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Proof-of-Concept Conversion of Nitrile Rubber Gloves into Durable Biochar Briquettes Using Sawdust Binder for Sustainable Energy Recovery

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ABSTRACT

The increasing generation of disposable nitrile rubber gloves has raised environmental concerns due to their non-biodegradable nature and limited recycling options. This study presents a proof-of-concept approach for converting clean and unused nitrile butadiene rubber (NBR) gloves, used as a model material for glove waste, into biochar briquettes through pyrolysis and sawdust-assisted densification. Pyrolysis was conducted at 300, 350, 400, and 450 °C under an inert atmosphere. The material treated at 300 °C retained rubber-like elasticity and was therefore not considered viable biochar, whereas pyrolysis at 350, 400, and 450 °C produced solid carbonaceous residues with biochar yields of 68.4%, 48.5%, and 13.5%, respectively. Biochar produced at 350 °C was selected for briquette preparation because it provided the best balance between solid recovery and physical conversion into a brittle carbonaceous material. Sawdust was incorporated as a natural lignocellulosic binder at 0, 10, 20, and 30 wt.%, and the mixtures were densified at 200 °C and 3 MPa. The 20 wt.% sawdust formulation showed the best overall performance, with a hardness of 93.6, pellet durability index of 99.6%, water absorptivity of approximately 22%, and heating value of 17.40 MJ/kg. Although sawdust enhanced briquette binding, excessive sawdust addition increased water uptake because of its hydrophilic structure, which may affect storage stability and combustion performance. These findings demonstrate the potential of sawdust-bound NBR-derived biochar briquettes as sustainable solid fuel materials; however, further validation using actual contaminated medical glove waste is required.

Keywords: Nitrile rubber gloves; biochar briquettes; pyrolysis; sawdust binder

INTRODUCTION

Global waste production continues to rise at an alarming rate. According to a World Bank Group report, annual global waste generation is projected to increase by 70%, from 2.01 billion tonnes in 2016 to 3.40 billion tonnes by 2050 (Kaza et al. 2018). If left unmanaged, particularly through landfill disposal without energy recovery, this mounting waste stream could contribute significantly to environmental degradation and carbon dioxide emissions (Manfredi and Christensen 2009). The outbreak of COVID-19, initially detected in Wuhan, China, at the end of 2019 and officially recognised as a global pandemic by the World Health Organization in March 2020, intensified challenges related to waste management. To combat the rapid transmission of the virus, governments and healthcare organisations across the world adopted extensive measures, which included a substantial increase in the utilisation of personal protective equipment (PPE) (Singh et al. 2020). These measures, while essential for public health, triggered a dramatic increase in medical and plastic waste, particularly from healthcare facilities (Sharma et al. 2020). Even before the pandemic, the accumulation of plastic waste had reached critical levels due to the mass production and short lifespan of plastic-based products (Miandad et al. 2019). The pandemic intensified this issue, with surging

demand for disposable PPE contributing to elevated levels of plastic pollution globally (De-la-Torre and Aragaw, 2021). Nitrile butadiene rubber (NBR), a common alternative to latex gloves due to allergy concerns, emerged as one of the most abundant PPE waste items. The management of medical waste has become a growing economic and environmental concern worldwide in recent years. Medical waste often contains various infectious and hazardous substances that pose risks to both human health and the environment if inadequately treated. In China, mixing medical waste with other waste types, such as non-hazardous household refuse, is strictly prohibited. Consequently, ensuring effective treatment of medical waste is a significant challenge for environmental safety and public health, especially in developing countries. Additionally, rubber products, which are composed of synthetic polymers, are non-biodegradable and degrade much more slowly in landfills than biomass materials. Although disposable gloves are commonly associated with medical and healthcare waste, actual used medical gloves may contain biological and chemical contaminants that require strict handling, transport, sterilisation, and disposal control (Ramalingam et al. 2023). Such contaminants may also influence pyrolysis behaviour, gaseous emissions, and the final composition of the solid residue. Therefore, direct extrapolation from clean glove material to infectious medical glove waste should be made with caution. In this study, clean and unused NBR gloves were employed as a model material to establish the feasibility of converting glove-based polymer waste into biochar briquettes. Thus, the work is positioned as a proof-of-concept study rather than a direct treatment assessment of contaminated medical waste.

Conventional disposal methods for medical waste include incineration, autoclaving, gas sterilisation, and chemical disinfection. However, each technique has inherent drawbacks; for instance, incineration can release harmful emissions, including dioxins and other pollutants, into the atmosphere. Pyrolysis presents an alternative that converts solid wastes such as medical and electronic wastes into valuable products like oil and carbon black, which can be reused. This process offers advantages such as significantly lower emissions of nitrogen oxides, sulphur dioxide, and heavy metals, owing to its low-oxygen environment, moderate temperature, and minimal airflow, making emission control easier (Mavukwana et al. 2021). Pyrolysis also serves as the initial stage for gasification and combustion processes. Rubber-based materials, including gloves and tubing, represent a small but relevant fraction of medical waste and are attractive for thermochemical valorisation because of their high volatile content and fuel potential. Previous studies have shown that waste nitrile gloves and other rubber-containing medical wastes can be converted through pyrolysis into liquid fuels and solid residues. Mishra and Mohanty (2020) reported that waste nitrile gloves had a higher heating value of 37.12 MJ/kg, while Ramalingam et al. (2023) reported that pyrolytic oil derived from glove waste exhibited a calorific value of 40.11 MJ/kg. These values are comparable to conventional liquid fuels and can exceed the heating values of several coal types, which generally range from about 14 to 33 MJ/kg depending on coal rank. Therefore, rising energy demand and the need for safer disposal of rubber-based medical waste have stimulated interest in pyrolysis as a waste-to-energy pathway for rubber gloves and related medical polymer wastes.

Nitrile butadiene rubber (NBR) gloves are mainly composed of acrylonitrile and butadiene units, which provide chemical resistance, elasticity, and durability. From a waste valorisation perspective, the carbon-rich polymeric structure of NBR makes it a promising precursor for producing carbonaceous solid products through thermal conversion (Pathiraja et al. 2025). During pyrolysis, NBR undergoes thermal bond cleavage, depolymerisation, devolatilisation, and secondary reactions involving crosslinking and aromatisation. Part of the material is released as volatile products, while the remaining carbon-rich fraction contributes to char formation. Previous studies on waste nitrile gloves and recycled NBR have shown that these materials decompose mainly at elevated temperatures and leave measurable char or solid residues, confirming their potential for thermochemical conversion.

The formation of char from NBR is strongly influenced by its chemical composition and formulation. The butadiene-rich segments can generate unsaturated and cyclic degradation products during pyrolysis, while acrylonitrile-containing segments contribute nitrogen-containing products and affect the thermal stability of the rubber matrix (Zainal et al. 2018). Crosslinking and secondary condensation reactions may stabilise part of the degraded polymer structure, forming a more carbon-rich residue (Zainal et al. 2018). In addition, the relatively low oxygen content reported for waste nitrile gloves reduces the tendency for carbon to be released as oxygenated gases compared with oxygen-rich biomass. However, the extent of conversion depends on pyrolysis temperature, residence time, heating conditions, and the presence of additives or fillers in the glove formulation. Therefore, temperature optimisation is required to balance solid residue recovery with sufficient transformation of the rubbery material into brittle biochar. Carbon-rich biochar is highly valued for its potential performance in a wide range of applications, including biofuel production as an alternative to non-renewable coal, carbon dioxide adsorption, catalysis, and electrochemical energy storage. Given the limitations of existing waste management practices, especially the

challenges of recycling or safely disposing of contaminated personal protective equipment (PPE) (Baird et al. 2025), converting nitrile rubber gloves into energy via thermal treatment has emerged as a promising solution. A waste-to-energy (WTE) approach is particularly advantageous for non-reusable and non-recyclable waste streams, offering multiple benefits, including significant volume reduction, destruction of hazardous contaminants, recovery of valuable energy, and reduction of harmful emissions (Cucchiella et al. 2014). Among thermal treatment methods, pyrolysis stands out as a dependable and environmentally responsible strategy for handling PPE waste (Qin et al. 2018). This process involves thermal decomposition in an oxygen-limited environment, typically at temperatures between 400 °C and 500 °C (Aragaw and Mekonnen 2021), and has been shown to effectively convert nitrile glove waste into value-added products such as bio-oil, syngas, and biochar.

Notably, pyrolysis can achieve up to 95% reduction in inert residue and approximately 90% mass reduction, while maintaining low emission levels (Selvaranjan et al. 2021). The bio-oil produced during the process closely mirrors conventional fossil fuels in both composition and energy content. Meanwhile, biochar, the solid carbonaceous residue formed, exhibits high carbon sequestration potential and an impressive heating value in the range of 28.5 to 29 MJ/kg, positioning it as a viable alternative fuel (Kabakcı and Hacıbektaşoğlu 2017). Structurally, although NBR gloves are elastic and durable, they undergo significant thermal rearrangement during pyrolysis, transforming into a more stable, brittle carbon matrix when processed under appropriate conditions.

In addition to its function as a solid fuel, biochar is increasingly recognised for its potential as a precursor for the production of activated carbon, which is widely used in industrial, environmental, and purification technologies (Dharmaraj et al. 2021). The physical transformation of NBR gloves into biochar also offers a practical solution to the pressing issue of medical and plastic waste accumulation. The integration of pyrolysis into the management of NBR glove waste presents a dual benefit: it addresses a growing environmental concern while yielding high-value carbon materials (S. M. Al-Salem, 2019). The carbon and nitrogen-rich nature of NBR, combined with the efficiency and sustainability of pyrolysis, makes this pathway highly suitable for scalable and impactful waste valorisation strategies (Bernardo 2011).

Biochar produced through pyrolysis is often fragile, which presents challenges during handling and transportation. To address this issue, densification into pellets or briquettes is employed; this process compacts biomass into a denser form to enhance its mechanical strength. Although pellets and briquettes are similar, they differ in shape, size, and density. The primary objective of densification is to restore and improve the durability of biochar, which is typically compromised during pyrolysis. This improvement is achieved by incorporating binding agents that facilitate the formation of stable, high-quality briquettes. Binding agents play a vital role in preventing caking and maintaining the mechanical integrity of the densified product (Beckhoff et al. 2007). Consequently, pelletized or briquetted biochar is preferred for more efficient handling, storage, and transportation (Selvarajoo et al. 2021).

While pyrolysed biochar briquettes generally possess superior fuel qualities compared to untreated biochar, the densification process is complex and requires optimisation to enhance durability without compromising fuel performance. Binding agents containing lignin are particularly valuable due to lignin's natural adhesive properties. During densification, softened or melted lignin solidifies to form interparticle bridges that strengthen structural cohesion (Peng et al. 2015). For example, Selvarajoo et al. (2021) demonstrated that commercial starch, an organic binder, produces robust and rigid biochar briquettes that are easier to handle, store, and transport compared to those without binders. Saini et al. (2011) investigated natural clay as a binder, which not only improved mechanical strength but also modifies gas separation properties in adsorbents. Several studies have shown that binder selection strongly affects the mechanical durability, handling stability, and combustion behaviour of biomass and biochar briquettes. Commonly used binders include starch, molasses, clay, lignin, paper waste, and other biomass-derived materials (Alhimali et al. 2019; Obi et al. 2022). Although starch is widely used because of its effective adhesive properties, its food-based origin may limit its sustainability and scalability for large-scale briquette production. Therefore, alternative non-food binders that are lignin-rich, low-cost, locally available, and abundant are increasingly preferred to improve briquette cohesion while maintaining sustainable production.

Sawdust is proposed as a binder for pyrolysed biochar due to its abundance as a byproduct of wood processing and its favourable chemical composition, particularly its natural content of lignin, cellulose, and hemicellulose (Madhusanka et al. 2025). Typically, sawdust comprises around 30–34% lignin, 38–48% cellulose, and 16–33% hemicellulose, depending on the wood source. Lignin is especially critical in enhancing binding properties because it softens under heat and pressure, acting as a natural adhesive that stiffens cellulose microfibrils and improves particle cohesion during biochar briquette densification (Boadu et al. 2023; Lumadue et al. 2012). Cellulose provides the fibrous structural support essential for mechanical integrity, while hemicellulose, although less

crystalline and more easily degradable, contributes to overall matrix stability and porosity management (Inkrod et al. 2017). Furthermore, lignin's aromatic and crosslinked structure contribute to the formation of a thermally stable carbon matrix in biochar and improves physical integrity.

Accordingly, sawdust will be incorporated as a binder with biochar derived from the pyrolysis of nitrile butadiene rubber gloves to utilise the natural synergistic effects of its lignocellulosic components. The resulting densified biochar briquettes will be evaluated through physical property tests including hardness, durability, and water resistance to determine the mechanical benefits conferred by sawdust's composition. Chemical functional groups related to lignin, cellulose, and hemicellulose will be characterised using Fourier transform infrared spectroscopy (FTIR), providing insights into the nature and extent of chemical bonding within the briquettes. Thermogravimetric analysis (TGA) will assess thermal degradation behaviour, reflecting differences in stability and decomposition patterns influenced by varying sawdust content. Proximate analysis including moisture content, volatile matter, fixed carbon, and ash content will be conducted at different sawdust binding ratios alongside measurements of higher heating value (HHV) to evaluate the effects on biochar composition and energy content.

This study aims to develop a proof-of-concept process for converting clean and unused nitrile butadiene rubber (NBR) gloves, used as a model material for glove waste, into energy-rich biochar briquettes through pyrolysis and sawdust-assisted densification. Sawdust was selected as a low-cost, lignocellulosic, and non-food-based binder due to its abundance and natural adhesive properties. Its lignin, cellulose, and hemicellulose components can enhance particle cohesion during densification, thereby improving the mechanical integrity of the briquettes.

The effects of pyrolysis temperature and sawdust binder ratio on biochar yield, briquette hardness, briquette durability, water absorptivity, thermal behaviour, proximate composition, heating value, chemical functionality, and morphology were investigated. By combining pyrolysis and densification, this study supports circular economy development by converting model NBR glove waste into a value-added solid fuel material. The growing commercial interest in biochar further highlights the potential relevance of this research area, as the global biochar market was estimated at USD 1.48 billion in 2018 and was projected to reach USD 3.82 billion by 2025 (Research, 2019).

Overall, this study provides preliminary evidence for the valorisation of NBR glove-derived char into solid fuel briquettes. However, further work using actual contaminated medical glove waste is required to evaluate biosafety, contaminant transformation, emission profiles, and practical waste-treatment feasibility.

METHODOLOGY

MATERIAL PREPARATION

The nitrile butadiene rubber (NBR) gloves used in this study were new and unused products purchased directly from Ace Glove (M) Sdn. Bhd., a certified glove manufacturing company. The gloves were obtained on an as-received basis and had not been used in medical, laboratory, or industrial applications. This approach was adopted to comply with biosafety and environmental regulations, as the collection, handling, transportation, and treatment of used medical gloves are strictly controlled under the Environmental Quality (Scheduled Wastes) Regulations 2005 (Malaysia) and require specific approval. Therefore, clean and unused NBR gloves were used as a model feedstock to represent glove-based polymer waste in this proof-of-concept study. The use of clean model material enabled the thermal conversion and densification behaviour of NBR gloves to be examined safely without introducing biological or chemical contamination variables.

The binding agent, sawdust, was collected from a wood supplier, Impressive Transforms Sdn. Bhd. The sawdust was ground and sieved to obtain a particle size below 200 µm (Figure 1).

(a)

(b)

FIGURE 1. (a) Sawdust as binding agent, (b) Nitrile butadiene rubber gloves

DENSIFICATION PROCESS

A 50 g sample of nitrile gloves was placed on a stainless-steel tray and introduced into a muffle furnace for pyrolysis. The furnace was preheated to the target temperature of 450 °C. Once the set temperature was reached, the furnace was purged with high-purity nitrogen gas at a flow rate of 0.1 L/min for 15 min to create an inert atmosphere. The chopped gloves were then loaded into the furnace and subjected to a holding time of 30 min at the desired temperature. This procedure was repeated at additional temperatures of 300 °C, 350 °C, and 400 °C. The biochar produced at each temperature was collected and analysed, and the biochar yield was calculated according to Equation 1. For briquette preparation, 8 g of biochar was mixed with sawdust as a binding agent at varying ratios of 0 wt.%, 10 wt.%, 20 wt.%, and 30 wt.%. The mixtures were thoroughly blended and placed into a stainless-steel mould lined with protective film. Densification was performed using a Carver hot-press machine (Figure 2) under controlled conditions of 200 °C, 3 MPa pressure, and 8 min of heating. These parameters were selected based on Tharazi et al. (2017), who reported this combination of hot-pressing conditions as optimal for achieving maximum tensile strength of the densified material. The resulting briquettes measured approximately 50 mm in diameter and 5 mm in thickness.

$$\textbf{Biochar Yield (\%)} = \frac{\textit{Weight of biochar}}{\textit{Weight of raw material}} \textbf{ x 100\%} \quad (1)$$

(a) (b)

FIGURE 2. (a) Hot press machine used for densification process and (b) Mixture of biochar and sawdust filled in a mold before densification

CHARACTERISATION OF RAW MATERIAL AND BIOCHAR BRIQUETTES

Fourier transform infrared (FTIR) spectroscopy was conducted using a Nicolet™ iS™ 10 FTIR spectrometer over a scanning range of 400 to 4000 cm^{-1}, enabling comprehensive characterisation of the chemical functional groups and structural changes induced by pyrolysis and densification. In the context of biochar derived from pyrolysed nitrile rubber gloves and densified with sawdust, FTIR analysis provided molecular-level insight into the chemical transformations that occur during pyrolysis, revealing changes in the organic structure of the raw nitrile rubber as it decomposes into biochar. This includes identifying the breakdown of polymeric chains and the formation or loss of specific functional groups such as hydroxyls, carbonyls, aromatic rings, and nitrogen-containing groups, which influence the biochar's chemical reactivity and stability.

Proximate analysis of the biochar briquettes, prepared with varying sawdust binding ratios, was performed using a Mettler Toledo thermogravimetric analyser (TGA) following ASTM E870-82. Approximately 15–25 mg of each sample was subjected to a controlled thermal program beginning with heating from 40 °C to 110 °C at a heating rate of 20 °C per minute under a nitrogen atmosphere at a flow rate of 100 mL/min. This stage allowed for the quantification of moisture content through mass loss. Subsequently, the temperature was increased from 110 °C to 900 °C at 10 °C per minute, still under nitrogen, to measure volatile matter released from the sample. Upon reaching 900 °C, the purge gas was switched to oxygen while maintaining the same heating rate to facilitate the combustion of fixed carbon and determine ash content.

Fixed carbon was calculated on a dry basis as the remaining mass percentage after subtracting volatile matter and ash. This detailed proximate analysis provided critical insights into the fuel composition and combustion characteristics of the biochar briquettes, which are essential for evaluating their suitability as alternative energy sources.

The mechanical properties of the biochar briquettes were assessed through hardness, water absorptivity, and durability tests. Hardness was measured using a Shore durometer, which determines the resistance of the briquette surface to indentation under a standard spring load (Hanifeh et al. 2017). The hardness scale ranges from 0 to 100, with higher values indicating greater surface strength and resistance to mechanical damage.

Water absorptivity was determined using a procedure adapted from ASTM D570. Before testing, the briquette samples were dried at 105 °C for 24 h until constant mass was achieved. The initial dry mass of each sample was then recorded before immersion. The samples were immersed in tap water at room temperature for five minutes. After immersion, excess surface water was gently removed using absorbent paper, and the final mass was immediately recorded. Water absorptivity was calculated based on the percentage increase in mass relative to the initial dry mass. All tests were conducted in triplicate for each briquette formulation, and the results were reported as mean ± standard deviation. A similar methodology has also been reported by Abdullah et al. (2017) and Davies and Davies (2013), allowing comparison with related studies.

Durability was evaluated using the Tumbling Can Method according to ISO 17831-1, which is commonly used to assess the resistance of densified solid fuels to breakage and fines generation during handling and transportation (Gilvari et al. 2020; Matúš et al. 2018; Miranda et al. 2018; Mohammadi Ghasem Abadi et al. 2019; Riva et al. 2019; Tang et al. 2018; Tumuluru, 2019). The pellet durability index (PDI) was calculated using the following equation:

$$\text{PDI (\%)} = [\text{mass after tumbling (g)} / \text{mass before tumbling (g)}] \times 100 \quad (2)$$

All hardness, water absorptivity, and durability tests were conducted in triplicate. The results were reported as mean ± standard deviation. Statistical analysis was performed using one-way analysis of variance (ANOVA) to determine significant differences among the briquette formulations. Differences were considered statistically significant at $p < 0.05$. Together, these analytical techniques provide a comprehensive assessment of the physical, chemical, and mechanical properties of biochar briquettes derived from pyrolysed nitrile rubber gloves and densified with sawdust binders. Such detailed characterisation is fundamental for optimising the production process and tailoring material properties to meet the requirements of sustainable fuel applications.

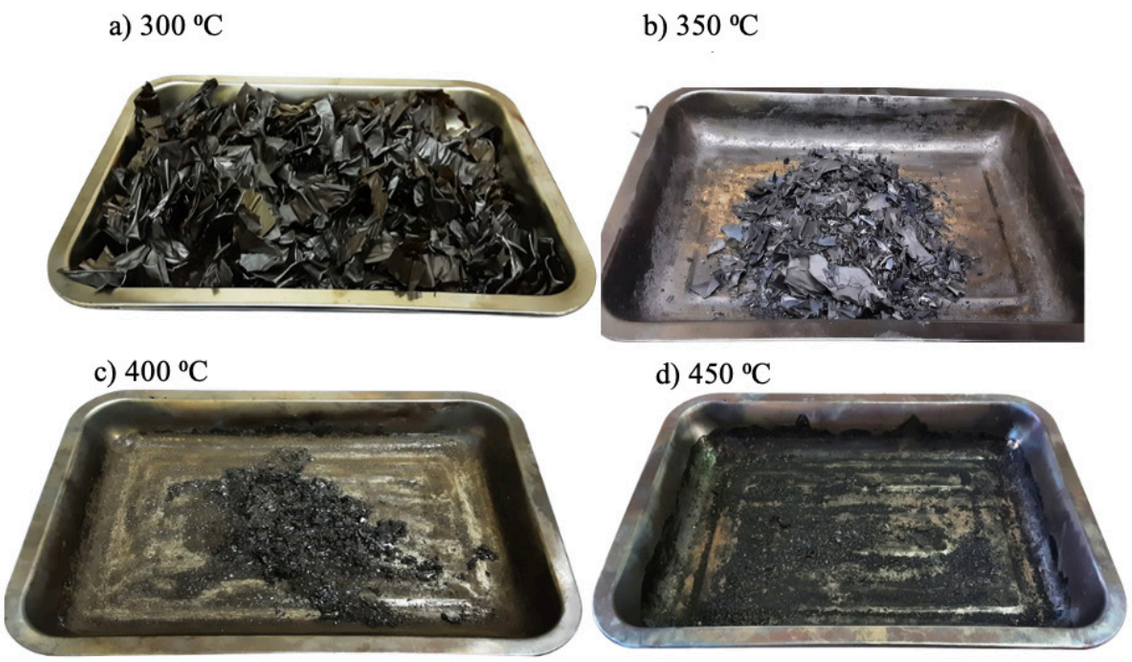

FIGURE 3. Pyrolysed NBR glove at different temperatures

RESULTS AND DISCUSSION

BIOCHAR PRODUCTION AND DENSIFICATION INTO BRIQUETTES

The pyrolysis behaviour of nitrile butadiene rubber (NBR) gloves at different temperatures of 300, 350, 400, and 450 °C is illustrated in Figure 3. At 300 °C, the pyrolysed NBR retained its rubber-like properties, including elasticity and stretchability, and did not exhibit the brittle, charcoal-like structure typically associated with biochar. Therefore, the material obtained at this temperature was not considered a viable biochar for briquette preparation.

In contrast, pyrolysis at 350 °C produced a solid carbonaceous residue with a mass of 34.2 g, corresponding to a biochar yield of 68.4%. Increasing the temperature to 400 °C reduced the biochar yield to 48.5%, with a recovered mass of 24.27 g. Further increasing the temperature to 450 °C caused a substantial reduction in solid yield, producing only 6.75 g of biochar, equivalent to 13.5%. These results indicate that higher pyrolysis temperatures promoted greater devolatilisation, resulting in lower solid recovery.

Although the TGA/DTG analysis showed that the major decomposition of NBR occurred at a higher temperature, with the maximum degradation rate occurring at around 458 °C, 350 °C was selected as the most suitable pyrolysis temperature for briquette preparation. This selection was based on a practical balance between sufficient physical transformation into a brittle carbonaceous material and high solid recovery. At 350 °C, the glove material was adequately converted into biochar while retaining the highest yield among the viable biochar samples.

Nevertheless, because 350 °C is below the main decomposition peak observed in the TGA/DTG profile, the resulting biochar may still contain residual volatile matter. These residual volatiles may assist ignition and promote energy release during combustion. However, excessive volatile matter may also influence smoke formation, combustion stability, and emission behaviour. Therefore, further combustion performance and emission analyses are recommended to evaluate the fuel suitability of the resulting briquettes.

The densification of biochar was conducted under the following conditions: 200 °C, 3 MPa pressure, and 8 min of heating. Figure 4 shows an image of the biochar briquette after densification.

FIGURE 4. Densification of NBR biochar with and without sawdust as binding agent

PHYSICAL PROPERTIES OF RAW MATERIAL AND BIOCHAR BRIQUETTES

Table 1 presents the hardness, durability, and water absorptivity of biochar briquettes prepared with different sawdust contents, while Table 2 shows the ANOVA results for these properties. Overall, the results indicate that sawdust content has a strong influence on the physical performance of the briquettes. The addition of sawdust generally improved the mechanical properties of the briquettes, particularly hardness and durability, compared with briquettes prepared without sawdust. However, increasing sawdust content also increased water absorptivity, indicating a trade-off between mechanical strength and moisture resistance.

The hardness results showed that briquettes without sawdust recorded the lowest hardness value of 75.7, confirming that biochar alone has poor binding ability. This is expected because biochar particles are usually brittle, porous, and friable, with limited natural adhesion between particles. When sawdust was added, the hardness increased substantially. The hardness improved to 85.6 at 10 wt.% sawdust and further increased to 93.6 at 20 wt.% sawdust. This indicates that sawdust acted effectively as a natural binder by improving particle packing and interparticle bonding during briquette formation.

However, the hardness slightly decreased to 92.2 when the sawdust content was increased to 30 wt.%. Although this value was still much higher than that of briquettes without sawdust, the reduction suggests that excessive sawdust does not necessarily lead to further improvement in mechanical strength. At a very high sawdust content, the briquette matrix may contain a larger proportion of fibrous biomass material, which can reduce compactness and create a less dense structure. Therefore, the 20 wt.% sawdust formulation appears to provide the most effective balance between biochar particles and binder content, resulting in the highest hardness.

The durability results showed a similar trend. Briquettes containing sawdust recorded very high durability values, ranging from 98.6 to 99.6%. The highest durability was obtained at 20 wt.% sawdust, while briquettes without sawdust recorded the lowest durability of 96.0%. This confirms that sawdust improves the resistance of briquettes to breakage and abrasion during handling. According to ISO 17225-2 (2021), solid biofuel pellets with mechanical durability values above 97.5% are generally considered to have good resistance to fines formation during handling and transportation. Based on this criterion, all sawdust-containing briquettes achieved excellent durability, whereas the briquette without sawdust was below this benchmark.

The slight reduction in durability at 30 wt.% sawdust may be attributed to excess sawdust forming a less compact outer layer on the briquette surface. During the durability test, this outer biomass-rich layer may be more easily detached, producing surface abrasion and material loss. This is supported by the visible colour change observed after the durability test, where removal of the brownish sawdust-rich layer exposed more of the black biochar underneath. Therefore, although sawdust is beneficial as a binder, excessive addition may reduce surface integrity and increase the tendency for abrasion.

The improvement in hardness and durability can be explained by the lignocellulosic structure of sawdust. Sawdust contains cellulose, hemicellulose, and lignin, which contribute to particle adhesion and mechanical reinforcement. Lignin is particularly important because it can behave as a natural thermoplastic binder under pressure and heat. During densification, lignin softens and helps bind adjacent particles together upon cooling. Meanwhile, cellulose and hemicellulose provide a fibrous network that supports the briquette structure. The combined effects of lignin softening, fibre entanglement, hydrogen bonding, and improved particle packing contribute to stronger and more durable briquettes.

The ANOVA results in Table 2 further confirmed that the effect of sawdust content on the physical properties of the briquettes was statistically significant. For hardness, the p-value was 1.619×10^{-16}, which was far below the significance level of 0.05. This indicates that the differences in hardness among the different sawdust ratios were not due to random variation but were strongly influenced by the mixing ratio. Similarly, the p-value for durability was 9.789×10^{-10}, showing that sawdust content also had a significant effect on briquette durability. The very low p-values provide strong statistical evidence that sawdust addition plays a critical role in improving the mechanical performance of biochar briquettes.

Figure 5 shows the water absorptivity of biochar briquettes prepared with different sawdust contents. In contrast to hardness and durability, water absorptivity increased continuously with increasing sawdust loading. The briquette without sawdust recorded the lowest water absorptivity of 3.2%, while water absorptivity increased to 15.3% at 10 wt.% sawdust, 22.3% at 20 wt.% sawdust, and 34.4% at 30 wt.% sawdust. This indicates that although sawdust improves mechanical performance, it also reduces the water resistance of the briquettes.

The ANOVA result for water absorptivity also showed a highly significant difference among the different formulations, with a p-value of 3.380×10^{-25}. This was the lowest p-value among the three tested properties, suggesting that sawdust content had the strongest statistical effect on water absorptivity. This finding is reasonable

because sawdust is more hydrophilic than biochar. Sawdust contains cellulose and hemicellulose, which contain abundant hydroxyl groups that can form hydrogen bonds with water molecules. As the sawdust content increases, the number of hydrophilic sites in the briquette matrix also increases, leading to greater moisture uptake.

In addition, the porous and fibrous structure of sawdust may create more pathways for water penetration. Water can enter the briquette through capillary action and be retained within the internal pores (Ferede, 2020). In contrast, briquettes without sawdust are likely to have fewer hydrophilic functional groups and a more carbon-rich structure, resulting in much lower water absorption. Therefore, the increasing trend in water absorptivity with sawdust addition can be attributed to the combined effects of hydrophilic functional groups and the porous lignocellulosic structure of sawdust.

From a practical perspective, the high-water absorptivity observed at 30 wt.% sawdust (34.4%), has important practical implications for the storage, handling, and fuel performance of the briquettes. Briquettes with high moisture uptake may be more vulnerable under humid storage conditions. Absorbed water can cause swelling, weaken inter-particle bonding, promote cracking or crumbling, and increase fines generation during handling and transportation. These effects may reduce the physical stability and shelf life of the briquettes.

From a combustion perspective, high water absorption is also undesirable because absorbed moisture can reduce the effective heating value of the fuel. Part of the energy released during combustion would be consumed to evaporate water before stable burning occurs. This may delay ignition, lower combustion temperature, reduce flame stability, and decrease overall fuel efficiency. Therefore, although the 30 wt.% sawdust briquette exhibited good hardness and durability, its high-water absorptivity makes it less favourable for practical fuel applications unless proper moisture protection is provided, such as dry storage, moisture-barrier packaging, or hydrophobic surface treatment.

In summary, the incorporation of sawdust is beneficial for improving the hardness and durability of biochar briquettes, but excessive sawdust addition increases water absorptivity and may compromise long-term storage stability, especially under humid conditions. Among the tested formulations, the 20 wt.% sawdust briquettes can be considered the most balanced composition. It achieved the highest hardness of 93.6 and the highest durability of 99.6%, while maintaining a moderate water absorptivity of 22.3%. In comparison, the 30 wt.% sawdust briquette showed similarly high mechanical performance but substantially higher water absorptivity. Thus, the 20 wt.% sawdust formulation was identified as the optimum formulation in this study, as it provided the best compromise between hardness, durability, and moisture resistance. Future work should evaluate the long-term storage stability of the briquettes under controlled humidity conditions and investigate strategies to reduce water absorption without compromising mechanical strength.

TABLE 1. Physical properties of biochar briquettes prepared with different sawdust contents, including hardness, durability, and water absorptivity, reported as mean ± standard deviation

Mixing Ratio wt.% (Biochar : Sawdust)	Hardness	Durability (%)	Water absorptivity (%)
30	92.2 ± 0.16	98.6 ± 0.26	34.4 ± 0.35
20	93.6 ± 0.51	99.6 ± 0.18	22.3 ± 0.22
10	85.6 ± 0.52	99.2 ± 0.34	15.3 ± 0.44
0	75.7 ± 0.68	96.0 ± 0.57	3.2 ± 0.33

TABLE 2. One-way analysis of variance (ANOVA) for evaluating the statistical significance of sawdust content on the physical properties of biochar briquettes

Briquette properties	Source of variation	SS	Df	MS	p-value
Hardness	Between groups	1006.954	3	335.651	1.619×10^{-16}
	Within groups	9.288	16	0.581	
	Total	1016.242	19		
Durability	Between groups	38.538	3	12.846	9.789×10^{-10}
	Within groups	2.660	16	0.166	
	Total	41.198	19		
Water absorptivity	Between groups	2554.410	3	851.470	3.380×10^{-25}
	Within groups	1.920	16	0.120	
	Total	2556.330	19		

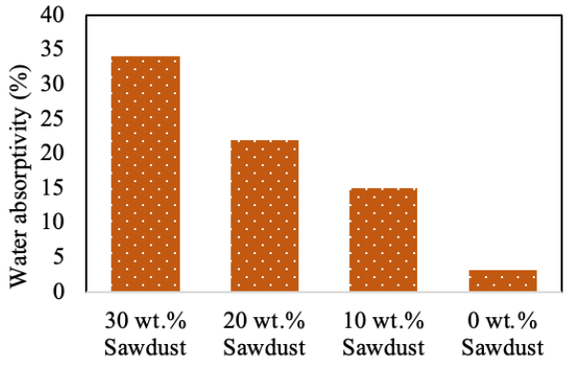

FIGURE 5. Water absorptivity of biochar briquettes prepared with different sawdust contents.

CHEMICAL PROPERTIES OF RAW MATERIAL AND BIOCHAR BRIQUETTES

The chemical structure and functional group changes of the nitrile butadiene rubber (NBR) glove, pyrolysed glove, and biochar composites incorporating sawdust were examined using Fourier transform infrared (FTIR) spectroscopy. This technique is widely applied for identifying specific functional groups and assessing molecular transformations during thermal treatments such as pyrolysis.

Figure 6 presents the FTIR spectra of the raw NBR glove and the biochar samples prepared from the pyrolysed glove with varying amounts of sawdust as a binder, alongside the spectrum of raw sawdust for comparison. The spectra provide insight into the chemical changes that occurred after pyrolysis and the influence of sawdust addition as a binding agent in the briquette matrix.

The FTIR spectrum of raw NBR glove displays several prominent absorption peaks. The peak observed at approximately 3414 cm^{-1} is attributed to O–H stretching vibrations (Aragaw and Mekonnen, 2021), which may arise from absorbed moisture or additives present in the glove material. A sharp and distinct peak at 2924 cm^{-1} corresponds to C–H stretching vibrations, which are characteristic of aliphatic hydrocarbon chains found in polymer backbones. At 2236 cm^{-1}, the spectrum reveals the presence of the nitrile (C≡N) functional group, a defining feature of NBR that originates from its acrylonitrile component (Aragaw and Mekonnen, 2021). The peak at 1644 cm^{-1} is associated with carbonyl (C=O) stretching vibrations, potentially from primary amides or overlapping C=C stretching, indicating the presence of carbonyl-containing structures (Chen and Sun, 2005). Another important peak appears at 964 cm^{-1}, which corresponds to out-of-plane bending vibrations of (=C–H) groups derived from butadiene units in the NBR formulation (Polat and Bursalı, 2019). Overall, these peaks align well with those reported in the literature for NBR materials (Alhareb et al. 2017; Polat and Bursalı, 2019; Samantarai et al. 2017), thereby confirming the chemical identity of the raw glove.

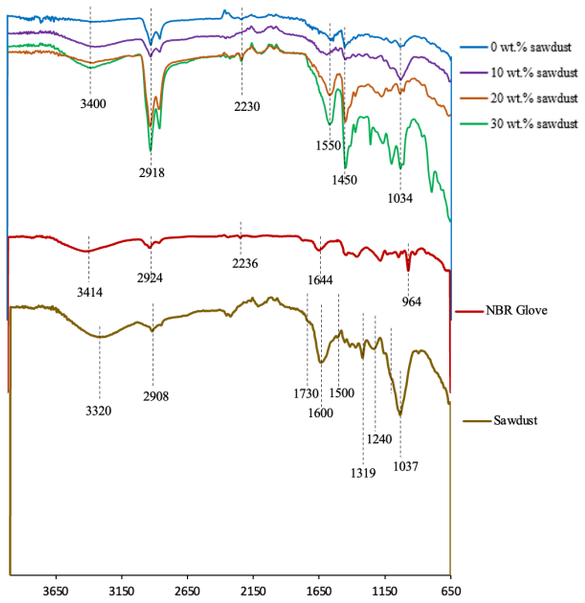

FIGURE 6. FTIR result for pyrolysed glove with and without sawdust as binding agent as well as FTIR spectra for raw sawdust

As shown in Figure 6, the FTIR spectrum of raw sawdust exhibits typical features of lignocellulosic biomass. A broad absorption band in the range of 3320–3400 cm^{-1} is indicative of O–H stretching vibrations, arising from the hydroxyl groups in cellulose and hemicellulose, which reflect the hydrophilic nature of sawdust. Peaks around 2908 cm^{-1} correspond to C–H stretching vibrations from methyl and methylene groups, also originating from cellulose and lignin. The absorption peak at 1730 cm^{-1} corresponds to the stretching vibrations of C=O bonds typically found in hemicellulose (carboxylic acids and esters) (Bagane and Guiza, 2000). Additional peaks between 1500 and 1319 cm^{-1} represent aromatic skeletal vibrations and C–O stretching, confirming lignin and carbohydrate structures. The band around 1600 cm^{-1} further supports aromatic C=C vibrations in lignin. Meanwhile, the peak observed at 1240 cm^{-1} is associated with C–O stretching vibrations in hemicellulose, suggesting the incorporation of sawdust into the briquette matrix. Additionally, the peak at 1037 cm^{-1} is indicative of C–X bonds, pointing to the presence of halogenated compounds on the sawdust surface (Farinella et al. 2007).

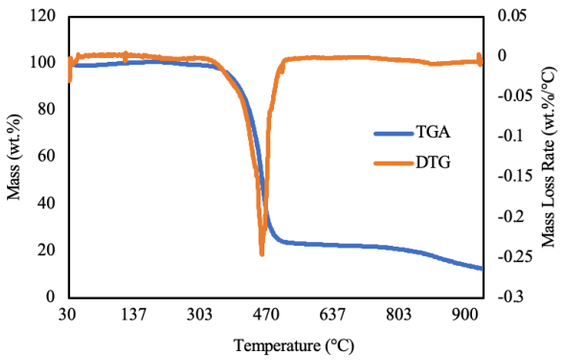

FIGURE 7. Rubber glove TGA and DTG profile

For the pyrolysed glove samples densified with different sawdust contents (0 wt.%, 10 wt.%, 20 wt.%, and 30 wt.%), the FTIR spectra demonstrate characteristic features derived from both the rubber and sawdust components. As the amount of sawdust increases, the intensity of absorption bands associated with O–H and C–O functional groups near 3400 and 1034 cm^{-1}, respectively, also increased. These bands are attributed to the oxygen-containing groups present in the lignocellulosic material of the sawdust, indicating that the biomass binder is effectively incorporated into the pyrolysed matrix. The peak representing the nitrile group around 2236 cm^{-1}, which is distinctive of the original nitrile butadiene rubber glove, decreases in intensity due to thermal degradation during the pyrolysis process but remains detectable, indicating the partial retention of chemical features from the rubber. The peaks related to C–H stretching around 2900 cm^{-1} increased in intensity as the sawdust content rises within the briquette matrix. Specifically, peaks near 2920 cm^{-1} are characteristic of methyl and methylene groups, which are commonly found in lignocellulosic biomass components (Tejada-Tovar et al. 2021). The band at 964 cm^{-1}, associated with butadiene structures, significantly diminishes following pyrolysis, suggesting the breakdown of these components. Furthermore, peaks related to aromatic and carbonyl group vibrations in the 1550–1450 cm^{-1} region become more prominent with increasing sawdust content, reflecting an enhanced presence of aromatic and oxygenated functional groups introduced by the sawdust.

Overall, the FTIR analysis confirmed that the raw glove exhibits typical chemical characteristics of nitrile rubber, while the raw sawdust displays typical lignocellulosic chemical groups. The pyrolysed glove samples mixed with sawdust demonstrate spectral evidence that the carbon-rich pyrolysis residue integrates effectively with the biomass binder. This results in an increased abundance of oxygen-containing groups while partially retaining rubber-related chemical signatures. This implies that sawdust functions not only as a physical binder but also chemically interacts with the pyrolysed material to form a composite with richer functional group diversity. Such interactions likely underlie the observed improvements in the mechanical strength and fuel properties of the briquettes. The presence of spectral characteristics from both components in the composites verifies the successful combination of rubber pyrolysis residue and sawdust binder.

Thermogravimetric analysis (TGA) is an analytical technique used to assess the thermal stability and composition of a material by continuously measuring its mass as it is subjected to a controlled temperature program in a specific atmosphere. The resulting TGA curve, which plots mass loss against temperature or time, and its derivative counterpart, the DTG curve, are useful in identifying the stages of thermal degradation and estimating the proximate composition of materials. TGA of nitrile rubber (NBR) gloves was performed to determine the material's degradation behaviour and thermal characteristics. As shown in Figure 7, the thermal decomposition pattern of the NBR glove is evident across multiple temperature ranges. An initial mass loss was observed at around 110 °C, which corresponds to the evaporation of moisture adsorbed on the surface or absorbed within the matrix of the glove material. This stage represents the removal of physically bound water and is typical in most TGA assessments.

Between 110 °C and 220 °C, the mass of the glove remained largely unchanged, indicating thermal stability in this region and the absence of substantial volatile release. However, as the temperature increased beyond 220 °C, a gradual mass reduction was observed, signifying the onset of thermal decomposition of low-molecular-weight species or the initial breakdown of polymeric chains.

TABLE 3. Result of proximate analysis for NBR glove

Proximate Analysis	As-received basis (wt.%)
Moisture Content	0.95
Volatile Matter	80.10
Fixed Carbon	8.30
Ash Content	10.65
Higher Heating Value (MJ/kg)	15.51

[a]calculated by using correlation proposed by Parikh et al. (2005) where HHV = 0.3536FC+0.1559VM-0.0078Ash

A significant and rapid mass loss occurred between 300 °C and 500 °C, marking the primary decomposition phase of the NBR glove. This range is characteristic of the pyrolytic degradation of nitrile-based elastomers. The major decomposition step, particularly between 200 °C

and 500 °C, aligns with findings reported by Deng et al. (2008), who described this interval as the dominant pyrolysis region for rubber materials. The most substantial decomposition event was recorded at 458 °C, which can be considered the peak degradation temperature of the NBR glove. Beyond 500 °C, the mass loss continued but at a slower rate, suggesting the breakdown of more stable aromatic structures or inorganic fillers. The thermal degradation extended up to 900 °C, at which point the residue stabilised. However, upon switching the carrier gas from nitrogen to air, an anomalous increase in mass was detected. This mass gain is likely due to oxidation reactions, where residual carbonaceous matter reacts with atmospheric oxygen to form oxygen-containing compounds or surface oxides. This unintended reaction may introduce error into the heating value estimation and affects the combustion profile.

According to Alneamah and H. Al-Maamori (2015), nitrile rubber generally undergoes a major thermal degradation stage within the range of 25–600 °C, which supports the observation of a dominant decomposition region in this study. The TGA/DTG results showed that the NBR glove experienced its main mass loss between approximately 300 and 500 °C, with the maximum degradation rate occurring around 458 °C. This behaviour is consistent with Mishra and Mohanty (2020), who reported that waste nitrile gloves undergo their major decomposition stage between 340 and 500 °C, with a DTG peak at approximately 462 °C. It is also supported by Baird et al. (2025), who reported that nitrile gloves in mixed PPE waste mainly decomposed within the range of 400–500 °C, while the highest mass-loss rate for the PPE mixture occurred between 422.75 and 469 °C. These comparable degradation ranges confirm that nitrile-based gloves require relatively high thermal energy for substantial polymer breakdown due to the thermal stability of acrylonitrile and butadiene units.

The TGA data were also used to determine the proximate composition of the NBR glove, as summarised in Table 3. The NBR glove contained 0.95 wt.% moisture content, 80.10 wt.% volatile matter, 8.30 wt.% fixed carbon, and 10.65 wt.% ash content, with a calculated higher heating value (HHV) of 15.51 MJ/kg. The low moisture content indicates the hydrophobic nature of synthetic rubber and suggests that minimal energy would be required for moisture removal during thermal conversion. The high volatile matter content confirms that the glove is mainly composed of thermally degradable polymeric fractions that can be released as condensable and non-condensable volatile products during pyrolysis.

Compared with the literature, the volatile matter content obtained in this study is close to the value reported by Ramalingam et al. (2023), who found that glove waste contained 79.3 wt.% volatile matter, 8.9 wt.% fixed carbon, and 11.8 wt.% ash. It is also comparable to the nitrile glove data reported by Baird et al. (2025), where nitrile gloves contained 84.74 wt.% volatile matter, 3.72 wt.% fixed carbon, 10.62 wt.% solid residue, and 0.93 wt.% moisture. The close agreement in moisture and ash content values between this study and Baird et al. (2025) suggests that the NBR glove used in the present work exhibited similar feedstock characteristics to nitrile PPE waste, particularly in terms of low moisture content, high volatile release, and measurable inorganic or residual fraction. However, Mishra and Mohanty (2020) reported a higher volatile matter content of 94.26 wt.%, a lower fixed carbon content of 0.62 wt.%, a lower ash content of 4.57 wt.%, and a much higher heating value of 37.12 MJ/kg for waste nitrile gloves. The differences may be attributed to variations in glove formulation, additives, fillers, sample origin, and analytical method. Commercial gloves may contain different amounts of inorganic fillers, stabilisers, pigments, curing agents, and processing additives, which can significantly influence ash content, fixed carbon, and heating value.

The ash content obtained in this study was 10.65 wt.%, which is closely comparable to the 10.62 wt.% solid residue reported by Baird et al. (2025) and the 11.8 wt.% ash reported by Ramalingam et al. (2023). However, it is considerably higher than the 4.57 wt.% ash reported by Mishra and Mohanty (2020). This suggests that the NBR glove used in the present study may contain a relatively higher proportion of inorganic fillers or additives. This interpretation is supported by Baird et al. (2025), who reported that nitrile gloves contained higher oxygen and nitrogen contents than mask offcuts, which were attributed to the acrylonitrile group and oxygen-containing additives used during glove manufacturing. These findings indicate that glove formulation and additive composition can strongly influence the thermal and fuel properties of NBR glove waste.

Since ash is non-combustible, a higher ash content can reduce the effective higher heating value and contribute to greater solid residue formation after thermal treatment. This may partly explain why the calculated HHV in the present study, 15.51 MJ/kg, is lower than the value reported by Mishra and Mohanty (2020). However, this comparison should be made cautiously because the HHV in the present study was estimated using the Parikh et al. (2005) correlation based on proximate analysis, whereas some literature values may have been determined using bomb calorimetry. Therefore, the HHV reported in this study should be interpreted as an estimated value, and direct calorimetric measurement is recommended for more accurate fuel evaluation.

Overall, the proximate analysis confirms that the NBR glove is a highly volatile, low-moisture polymeric

feedstock with moderate fixed carbon and relatively high ash content. These characteristics indicate that the material is suitable for pyrolysis, as the high volatile matter supports thermal conversion, while the fixed carbon and ash fractions contribute to the formation of solid residue. However, the differences between this study and previous reports highlight that the thermal and fuel properties of nitrile gloves can vary significantly depending on glove composition, filler content, and analytical method. Therefore, direct calorimetric measurement and more detailed elemental analysis are recommended in future work to improve the accuracy of HHV estimation and to better understand the role of additives in NBR glove pyrolysis.

Following the characterisation of the raw NBR glove, the thermal degradation behaviour and proximate composition of the resulting biochar briquettes were further investigated. The aim was to evaluate how sawdust binder ratios of 0, 10, 20, and 30 wt.% affected the decomposition behaviour, thermal stability, and fuel-related properties of the briquettes. Thermogravimetric analysis (TGA) was used to monitor mass loss as a function of temperature, while derivative thermogravimetry (DTG) was used to identify the rate and main stages of thermal decomposition.

As shown in Figure 8, the TGA and DTG curves revealed distinct degradation patterns depending on the amount of sawdust incorporated. The briquettes containing 0 wt.% and 10 wt.% sawdust exhibited thermal behaviour closely resembling that of the original pyrolysed nitrile rubber glove material, particularly those produced at pyrolysis temperatures of 350 and 400 °C. These samples underwent the typical thermal stages: an initial moisture evaporation phase, followed by primary thermal degradation. For the 10 wt.% sample, however, an additional DTG peak was observed at approximately 338 °C, which was absent in the 0 wt.% formulation. This intermediate degradation peak can be attributed to the thermal decomposition of the lignocellulosic component introduced by sawdust.

According to Zhang et al. (2016), sawdust undergoes thermal degradation within the range of 140–400 °C, consistent with the observed DTG peak. This degradation step is associated with the devolatilization of cellulose and hemicellulose, both of which are major constituents of sawdust. Ahn et al. (2014) reported that hemicellulose typically decomposes between 200 and 350 °C, while cellulose degrades around 300–400 °C, supporting the interpretation of the 338 °C peak as a devolatilization phase. The primary thermal degradation phase for the biochar matrix itself was observed at 459 °C and 461 °C for the 0 wt.% and 10 wt.% briquettes, respectively. This is in line with the degradation temperature of NBR-based biochar, further confirming the dominant contribution of rubber-derived char in these samples. In contrast, the biochar briquettes containing 20 wt.% and 30 wt.% sawdust exhibited a more complex thermal degradation profile, characterised by three distinct phases. The first phase occurred at relatively low temperatures, 82 °C and 81 °C, and corresponded to the evaporation of physically bound moisture. The more pronounced mass loss at this stage for samples with higher sawdust content suggests that sawdust introduces higher inherent moisture, likely due to its hydrophilic nature and porous structure. This is consistent with findings by Hu et al. (2015), who reported enhanced moisture release in biochar blends with greater lignocellulosic content.

The second degradation phase was observed at 340 °C and 342 °C for the 20 wt.% and 30 wt.% samples, respectively. This stage is attributed to the thermal degradation of lignin, a major component of sawdust. Lignin decomposes over a wide temperature range (approximately 100–900 °C) due to its complex, cross-linked aromatic structure, which includes various ether and carbon–carbon bonds. Unlike cellulose and hemicellulose, lignin degrades more slowly and over a broader temperature interval, which explains the sustained mass loss during this phase (Yang et al. 2007). The final thermal degradation phase, occurring at 455 °C and 457 °C, is attributed to the breakdown of the residual biochar structure, primarily derived from the nitrile rubber matrix. This stage is similar to that observed in the 0 wt.% and 10 wt.% samples and represents the final decomposition of thermally stable carbonaceous residues.

The observed differences in thermal degradation behaviour between the various sawdust loadings provide valuable insights into the interaction between synthetic rubber-derived biochar and biomass-based binders. As the proportion of sawdust increases, the TGA curves shift to display multi-step degradation behaviour, reflecting the composite nature of the material and the contribution of different thermal degradation mechanisms associated with each component. This also affects the proximate analysis, thermal stability, and potential energy release characteristics of the briquettes, which are critical for evaluating their suitability for fuel or material applications.

The proximate analysis of biochar briquettes produced with different binding ratios of sawdust (0 wt.%, 10 wt.%, 20 wt.%, and 30 wt.%) provides valuable insight into their fuel quality and thermal behaviour. The parameters analysed include moisture content (MC), volatile matter (VM), fixed carbon (FC), ash content (AC), and higher heating value (HHV), as summarised in Table 4.

The results revealed that moisture content increased gradually with the addition of sawdust. The biochar briquette without sawdust (0 wt.%) had a negligible moisture content of 0.01 wt.%, indicating a very dry

material. With the incorporation of sawdust, the moisture content increased to 0.74 wt.% (10 wt.%), 2.20 wt.% (20 wt.%), and 2.17 wt.% (30 wt.%). This trend is attributed to the hygroscopic nature of sawdust, a lignocellulosic material rich in hydroxyl groups, which enhances its water retention capacity. The porous structure of sawdust also contributes to its ability to absorb and hold water. This increase in moisture content should be taken into consideration when evaluating briquette storage and combustion efficiency, as higher moisture levels can reduce thermal output and increase ignition time.

Conversely, ash content decreases significantly with increasing sawdust content. The ash content dropped from 13.09 wt.% in the 0 wt.% sample to 4.13 wt.% in the 30 wt.% sample. This inverse relationship reflects the composition of the two feedstocks: nitrile rubber-derived biochar tends to yield higher ash content due to the presence of inorganic fillers or residual catalysts, whereas sawdust is primarily organic and generates comparatively less ash upon combustion. A lower ash content is generally favourable for biofuel applications, as it minimises slagging and fouling issues in combustion systems and improves overall energy conversion efficiency.

The fixed carbon content, which directly influences the combustion stability and char reactivity of the briquettes, showed a non-linear trend. An initial increase was observed, with FC rising from 9.60 wt.% (0 wt.% sawdust) to 14.86 wt.% (20 wt.% sawdust), suggesting that a moderate addition of sawdust enhances the carbonaceous residue due to improved biomass-to-biochar conversion efficiency. However, a slight decline to 13.14 wt.% was noted in the 30 wt.% sawdust sample. This may be due to the relatively lower thermal stability of hemicellulose and cellulose in sawdust compared with the more thermally resistant rubber-based char matrix. The degradation of these polysaccharides at lower temperatures produces more volatile compounds, thereby reducing the final carbon-rich residue. This anomaly highlights the need for further study beyond 30 wt.% sawdust to identify the optimal binder ratio that balances carbon retention and structural integrity.

The volatile matter content varied among the briquette formulations, increasing from 77.30 wt.% for the sample without sawdust to 84.29 wt.% at 10 wt.% sawdust. It then decreased to 78.15 wt.% at 20 wt.% sawdust before increasing slightly to 80.56 wt.% at 30 wt.% sawdust. This variation may be attributed to the complex thermal behaviour of the hybrid feedstock, which consists of rubber-derived biochar and lignocellulosic sawdust. Sawdust contains cellulose and hemicellulose, which are known to release volatile compounds during thermal degradation. However, the interaction between rubber-derived and biomass-derived components may influence the overall devolatilisation behaviour, resulting in non-linear changes in volatile matter content.

The relatively high volatile matter content of the briquettes suggests that the biochar produced at 350 °C still retained thermally releasable components. This is expected because 350 °C is below the maximum degradation temperature of the original NBR glove observed in the TGA/DTG analysis. The presence of residual volatile matter may be beneficial for ignition, as volatile compounds released during the early stage of heating can assist flame development. However, excessive volatile matter may reduce combustion stability and contribute to smoke or condensable emissions under conditions of incomplete combustion.

Therefore, the selection of 350 °C represents a practical compromise between maintaining sufficient solid yield for briquette production and achieving adequate thermal conversion of the glove material. Further work should include direct combustion testing, emission analysis, and optimisation of pyrolysis residence time to determine whether additional reduction of volatile matter is required.

The higher heating value, which indicates the total energy potential of the briquettes, increased with sawdust content from 15.34 MJ/kg (0 wt.%) to a maximum of 17.40 MJ/kg (20 wt.%), before a slight decline to 17.17 MJ/kg at 30 wt.% sawdust. The increasing trend in HHV is associated with the enhanced lignin content contributed by sawdust. Lignin is known to have a higher calorific value compared to cellulose and hemicellulose due to its aromatic structure, and its presence can significantly improve energy yield. This finding is supported by Demirbas (2002), who emphasised that biomass fuels with higher lignin concentrations tend to exhibit higher HHVs. Interestingly, despite the higher sawdust content in the 30 wt.% sample, the HHV was marginally lower than that of the 20 wt.% sample. This reduction can be correlated with the drop in fixed carbon and a possible increase in non-combustible ash-forming materials. Moreover, an excessive amount of sawdust may lead to a looser briquette structure with lower density, reducing combustion efficiency. These results suggest that 20 wt.% sawdust may represent an optimal ratio for achieving high energy output while maintaining thermal stability and structural integrity.

Further comparison with the study by Zhang et al. (2019) reinforces this observation. In their work, biochar pellets composed of 40 wt.% biochar and 60 wt.% supporting materials (apple tree branches, water, and corn straw) achieved an HHV of 22.15 MJ/kg. The higher HHV is likely due to the larger proportion of lignin-rich biomass

used. Nonetheless, the trend remains consistent: increasing biomass binder content enhances the energy value of the resulting solid fuel. Thus, incorporating sawdust into biochar briquettes not only improved their thermal characteristics but also enhanced their feasibility as a renewable, high-calorific-value fuel source.

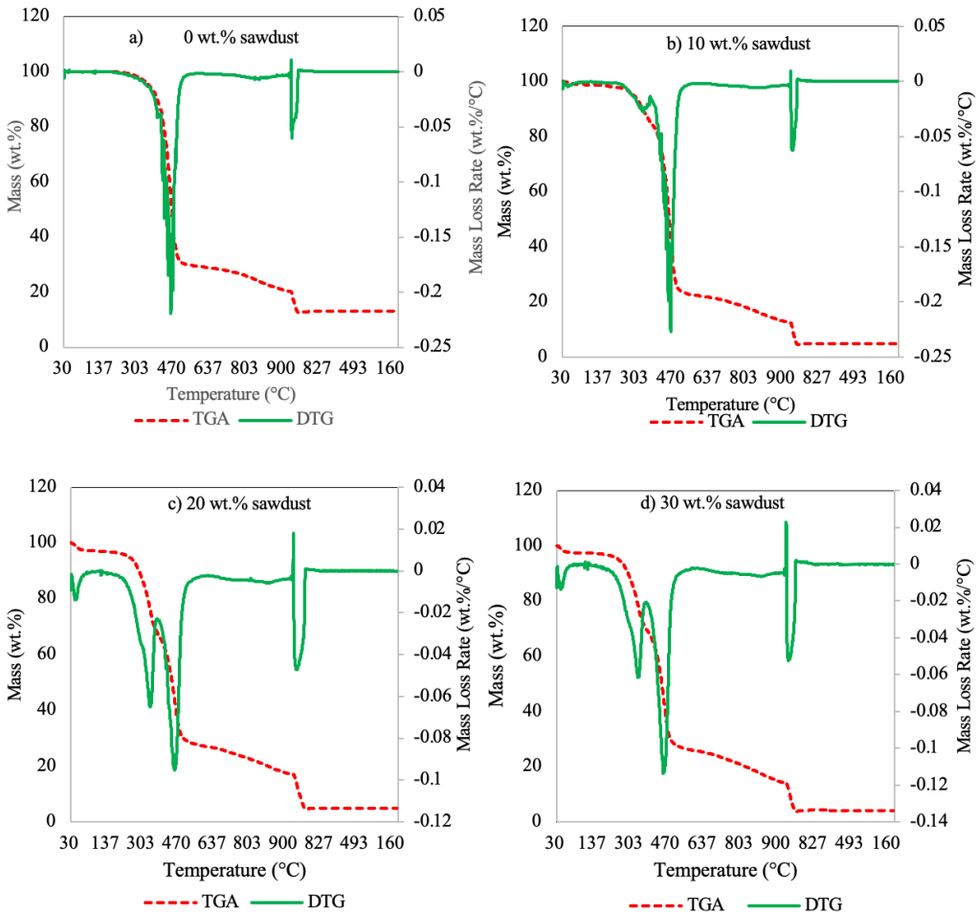

FIGURE 8. Thermogravimetric analysis result for biochar briquette with 0wt.%, 10 wt.%, 20 wt.%, and 30 wt.% of sawdust

MORPHOLOGICAL STRUCTURE OF THE BRIQUETTE

Figures 9-12 presents SEM micrographs illustrating the microstructural differences among briquettes prepared with varying sawdust contents ranging from 0 to 30 wt.%. These images reveal the critical role of sawdust and its lignin content in enhancing particle bonding and overall briquette integrity. The briquette surface without sawdust (Figure 9) shows a porous structure with pronounced voids and gaps between particles, indicating poor inter-particle bonding and low material density. This correlates with the low hardness observed for briquettes without sawdust, as the presence of large pore spaces reduces resistance to deformation. The absence of lignin-rich sawdust means there is minimal natural binder to facilitate strong particle adhesion. Additionally, char particles from pyrolysed biomass reduce hydrogen bonding and particle plasticity, further weakening the structure.

When 10 wt.% sawdust is added (Figure 10), there is a clear improvement in particle contact and packing density, although some micro-voids remain visible. This enhancement can be attributed to the lignin in sawdust, which softens around 70 °C and acts as a natural binder, reinforcing cellulose microfibrils and encouraging better particle cohesion. This correlates with the EDX data (Table 5), which show a slight decrease in carbon content from 78.75% to 76.98% accompanied by an increase in oxygen from 6.76% to 9.37%. The presence of additional oxygen likely reflects the organic components in sawdust, including lignin, which contribute to improved bonding (Budiyantoro and Yudhanto 2024). Consequently, briquette hardness improves compared to samples lacking sawdust, though internal voids are not fully eliminated.

At 20 wt.% sawdust (Figure 11), the microstructure displays significant densification characterised by reduced interparticle boundaries and more uniform integration of lignin with other biochar components. The increased sawdust content enhances lignin availability, allowing better particle adhesion under compression, thereby improving pellet hardness. The interparticle contact area was maximised, and the boundary thickness between particles was minimised, confirming the strong binding effect of lignin after hot pressing. The EDX results support this observation, indicating a further decrease in carbon content to 70.23% and a corresponding rise in oxygen to 12.06%, alongside stable trace minerals around 12.01%. The increased oxygen signifies sustained organic presence, consistent with lignin and cellulose integration. These microstructural improvements enhanced the contact area between particles and minimize boundary thickness, which explains the superior hardness and mechanical stability of briquettes at this composition. However, some small internal voids persist because lignin, while softening under heat and pressure, does not uniformly infiltrate hemicellulose- and cellulose-rich regions.

When sawdust content increases to 30 wt.% (Figure 12), the microstructure becomes more heterogeneous, displaying visible cracks and loosely bound outer layers. This structure results from uneven packing and localized agglomeration due to excess sawdust. Consistently, Hamri et al. (2024) reported that increasing sawdust content from 10% to 25% in cement boards markedly decreases density and flexural performance because higher sawdust levels increase porosity and limit the available cement to bind particles. Supporting this, EDX data reveal a notable increase in trace minerals to 24.63%, alongside a further drop in carbon content to 65.38% and an increase in oxygen to 15.08%. The elevated trace mineral level may indicate uneven distribution of filler materials or impurities associated with high sawdust content, creating weak zones prone to abrasion and mechanical failure. Despite the presence of ample lignin, this heterogeneity explains the observed decrease in briquette durability, with loosely bound outer layers more susceptible to detachment during handling and mechanical testing. It should also be noted that the Au signal detected in the EDX analysis does not originate from the NBR glove, sawdust, or biochar briquette. The presence of Au is attributed to the gold sputter coating applied during SEM sample preparation to improve surface conductivity and reduce charging effects during imaging. Therefore, Au was excluded from the interpretation of the intrinsic elemental composition of the briquettes. The discussion of the EDX results focuses mainly on carbon, oxygen, and trace mineral contents, which are more relevant to the composition of the glove-derived biochar and sawdust binder.

Overall, the SEM and EDX analyses demonstrated that incorporating 20 wt.% sawdust achieves the optimal balance of densification, hardness, and durability by maximising the binding effect of lignin. In contrast, excessive sawdust compromises uniform compaction and mechanical strength, while the complete absence of sawdust resulted in a brittle, low-density structure with inadequate particle bonding. This integrated microstructural and elemental insight highlights the critical interplay between sawdust content, lignin functionality, and biochar composition in defining briquette performance.

TABLE 4. Moisture content (MC), volatile matter (VM), fixed carbon (FC), ash content (AC), and higher heating value (HHV) of the biochar briquettes

Proximate Analysis of Biochar Briquette	Biochar Briquette with 0% Sawdust	Biochar Briquette with 10% Sawdust	Biochar Briquette with 20% Sawdust	Biochar Briquette with 30% Sawdust
Moisture Content (wt.%)	0.01	0.74	2.20	2.17
Volatile Matter (wt.%)	77.30	84.29	78.15	80.56
Fixed Carbon (wt.%)	9.60	10.02	14.86	13.14
Ash Content (wt.%)	13.09	4.95	4.79	4.13
Higher Heating Value (MJ/kg)[a]	15.34	16.65	17.4	17.17

[a]*calculated by using correlation proposed by Parikh et al. (2005) where HHV = 0.3536FC+0.1559VM-0.0078Ash*

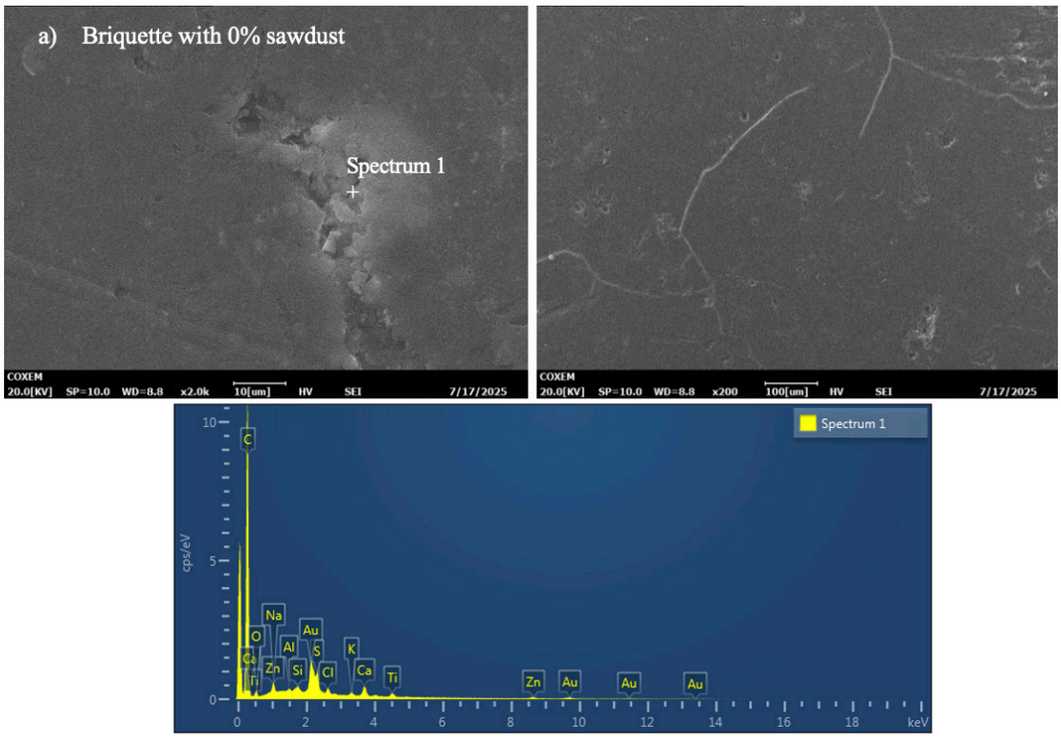

FIGURE 9. SEM micrographs of biochar briquettes prepared with varying sawdust contents (0 wt.%)

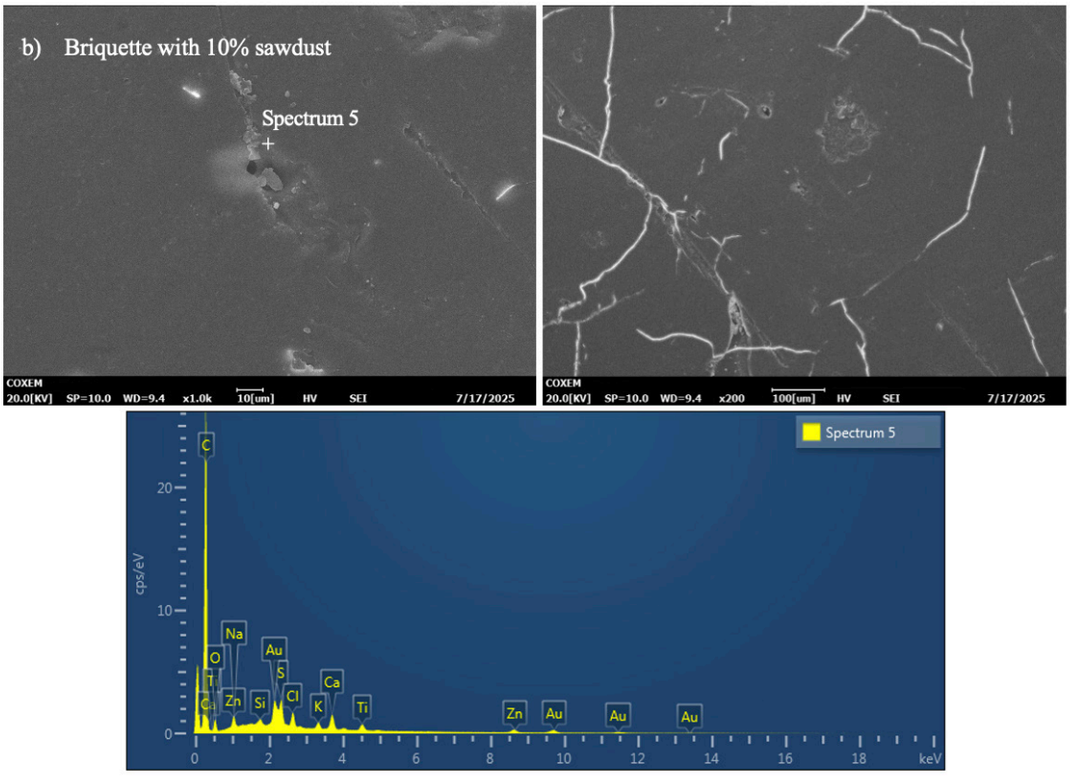

FIGURE 10. SEM micrographs of biochar briquettes prepared with varying sawdust contents (10 wt.%)

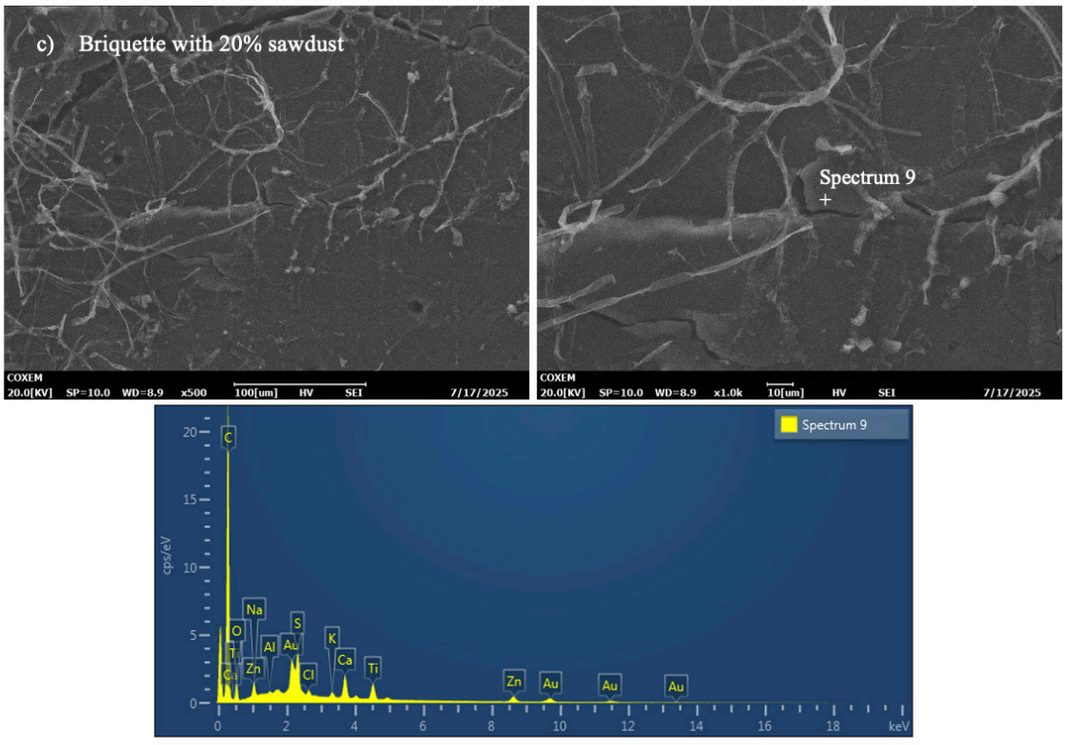

FIGURE 11. SEM micrographs of biochar briquettes prepared with varying sawdust contents (20 wt.%)

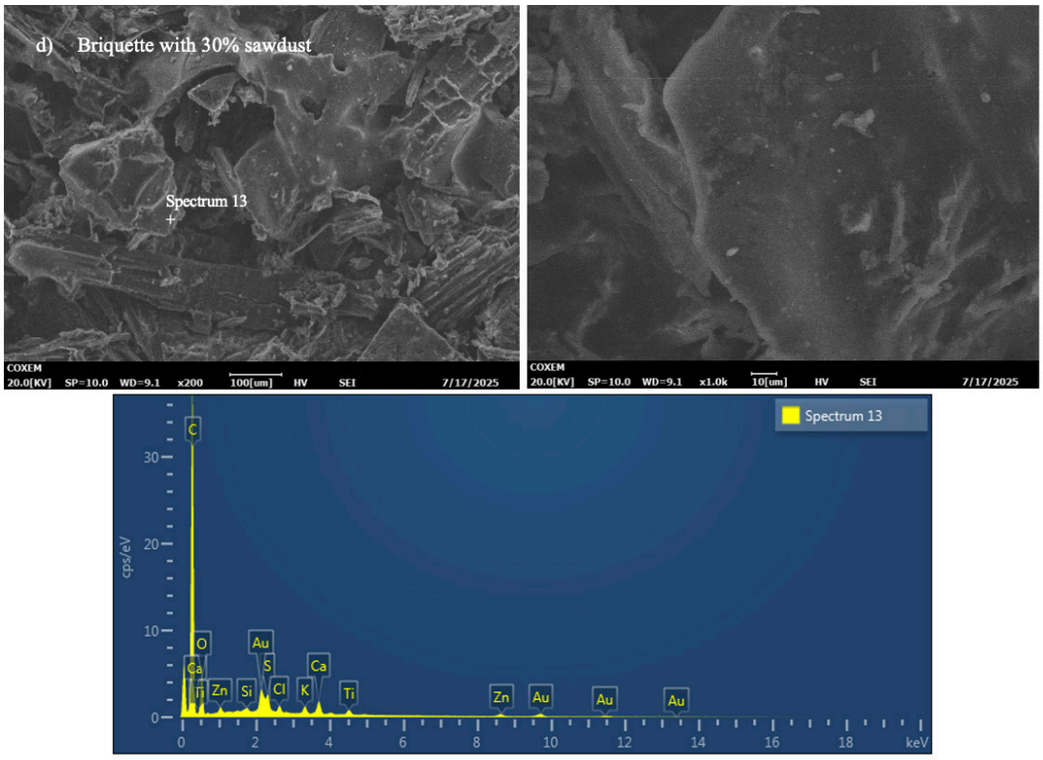

FIGURE 12. SEM micrographs of biochar briquettes prepared with varying sawdust contents (30 wt.%)

TABLE 5. EDX elemental composition of biochar briquettes prepared with varying sawdust contents

EDX analysis (Atomic %)	Biochar glove with 0 wt.% sawdust	Biochar glove with 10 wt.% sawdust	Biochar glove with 20 wt.% sawdust	Biochar glove with 30 wt.% sawdust
Carbon Content (C)	78.75	76.98	70.23	65.38
Oxygen (O)	6.76	9.37	12.06	15.08
Trace Minerals (Ca, Zn, K, S, Cl, Na, Si, Ti, Al)	6.93	8.86	12.01	24.63
Au	7.56	4.79	5.70	4.13

CONCLUSION AND FUTURE RESEARCH DIRECTIONS

This study successfully demonstrated a proof-of-concept approach for converting clean and unused nitrile butadiene rubber (NBR) gloves into biochar briquettes through pyrolysis followed by sawdust-assisted densification. The pyrolysis temperature strongly influenced the physical transformation and solid recovery of the glove-derived residue. The sample treated at 300 °C retained rubber-like elasticity and was therefore unsuitable for briquette preparation. In contrast, pyrolysis at 350 °C produced a brittle carbonaceous residue with the highest viable biochar yield of 68.4%, while further increases in temperature to 400 and 450 °C reduced the solid yield to 48.5% and 13.5%, respectively. Therefore, 350 °C was identified as the most practical pyrolysis temperature because it provided a suitable balance between biochar formation and solid recovery.

The incorporation of sawdust as a lignocellulosic binder significantly improved the mechanical integrity of the biochar briquettes. Among the tested formulations, the briquette containing 20 wt.% sawdust showed the best overall performance, with the highest hardness of 93.6, excellent durability of 99.6%, moderate water absorptivity of 22.3%, and the highest HHV of 17.40 MJ/kg. These improvements are attributed to the natural binding ability of sawdust, particularly the contribution of lignin, cellulose, and hemicellulose, which enhance particle cohesion, interparticle bonding, and structural stability during hot pressing.

However, the results also revealed an important trade-off between mechanical strength and moisture resistance. Increasing sawdust content improved hardness and durability, but excessive sawdust addition increased water absorptivity due to the hydrophilic nature of the lignocellulosic binder. The 30 wt.% sawdust briquette recorded the highest water absorptivity of 34.4%, which may affect storage stability, handling durability, ignition behaviour, and effective fuel performance under humid conditions. Thus, although sawdust is beneficial as a binder, its content must be carefully optimised to avoid excessive moisture uptake.

The FTIR, TGA/DTG, proximate analysis, SEM, and EDX results further supported the successful formation of sawdust-bound NBR-derived biochar briquettes. FTIR analysis confirmed the presence of rubber-derived functional groups together with sawdust-related oxygenated and lignocellulosic functional groups, indicating effective incorporation of the binder into the biochar matrix. Thermal and proximate analyses showed that the briquettes retained fuel-relevant characteristics, although the relatively high volatile matter suggests that combustion behaviour and emission profiles should be further investigated. SEM and EDX analyses also confirmed the carbon-rich nature of the briquette structure, while the detected gold signal was attributed to sputter coating during sample preparation rather than the intrinsic composition of the briquettes.

Overall, this study shows that NBR glove-derived biochar can be converted into mechanically durable solid fuel briquettes using sawdust as a low-cost and non-food-based binder. The 20 wt.% sawdust formulation was identified as the optimum composition because it provided the best balance between hardness, durability, heating value, and water resistance. These findings support the potential valorisation of glove-based polymer waste into value-added solid fuel materials and contribute to sustainable waste management and circular economy development.

Nevertheless, the findings should be interpreted as preliminary because clean and unused NBR gloves were used as a model feedstock. Future research should validate the process using actual contaminated medical glove waste, with specific attention to sterilisation requirements, biosafety, contaminant transformation, gaseous emissions, combustion performance, and ash characteristics. Further work should also evaluate long-term storage stability under controlled humidity conditions and explore moisture-control strategies such as hydrophobic surface treatment, moisture-barrier packaging, alternative biomass binders, and optimisation of densification parameters including pressure, temperature, and holding time. These additional studies are necessary before the proposed approach can be considered for practical waste-to-energy applications.

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DECLARATION OF COMPETING INTEREST

None.

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