https://doi.org/10.1016/j.proeng.2015.01.397

Jiang, Y., Zhuo, L., Wu, X., Zhang, Z., Guo, X., & Fan, J. (2024). Study on the interaction between inherent minerals of coal with refuse derived fuel (RDF) during co-firing. *Carbon Resources Conversion*, *7*(3), 100208. https://doi.org/10.1016/j.crcon.2023.100208

Kaniowski, W., Taler, J., Wang, X., Kalemba-Rec, I., Gajek, M., Mlonka-Mędrala, A., Nowak-Woźny, D. & Magdziarz, A. (2022). Investigation of biomass, RDF and coal ash-related problems: Impact on metallic heat exchanger surfaces of boilers. *Fuel*, *326*, 125122. https://doi.org/10.1016/j.fuel.2022.125122

Khammee, P., Unpaprom, Y., Buochareon, S., & Ramaraj, R. (2019). Potential of Bioethanol Production from Marigold Temple Waste Flowers Potential of Bioethanol Production from Marigold Temple Waste Flowers. In *Proceeding of the 1st Thailand biorefinery conference, the future of biorefinery for Thailand*, 4, 25-26.

Kijo-Kleczkowska, A., Szumera, M., Gnatowski, A., & Sadkowski, D. (2022). Comparative thermal analysis of coal fuels, biomass, fly ash and polyamide. *Energy*, *258*, 124840. https://doi.org/10.1016/j.energy.2022.124840

Li, Y., Yao, N., Liang, J., Wang, X., Niu, B., Jia, Y., Jiang, F., Yu, Q., Liu, D.L., Feng, H., He, H., Yang, G., & Pulatov, A. (2023). Rational biochar application rate for cotton nutrient content, growth, yields, productivity, and economic benefits under film-mulched trickle irrigation. *Agricultural Water Management*, *276*(1), 108079. https://doi.org/10.1016/j.agwat.2022.108079

Liedmann, B., Wirtz, S., Scherer, V., & Krüger, B. (2017). Numerical Study on the Influence of Operational Settings on Refuse Derived Fuel Co-firing in Cement Rotary Kilns. *Energy Procedia*, *120*, 254–261. https://doi.org/10.1016/j.egypro.2017.07.176

Maj, I., Kalisz, S., Wejkowski, R., Pronobis, M., & Gołombek, K. (2022). High-temperature corrosion in a multifuel circulating fluidized bed (CFB) boiler co-firing refuse derived fuel (RDF) and hard coal. *Fuel*, *324*(Part C), 124749. https://doi.org/10.1016/j.fuel.2022.124749

Makwana, J., Dhass, A. D., Ramana, P. V., Sapariya, D., & Patel, D. (2023). An analysis of waste/biomass gasification producing hydrogen-rich syngas: A review. *International Journal of Thermofluids*, *20*. 100492. https://doi.org/10.1016/j.ijft.2023.100492

Martana, S. P. (2019). Pura as a Fortress in Balinese Religious Traditional Architecture Building. *IOP Conference Series: Materials Science and Engineering*, *662*(4). Institute of Physics Publishing. https://doi.org/10.1088/1757-899X/662/4/042011

Materazzi, M., Lettieri, P., Taylor, R., & Chapman, C. (2016). Performance analysis of RDF gasification in two stages fluidized bed-plasma process. *Waste Management*, *47*, 256–266. https://doi.org/10.1016/j.wasman.2015.06.016

Mlonka-Mędrala, A., Dziok, T., Magdziarz, A., & Nowak, W. (2021). Composition and properties of fly ash collected from a multifuel fluidized bed boiler co-firing refuse derived fuel (RDF) and hard coal. *Energy*, *234*, 121229. https://doi.org/10.1016/j.energy.2021.121229

Munshi, T. A., Jahan, L. N., Howladar, M. F., & Hashan, M. (2024). Prediction of gross calorific value from coal analysis using decision tree-based bagging and boosting techniques. *Heliyon*, *10*(1), e23395. https://doi.org/10.1016/j.heliyon.2023.e23395

Nasiri, S., Hajinezhad, A., Kianmehr, M. H., & Tajik, S. (2023). Enhancing municipal solid waste efficiency through Refuse Derived Fuel pellets: Additive analysis, die retention time, and temperature impact. *Energy Reports*, *10*, 941–957. https://doi.org/10.1016/j.egyr.2023.07.039

Nobre, C., Vilarinho, C., Alves, O., Mendes, B., & Gonçalves, M. (2019). Upgrading of refuse derived fuel through torrefaction and carbonization: Evaluation of RDF char fuel properties. *Energy*, *181*, 66–76. https://doi.org/10.1016/j.energy.2019.05.105

Nowak, M. (2023). Features of Refuse Derived Fuel in Poland – Physicochemical Properties and Availability of Refuse Derived Fuel. *Journal of Ecological Engineering*, *24*(3), 1–9. https://doi.org/10.12911/22998993/157159

ÖzyuğUran, A., & Yaman, S. (2017). Prediction of Calorific Value of Biomass from Proximate Analysis. *Energy Procedia*, *107*, 130–136. https://doi.org/10.1016/j.egypro.2016.12.149

Paolo, M., & Paola, M. (2015). RDF: From waste to resource - The Italian case. *Energy Procedia*, *81*, 569–584. https://doi.org/10.1016/j.egypro.2015.12.136

Papastefanatos, G., Meimaris, M., & Vassiliadis, P. (2022). Relational schema optimization for RDF-based knowledge graphs. *Information Systems*, *104*, 101754. https://doi.org/10.1016/j.is.2021.101754

Pardo, R., Taboada-Ruiz, L., Fuente, E., Ruiz, B., Díaz-Somoano, M., Calvo, L. F., & Paniagua, S. (2023). Exploring the potential of conventional and flash pyrolysis methods for the valorisation of grape seed and chestnut shell biomass from agri-food industry waste. *Biomass and Bioenergy*, *177*, 106942. https://doi.org/10.1016/j.biombioe.2023.106942

Porshnov, D., Ozols, V., Ansone-Bertina, L., Burlakovs, J., & Klavins, M. (2018). Thermal decomposition study of major refuse derived fuel components. *Energy Procedia*, *147*, 48–53. https://doi.org/10.1016/j.egypro.2018.07.032

Rajca, P., Poskart, A., Chrubasik, M., Sajdak, M., Zajemska, M., Skibiński, A., & Korombel, A. (2020). Technological and economic aspect of Refuse Derived Fuel pyrolysis. *Renewable Energy*, *161*, 482–494. https://doi.org/10.1016/j.renene.2020.07.104

Rania, M. F., Lesmana, I. G. E., & Maulana, E. (2019). Analisis Potensi Refuse Derived Fuel (RDF) dari Sampah pada Tempat Pembuangan Akhir (TPA) di Kabupaten. *Sintek Jurnal : Jurnal Ilmiah Teknik Mesin*, *13*(1), 51–59. https://doi.org/10.24853/sintek.13.1.51-59

Rezaei, H., Panah, F. Y., Lim, C. J., & Sokhansanj, S. (2020). Pelletization of refuse-derived fuel with varying compositions of plastic, paper, organic and wood. *Sustainability (Switzerland)*, *12*(11), 4645. https://doi.org/10.3390/su12114645

Samadhiya, H., Gupta, R., & Agrawal, O. (2017). Disposal and management of temple waste: Current status and possibility of vermicomposting. *International Journal of Advanced Research and Development, 2,* 359-366.

Sarc, R., & Lorber, K. E. (2013). Production, quality and quality assurance of Refuse Derived Fuels (RDFs). *Waste Management*, *33*(9), 1825–1834. https://doi.org/10.1016/j.wasman.2013.05.004

Schritt, H., & Pleissner, D. (2022). Recycling of organic residues to produce insulation composites: A review. *Cleaner Waste Systems*, *3*, 100023. https://doi.org/10.1016/j.clwas.2022.100023

Schwarzböck, T., Aschenbrenner, P., Spacek, S., Szidat, S., Rechberger, H., & Fellner, J. (2018). An alternative method to determine the share of fossil carbon in solid refuse-derived fuels – Validation and

comparison with three standardized methods. *Fuel*, *220*(15), 916–930. https://doi.org/10.1016/j.fuel.2017.12.076
Shehata, N., Obaideen, K., Sayed, Enas T., Abdelkareem, Mohammad A., Mahmoud, Mohamed S., El-Salamony, AbdeL-Hay R., Mahmoud, Hamada M., Olabi, A.G. (2022). Role of refuse-derived fuel in circular economy and sustainable development goals. *Process Safety and Environmental Protection*, 163, 558–573. https://doi.org/10.1016/j.psep.2022.05.052
Shumal, M., Taghipour Jahromi, A. R., Ferdowsi, A., Mehdi Noorbakhsh Dehkordi, S. M., Moloudian, A., & Dehnavi, A. (2020). Comprehensive analysis of municipal solid waste rejected fractions as a source of Refused Derived Fuel in developing countries (case study of Isfahan- Iran): Environmental Impact and sustainable development. *Renewable Energy*, *146*, 404–413. https://doi.org/10.1016/j.renene.2019.06.173
Siddiqi, M. H., Liu, X. min, Hussain, M. A., Qureshi, T., Waqas, M., Farooq, M., Iqbal, T., Nawas, S., & Nawaz, S. (2021). Evolution of kinetic and hydrothermal study of refused derived fuels: Thermo-gravimetric analysis. *Energy Reports*, *7*, 1757–1764. https://doi.org/10.1016/j.egyr.2021.03.010
Sieradzka, M., Rajca, P., Zajemska, M., Mlonka-Mędrala, A., & Magdziarz, A. (2020). Prediction of gaseous products from refuse derived fuel pyrolysis using chemical modelling software - Ansys Chemkin-Pro. *Journal of Cleaner Production*, *248*, 119277. https://doi.org/10.1016/j.jclepro.2019.119277
Sikarwar, V. S., Masláni, A., Hlína, M., Fathi, J., Mates, T., Pohorelý, M., Meers, E., Šyc, M., Jeremiás, M. (2022). Thermal plasma assisted pyrolysis and gasification of RDF by utilizing sequestered CO2as gasifying agent. *Journal of CO2 Utilization*, *66*, 102275. https://doi.org/10.1016/j.jcou.2022.102275
Singh, A., Jain, A., Sarma, B. K., Abhilash, P. C., & Singh, H. B. (2013). Solid waste management of temple floral offerings by vermicomposting using Eisenia fetida. *Waste management*, *33*(5), 1113-1118. https://doi.org/10.1016/j.wasman.2013.01.022
Singh, P., Borthakur, A., Singh, R., Awasthi, S., Pal, D. B., Srivastava, P., Tiwary, D. & Mishra, P. K. (2017). Utilization of temple floral waste for extraction of valuable products: A close loop approach towards environmental sustainability and waste management. *Pollution*, *3*(1), 39-45. https://doi.org/10.22059/poll.2017.59570
Smoliński, A., Wojtacha-Rychter, K., Król, M., Magdziarczyk, M., Polański, J., & Howaniec, N. (2022). Co-gasification of refuse-derived fuels and bituminous coal with oxygen/steam blend to hydrogen rich gas. *Energy*, *254*(Part A), 124210. https://doi.org/10.1016/j.energy.2022.124210
Suantara, P., Sumantra, K., Sudiana, A. A. K., & Wijaya, I. (2020). Physicochemical Properties Of Water Characterization In Petitenget Temple Estuary, Badung Regency. *International Journal of Applied Science and Sustainable Development*, *2*(2), 38–41.
Suryawan, I. W. K., Septiariva, I. Y., Widanarko, D. U. F., Qonitan, F. D., Sarwono, A., Sari, M. M., Prayogo, W., Arifianingsih, N.N., Suhardono, S., Lim, J.-W. (2024). Enhancing Energy Recovery from Wastewater Treatment Plant Sludge through Carbonization. *Energy Nexus*, *14*(21), 100290. https://doi.org/10.1016/j.nexus.2024.100290
Tihin, G. L., Mo, K. H., Onn, C. C., Ong, H. C., Taufiq-Yap, Y. H., & Lee, H. V. (2023). Overview of municipal solid wastes-derived refuse-derived fuels for cement co-processing. *Alexandria Engineering Journal*, *84*, 153–174. https://doi.org/10.1016/j.aej.2023.10.043
Widyatmoko, H., Sintorini, M. M., Suswantoro, E., Sinaga, E., & Aliyah, N. (2021). Potential of refused derived fuel in Jakarta. *IOP Conference Series: Earth and Environmental Science*, *737*(1), 012005. Institute of Physics. https://doi.org/10.1088/1755-1315/737/1/012005
Wijaya, I. M. W., & Putra, I. K. A. (2021). Potensi daur ulang sampah upacara adat di Pulau Bali. *Jurnal Ecocentrism*, *1*(1), 1–8. https://doi.org/10.36733/jeco.v1i1.1763
Wijaya, I. M. W., Ranwella, K. B. I. S., Revollo, E. M., Widhiasih, L. K. S., Putra, P. E. D., and Junanta, P. P. (2021). Recycling Temple Waste into Organic Incense as Temple Environment Preservation in Bali Island. *Jurnal Ilmu Lingkungan* , *19*(2), 365–371. https://doi.org/10.14710/jil.19.2.365
Wijaya, I. M. W., Wiratama, I. G. N. M., & Putra, I. K. A. (2023). *Patent No. IDS000006518*. Indonesia.
Wijaya, I. M. W., Wiratama, I. G. N. M., Putra, I. K. A., & Atmaja, N. P. C. D. (2023). Unlocking the Energy Potential of Temple Waste and Coconut Fiber through Refuse-Derived Fuel Production toward Sustainable Energy. *Ecological Engineering and Environmental Technology*, *24*(7), 19–29. https://doi.org/10.12912/27197050/169362
Wijaya, M. W., Wiratama, G. N. M., Putra, K. A., & Aris, A. (2023). Refuse Derived Fuel Potential Production from Temple Waste as Energy Alternative Resource in Bali Island. *Journal of Ecological Engineering*, *24*(4), 288–296. https://doi.org/10.12911/22998993/161015

Wiyono, A., Saw, L. H., Anggrainy, R., Husen, A. S., Purnawan, Rohendi, D., Gandidi, Indra M., Adanta, D., & Pambudi, N. A. (2021). Enhancement of syngas production via co-gasification and renewable densified fuels (RDF) in an open-top downdraft gasifier: Case study of Indonesian waste. *Case Studies in Thermal Engineering*, *27,* 101205. https://doi.org/10.1016/j.csite.2021.101205

Yadav, I., Juneja, S. K., & Chauhan, S. (2015). Temple waste utilization and management: A review. *International Journal of Engineering Technology Science and Research*, *2*, 14-19.

Yadav, I., Singh, S., Juneja, S. K., & Chauhan, S. (2018). Quantification of the temple waste of Jaipur city. Recent Trends in Agriculture. *Food Science, Forestry, Horticulture, Aquaculture, Animal Sciences, Biodiversity, Ecological Sciences and Climate Change*, 1-3.

Zaini, I. N., Wen, Y., Mousa, E., Jönsson, P. G., & Yang, W. (2021). Primary fragmentation behavior of refuse derived fuel pellets during rapid pyrolysis. *Fuel Processing Technology*, *216*, 106796. https://doi.org/10.1016/j.fuproc.2021.106796

Zajemska, M., Magdziarz, A., Iwaszko, J., Skrzyniarz, M., & Poskart, A. (2022). Numerical and experimental analysis of pyrolysis process of RDF containing a high percentage of plastic waste. *Fuel*, *320*, 123981. https://doi.org/10.1016/j.fuel.2022.123981

Zhang, K., Zheng, Z., Feng, L., Su, J., & Li, H. (2023). A byproduct gas distribution model for production users considering calorific value fluctuation and supply patterns in steel plants. *Alexandria Engineering Journal*, *76*, 821–834. https://doi.org/10.1016/j.aej.2023.06.063

Zhou, X., Liu, W., Zhang, P., & Wu, W. (2016). Study on Heavy Metals Conversion Characteristics During Refused Derived Fuel Gasification Process. *Procedia Environmental Sciences*, *31*, 514–519. https://doi.org/10.1016/j.proenv.2016.02.070