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A Comparison of Feedstock from Agricultural Biomass and Face Masks for the Production of Biochar through Co-Pyrolysis

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Abstract: This study explores the pyrolysis of disposable face masks to produce chemicals suitable for use as fuel, addressing the environmental concern posed by single-use face masks. Co-pyrolysis of biomass with face mask plastic waste offers a promising solution. The research focuses on the co-pyrolysis of biomass and face masks, aiming to characterise the properties for analysis and optimisation. Selected agricultural biomass and face mask plastic waste were subjected to temperatures from 250 °C to 400 °C for co-pyrolysis. Slow pyrolysis was chosen because face masks cannot be converted into useful bioproducts at temperatures exceeding 400 °C. The samples were tested in four different ratios and the study was conducted under inert conditions to ensure analysis accuracy and reliability. The results indicate that face masks exhibit a remarkable calorific value of 9310 kcal/kg. Face masks show a two-fold increase in calorific value compared with biomass alone. Additionally, the low moisture content of face masks (0.10%) reduces the heating value needed to remove moisture, enhancing their combustion efficiency. This study demonstrates the potential of co-pyrolysis with face masks as a means of generating valuable chemicals for fuel production, contributing to environmental sustainability.

Keywords: pyrolysis; face mask; biomass; sustainability; EFB

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1. Introduction

The World Health Organisation declared a pandemic in March 2020 in response to the global outbreak of COVID-19 [1]. This outbreak has led to the loss of millions of lives and directly impacted over 180 million individuals worldwide [2]. In quick response to this crisis, many nations mandated the use of personal protective equipment, particularly face masks [3–5]. With an estimated global production of over 120 billion face masks in 2020, these masks became critical tools for controlling the spread of the disease [6].

Since the onset of the COVID-19 outbreak, the disposal of these face masks has become an ongoing issue, from waste management to recycling challenges. In a local context, Malaysia often resorts to incineration and landfilling for waste disposal. Compounding the problem, no proper guidelines are set for the disposal of used face masks, leading to a surge in mismanaged face mask waste and raising genuine environmental concerns [7]. Regarding biomass waste, Malaysia is blessed with agricultural abundance, making the utilisation of waste from the agricultural industry, such as empty fruit bunch (EFB) and rice husk, a common approach for energy production. Biomass encompasses the by-products of crop cultivation and farming, including stems, husks, barks, grains, and leaves, which are typically overlooked. This biomass serves as a unique feedstock rich in carbon that can be repeatedly used without contributing to increased carbon dioxide emissions, thus aiding in climate protection. Converting biomass into useful materials, through heat and chemical reactions, plays a dual role by creating materials for renewable energy and promoting clean energy production [8].

Biochar is the solid product resulting from pyrolysis. It has a structure with hollow spaces between the particles and contains a considerable amount of carbon [9]. Biochar serves various purposes, such as extracting pollutants from water solutions [9,10], improving and healing soil [11], and crafting bio-based composites [9,12], among other uses. Therefore, the potential of biochar depends on the characteristics of the materials or feedstocks used [13]. Numerous studies have consistently shown that specific organic materials, such as EFBs, rice husks, and leaves, can substantially increase the carbon content and provide a substantial calorific value [14]. Commonly used agricultural biomass for biochar or bio-oil production include EFB, rice straw, rice husk and food waste [2,9,10]. These chosen agricultural biomass sources offer great potential due to their composition and organic content. However, information and data on the synergy between face masks and agricultural waste are lacking, which this study seeks to explore.

The most commonly used face masks, such as three-ply disposable face masks, are composed of mixtures of metallic compounds and various polymer types, including polyacrylonitrile, polycarbonate, polyurethane, polyester, polystyrene, polyethylene, and primarily polypropylene [15–17]. Disposable face masks have now become a major source of microplastic waste generation, potentially causing harmful effects [18,19]. Therefore, proper disposal of these masks must be ensured, as they may pose a major waste issue, especially for marine life [8,20]. This research aims to address this growing waste issue by repurposing both biomass and face mask waste for energy production. This approach can reduce the carbon footprint and help manage greenhouse gas emissions. It not only improves waste management but also contributes to renewable energy generation, promoting a more sustainable environment. This approach offers a promising solution to waste management challenges whilst simultaneously reducing greenhouse gas emissions in Malaysia.

The incineration of waste is a major source of greenhouse gas emissions, as it often releases carbon dioxide and other harmful pollutants into the atmosphere [21]. Additionally, improper disposal of used face masks can contribute to pollution and worsen the environmental waste problem. Co-pyrolysis aims to reduce greenhouse gas emissions whilst repurposing waste materials through the co-pyrolysis of biomass and face masks. This process can result in the production of biochar, a solid substance rich in carbon, which can be used as a solid fuel, contributing to more environmentally friendly and sustainable energy production. The carbon stored in biochar can help mitigate carbon emissions, and has the potential to increase char production during combustion due to alterations in the organic material's composition and subsequent energy release. In essence, these specific organic sources have proven effective in enhancing char production through combustion thanks to their unique characteristics, including their considerable carbon content and moderate calorific value.

Furthermore, biochar produces fewer emissions when used as a solid fuel compared with conventional fossil fuels, resulting in an overall reduction in the carbon footprint. In addition to contributing to proper waste management, this process also mitigates greenhouse gas emissions into the environment by using the potential of waste materials to create a valuable resource. This research direction aligns with Malaysia's efforts to reduce carbon emissions and achieve numerous environmental goals. The concurrent treatment of waste management and greenhouse gas emissions through the co-pyrolysis of face masks and biomass offers a more sustainable approach to addressing these issues in Malaysia. It represents a step towards developing an energy- and environmentally friendly solution that supports the nation's sustainability initiatives and reduces its carbon impact.

This novel approach not only holds the potential to enhance waste management practices but could also bolster the generation of renewable energy. The concept of sustainability, achieved through the conversion of waste into energy, provides a promising solution for a nation dealing with persistent waste management challenges, encompassing both medical and municipal waste. Furthermore, research on the combination of biomass is lacking, especially regarding rice husk and EFB, combined with disposable face masks using the co-pyrolysis method to produce solid fuel for energy production. Studies have explored the option of converting disposable face masks into biochar through pyrolysis [21–23]. However, unlike previous research, this study suggests innovative ways to manage medical waste by combining used face masks with biomass to create biochar and bio-oil.

A low-temperature reactor with a retort heating system was used for the slow co-pyrolysis to extract energy from the waste. The choice of slow pyrolysis is due to its low rate of heating and low heating temperature. A determined maximum temperature of 400 °C with a heating rate of 5 °C and a nitrogen flowrate of 2 L/min makes slow pyrolysis suitable for the type of feedstocks being used. The small size of face mask particles at 0.5 mm makes slow pyrolysis the preferred method, as the heat capacity of ground face masks at slow pyrolysis settings helps extract more bio-products, leaving a substantial amount of biochar and bio-oil from the various feedstocks used. The ratio of feedstocks is also a crucial factor, as this greatly influences the quality and yield of the biochar due to the synergistic effects each feedstock can contribute [24]. These criteria are essential to carefully determine to ensure the optimum temperature, heating rate, and ratio are established.

In summary, this study explores the conversion of disposable face masks into biochar through slow pyrolysis, which was chosen for its efficiency in extracting a better yield of biochar and bio-oil. The selection of feedstocks and their ratios plays a critical role in determining the biochar yield. The products from the co-pyrolysis undergo comprehensive analysis to identify the most promising sample for further optimisation.

2. Selection of Feedstock Samples

The recycling of face masks poses a significant challenge, primarily due to the risk of potential COVID-19 infections associated with their intricate structure. Improper disposal of used masks is a common occurrence, exacerbated by the large quantity of waste generated, which places additional stress on waste management systems [25]. This issue is even more critical in developing nations, where waste management often receives minimal attention, leading to uncontrolled disposal of face masks into aquatic environments, drainage systems, and soil. Reports suggest that improper handling of solid waste, including face masks, can increase the risk of COVID-19 transmission [26].

Directly incinerating masks is considered an easier disposal method as it effectively eliminates germs through high-temperature combustion [27]. However, this approach comes with numerous environmental challenges, including toxic gas emissions and air pollution [9]. Hence, it is essential to develop an innovative method to address this escalating waste problem. Thermochemical conversion is a highly promising approach for breaking down and transforming disposable masks effectively [28].

To achieve successful waste conversion, specific optimal temperatures are required. Combining face masks with other materials for co-pyrolysis offers the advantage of obtaining bio-products at much lower temperatures [29]. Among various source materials, the combination of face masks with biomass for conversion is viewed as a productive way to create more valuable end products [30]. Agricultural waste is often chosen for pyrolysis experiments due to its abundance. The high production of palm oil leads to substantial EFB waste [31], and such valuable products should not go to waste. This applies for rice husk and leaves as well. Although leaves can naturally decompose, optimising them as a valuable resource is a more sustainable approach due to their rich content.

Table 1 presents various feedstocks commonly used for pyrolysis within the biomass group, including those considered for this research. Sugarcane, wood chips, wheat straw, and bamboo [32–35] are compared to the feedstocks selected for this study, taking into account their calorific value and carbon content. In the case of face masks, their high calorific value may be attributed to the presence of several polymer materials. However, owing to the waste management challenges associated with face masks, they were chosen as a feedstock for this research.

Table 1. Feedstock Comparison.

Feedstocks	Calorific Value (kcal/kg)	Carbon Content (%)
Face Mask	9310	73.8
EFB	4113	43.3
Rice Husk	3411	35.8
Leaves	2955	31.8
Sugarcane	1969	58.28
Woodchip	3629	53.3
Wheat Straw	1808	46.2
Bamboo Leaves	4732	46.98

As for EFB and rice husk, these two materials are readily available in Malaysia, where the project is based, making them suitable choices. Malaysia is one of the largest producers of palm oil and rice, ensuring easy accessibility and abundance of these feedstocks. Leaves, on the other hand, are a common agricultural waste readily available worldwide. Despite their lower calorific value compared with face masks, EFB, wood chips, and bamboo, the choice is motivated by waste management issues. Selecting leaves aims to highlight their potential as an energy source due to their widespread availability and slow degradation. Bamboo is a high-calorific biomass source rich in carbon, but its limited abundance and waste management challenges, particularly in Malaysia, make it a less suitable choice. Wood chips have alternative applications, such as furniture production (e.g., plywood or pellets), which is why they are not the focus here. Environmental concerns, including deforestation for wood production, further discourage the use of wood chips. Throughout this project, substantial consideration is given to both environmental issues and economic aspects to guide the research effectively.

2.1. Feedstocks

Feedstocks are chosen in this study for several reasons. Considering environmental and economic factors, the selection is based on high availability and energy content.

2.1.1. Face Masks

Face masks have become a major waste issue during the COVID-19 outbreak. Even before the pandemic, disposable face masks were among the most highly accumulated medical waste. Recycling medical waste requires an efficient disposal method, and thermal transformation processes are the most effective approach after considering the potential constraints [36]. Co-pyrolysis offers a potential solution for the proper disposal of used face masks, preventing them from ending up in landfills or being improperly discarded. By converting face mask waste into valuable products through co-pyrolysis, environmental impacts can be minimised, promoting sustainable waste management practices.

The uniqueness of face masks lies in the composition of the materials. They are mostly made up of several plastics, such as polypropylene, often with fillers like polyester, polyurethane, polyamide, polyethylene, polystyrene, polyacrylonitrile, polycarbonate, and viscose fibre, with polypropylene having a high carbon content [37]. Referring to Table 1, their high carbon and calorific value make face masks a suitable feedstock. The calorific value can be converted into energy. With low moisture and oxygen content, face masks require much less heat energy for the combustion process, making them an attractive option.

Although processing face masks can be complicated, the initiative to use face masks is necessary due to the high waste volume despite COVID-19 being less prevalent nowadays [37]. Face masks still constitute a large portion of medical waste, and co-pyrolysis of face masks can lead to the recovery of valuable resources such as biochar, bio-oil, and bio-gas. These resources can be utilised for various purposes, including soil improvement, renewable energy generation, and biofuel or biochemical production.

2.1.2. Empty Fruit Bunch

Malaysia is a major producer of palm oil, and as a by-product of the palm oil industry, EFB is readily available in copious quantities. The abundance of EFB makes it a convenient and cost-effective feedstock for co-pyrolysis processes in the country. EFB has a high-energy content due to its lignocellulosic composition [38]. As such, it is a favourable biomass feedstock for co-pyrolysis, as it can contribute to the production of biochar, bio-oil, and syngas with significant energy potential. The utilisation of EFB in co-pyrolysis processes aligns with Malaysia's objective of producing more renewable energy sources and reducing its dependence on fossil fuels.

2.1.3. Rice Husk

Malaysia is a major producer of rice, and as a result, rice husk is available in massive quantities as an agricultural residue. This abundant supply makes rice husk a viable and cost-effective feedstock for co-pyrolysis processes in the country. Rice husk has a high silica content, which makes it a suitable candidate for co-pyrolysis [39]. The presence of silica acts as a catalyst or support material during the pyrolysis process, enhancing the production of valuable products such as biochar and bio-oil. Additionally, rice husk has a high calorific value, making it a desirable biomass feedstock for energy production in co-pyrolysis applications.

2.1.4. Leaves

Leaves are readily available in Malaysia, particularly in tropical regions with dense vegetation. As a common organic waste material, leaves can be easily collected, making them a convenient and accessible feedstock for co-pyrolysis processes. Leaves also pose a major waste management challenge when not properly disposed of. The challenges of using leaves are commonly due to their state of accumulating dirt and having to undergo thorough cleaning and grinding. The advantage of using leaves as feedstock is that they have high carbon and calorific value, which may contribute to potential energy [40]. Co-pyrolysis offers a sustainable solution by converting leaves into valuable by-products such as biochar, bio-oil, and bio-gas. This process not only reduces the environmental burden of leaf waste but also promotes resource recovery and contributes to sustainable waste management practices in Malaysia [9].

3. Slow Co-Pyrolysis as a Medium for Energy Production from Disposal of Face Masks and Agricultural Waste

Pyrolysis entails the controlled heating of biomass feedstocks, such as wood, agricultural residues, or energy crops, in an oxygen-free environment, resulting in the production of biochar, bio-oil, and syngas. Numerous research findings consistently demonstrate the effectiveness of biochar as a soil amendment. Its porous structure enhances soil fertility by improving water retention, reducing nutrient leaching, and promoting microbial activity. Additionally, the carbon sequestration potential of biochar contributes to long-term climate change mitigation [41].

The selection of these feedstocks for slow co-pyrolysis primarily stems from their compatibility with lower heating rates and temperature ranges. It was observed that subjecting the samples to higher temperatures above 450 °C [1] tends to result in ash formation. Therefore, slow pyrolysis is the most suitable method for processing these feedstock samples. This study focuses on biochar; therefore, maintaining the slow co-pyrolysis setting is desirable, as it enhances both the quantity and quality of biochar production whilst also yielding a significant amount of bio-oil [42]. The slow co-pyrolysis settings employed in this research are as follows: a maximum temperature of 400 °C, a heating rate of 5 °C per minute, and a nitrogen flowrate of 2 L/min. The average sample volume is 10–11 g and is manually mixed inside the crucible. The sieve size during grinding is set at 0.50 mm and the predetermined residence time is 30 min after reaching the target temperature. Residence time is crucial for stabilising the char [43]. After numerous tests, a residence time of 30 min was found to be optimal, as extending it beyond this time leads to the conversion of char into ashes.

Within the framework of co-pyrolysis, biochar is the solid, carbon-rich material produced when agricultural waste and used face masks are heated together in a low-oxygen atmosphere. This co-pyrolysis addresses two critical issues: maximising the utilisation of agricultural biomass waste and managing the increasing use of face masks due to the COVID-19 pandemic. In the context of the specific feedstocks used in this study, the primary emphasis is placed on the production of biochar. This choice is supported by strong evidence indicating that during slow pyrolysis, the production of char significantly surpasses that of bio-oil and bio-gas in terms of quantity. Additionally, biochar maintains a notable calorific value post-combustion, making it an attractive and sustainable resource for various energy applications.

The aim of co-pyrolysing these feedstocks is to produce biochar, a carbon-rich compound with potential uses in improving soil quality and sequestering carbon for use as a solid fuel. Biochar is a sustainable choice, as it repurposes waste materials to create a valuable end product that addresses various environmental and agricultural challenges. Biochar offers remarkable potential as a solid fuel due to its high-energy content, sustainability, and positive environmental impact. It efficiently generates heat for cooking and heating whilst also storing carbon, making it a carbon-negative option. Biochar combustion results in fewer emissions [44], making it an environmentally friendly choice. This versatile solid fuel can be used in various devices, and its local sourcing reduces transportation costs. Furthermore, the residual ash from biochar combustion enhances soil quality and agricultural output. Although the adoption of biochar as a solid fuel may vary, it aligns with environmentally friendly and sustainable energy practices.

The potential of bio-oil as a renewable fuel source is already well known and common in the industry. Its high energy density makes it suitable for heating and electricity generation, offering a sustainable alternative to conventional fossil fuels [45]. Moreover, the further refining of bio-oil will allow for the production of biofuels and biochemicals, addressing the need for cleaner and more sustainable alternatives. Bio-oil from the pyrolysis of various plastic waste, such as polyethylene or polypropylene, is reported to have calorific values of between 43% and 53%, respectively, whereas face masks, known for their higher calorific value, yield between 43% and 80% of bio-oil [46].

Bio-gas, a valuable by-product of pyrolysis, has been extensively studied for its versatility as a fuel source. It has shown promise in power generation through combustion in gas turbines or internal combustion engines. Additionally, bio-gas serves as a valuable feedstock for chemical synthesis, enabling the production of a diverse range of chemicals and fuels. The yield and compound identification in the sample are influenced by the heating temperature, heating rate, and mixture ratio [47]. However, co-pyrolysis produces fewer nitrogen oxides and sulphur oxides due to the inert environment in which the process takes place. This results in better quality and yield in the solid biochar and bio-oil processes [48].

The chosen method for slow co-pyrolysis involves the utilisation of the Carbolite Gero TG2 12/125/425, produced by Carbolite (Hope Valley, UK), which is a horizontal tube furnace, as depicted in Figure 1. This specific apparatus is selected due to its ability to operate over a broad temperature range, extending from as low as 30 °C to as high as 1200 °C [49]. This wide temperature range enables the execution of numerous tests aimed at determining the optimal temperature for feedstock combustion. The sample is placed within the horizontal tube, and the combustion testing is carried out according to predetermined settings. Upon completion of the testing, the apparatus is allowed to cool down until it reaches a temperature below 100 °C, at which point the biochar can be manually collected directly from the crucible. Subsequently, the biochar undergoes proximate and TGA analysis as a second step to ascertain the char yield, facilitating a comparison with raw samples. This comparative analysis is of paramount importance in the research, aiming to identify the most promising sample among the feedstocks and the ideal ratio with the highest char yield.

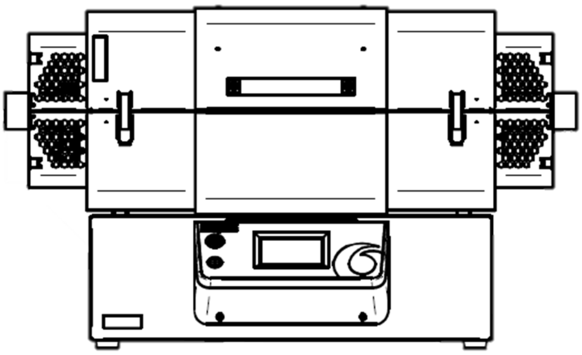

Figure 1. Carbolite Gero TG2 12/125/425 [49].

4. Design of Experiment

Figure 2 illustrates the methodology designed for this experiment. The process begins with the preparation of feedstocks, which involves blending biomass and face masks within a reactor. The feedstocks are subjected to grinding using a 0.5 mm sieve, and the average sample mass used for testing falls within the range of 10–11 g. Following this, the mixture is heated under an inert atmosphere within a temperature range of 250–400 °C [50]. The sample ratios are categorised as 25%, 50%, and 75% of face mask to 75%, 50% and 25% of biomass, as well as an exclusive 100% of all three types of biomass and 100% face mask [24]. The heating rate is set at 5 °C/min, with a constant nitrogen flow of 2 L/min to maintain an inert condition within the combustion chamber [51]. A dwelling duration of 30 min is observed after reaching the target temperature, as experiments have shown that a dwelling duration exceeding 30 min may result in the conversion of biochar into ash. The residence time plays a critical role as it aids in completing and further enhancing co-pyrolysis combustion [43].

The experimental properties are determined based on references from various research studies [24] and numerous trial-and-error runs conducted to identify the optimum temperature and heating rate for each sample. The processed samples remain within the chamber until they attain the appropriate operating temperature before they are collected and processed. This approach mitigates the risk of sudden temperature drops within the combustion tube. The co-pyrolysis experiments entail variations in the process parameters, including temperature, heating rate, and residence time, aimed at determining the optimal conditions for the thermal degradation of the feedstocks.

The subsequent steps involve subjecting the by-products to characterisation. The biochar produced in the experiments undergoes proximate and TGA analysis to determine the calorific value and yield of the samples. Characterisation also encompasses the analysis of the composition, heating value, viscosity, and density of the bio-oil. The experimental data are subject to statistical analysis to identify one final potential sample. When no significant improvements are noted in the yield, a re-evaluation of the parameters and a round of optimisation become necessary. In summary, the methodology for studying the co-pyrolysis of biomass with face mask waste entails a combination of experimental, analytical, and statistical techniques to optimise process parameters, evaluate product quality and yield, and assess the environmental and economic implications of the process.

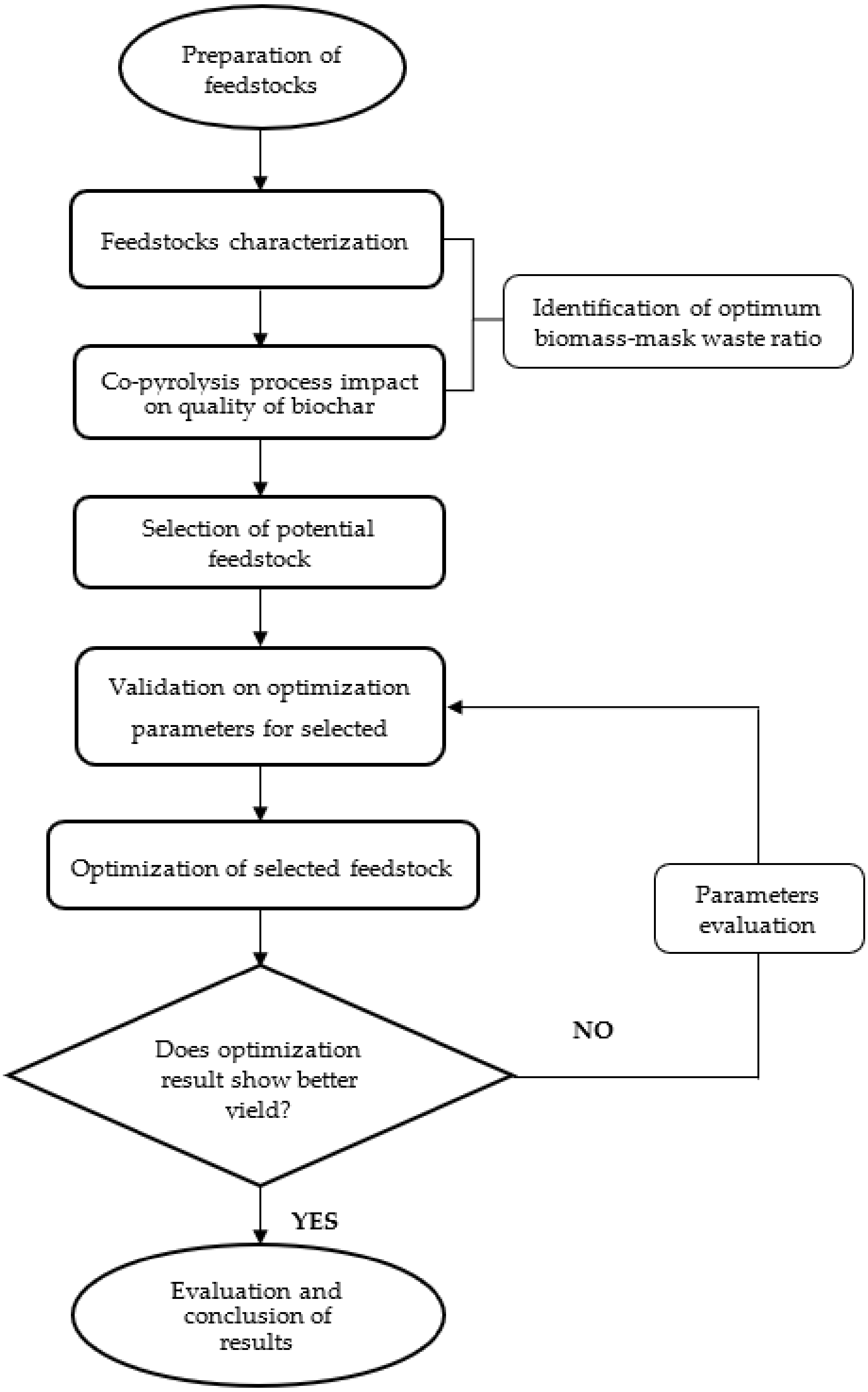

Figure 2. Flowchart of feedstock preparation.

5. Results

5.1. Ultimate and Proximate Analysis

Ultimate and proximate analysis are two crucial methods employed to characterise the composition of co-pyrolysis products. Ultimate analysis entails the determination of the elemental composition of the co-pyrolysis products, typically achieved through the combustion of a sample followed by a measurement of the resulting gases. This process furnishes information concerning the quantities of carbon, hydrogen, nitrogen, sulphur, and oxygen within the products. Proximate analysis provides data on moisture, ash, volatile matter, and fixed carbon in a material. These data are instrumental in evaluating the energy content and potential applications of co-pyrolysis products. Face mask analysis adheres to the ASTM E872-82 [52] and E1755-01 [53] standards [51]. For EFB, the ASTM E 1756-01 [54] standard is utilised [55]. In the case of rice husk and leaves, ASTM-D7582-15 [56] is used [57,58]. Table 2 presents the comprehensive results of the ultimate and proximate analysis conducted to ascertain the precise elemental content within the feedstocks.

Table 2. Ultimate, proximate analysis and calorific value results.

Analysis	Face Masks	EFB	Rice Husk	Leaves
Moisture Content (%)	0.10	11.9	11.7	31.7
Ash Content (%)	8.62	1.36	16.3	12.0
Volatile Matter (%)	91.3	72.2	58.0	45.7
Fixed Carbon (%)	<0.1	14.4	13.9	10.6
Carbon (%)	73.8	43.3	35.8	31.8
Hydrogen (%)	11.8	5.98	5.33	6.35
Nitrogen (%)	0.23	0.60	0.60	0.72
Oxygen (%)	14.2	50.1	58.2	61.0
Sulphur (%)	<0.01	0.03	0.05	0.21
Gross Calorific Value (kcal/kg)	9310	4113	3411	2955

5.1.1. Moisture Content

The moisture content of the sample is a crucial factor significantly influencing the material's strength properties. A low moisture content facilitates thorough combustion by reducing energy consumption during the combustion process and often lowering the heating rate during pyrolysis [59]. This absorbed moisture plays a role in creating binding forces between the particles by occupying available spaces between the biomass particles. Figure 3 illustrates that leaves have the highest moisture content at 31.7%, whereas EFB and rice husk have moisture contents of 11.9% and 11.7%, respectively, owing to their origins as agricultural residues. Face masks, due to their component materials, are expected to exhibit the lowest moisture content. Although the initial moisture content of the biomass particles was maintained at an optimised level, the samples remained prone to absorbing moisture during feedstock preparation.

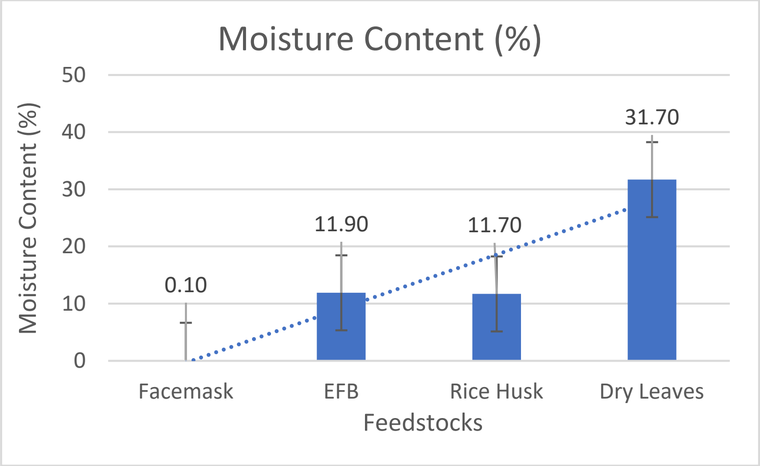

Figure 3. Moisture content.

5.1.2. Volatile Matter

Face masks contain synthetic materials that are highly flammable, enabling them to release numerous gases when subjected to heat. As depicted in Figure 4, face masks exhibit a volatile matter content of 91.3%. EFB demonstrates a substantial amount at 72.2%, whereas rice husk possesses 58%, and leaves contain 45.7% of combustible materials, rendering them suitable for applications such as biomass combustion or bioenergy production. Volatile matter refers to the flammable substances within a material that can transform into gases when exposed to heat. This percentage indicates how much of a material's weight will transition into gas during heating [60,61]. Materials with higher volatile matter content hold greater energy potential and can serve as valuable sources of renewable energy, whereas those with lower volatile matter content may find diverse uses, such as composting or mulching.

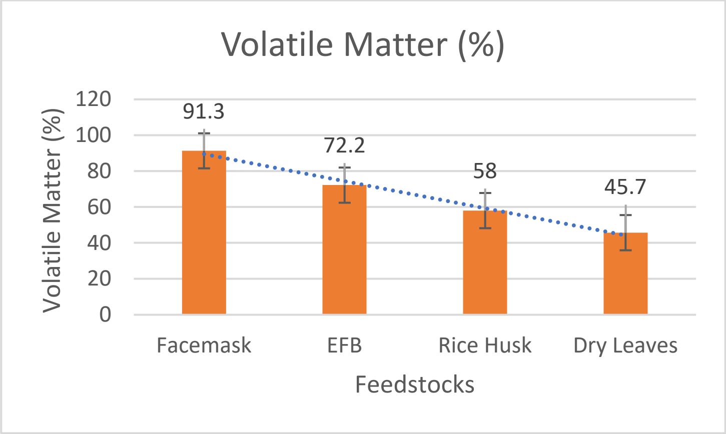

Figure 4. Volatile matter.

5.1.3. Ash Content

Ash content, the least desirable by-product arising from combustion, represents a non-combustible residue left behind after the combustion process. This residue, known as ash, comprises inorganic elements such as phosphorus, silicon, calcium, potassium, and chlorine [61]. After burning the face masks, approximately 8.62% of their weight remains as inorganic ash. This higher percentage may be attributed to the presence of additives or synthetic materials in the masks. EFB leaves behind only 1.36% ash after combustion, indicating a lower quantity of inorganic residue. This characteristic makes it suitable for biomass energy production, as it leads to cleaner combustion. Rice husk exhibits an ash content of 16.3%, whereas leaves exhibit 12.0% ash after combustion.

5.1.4. Fixed Carbon

For fixed carbon, face masks contain an insignificant amount of solid carbon (<0.1%), as they are primarily composed of non-carbon materials such as synthetic polymers. EFB contains a considerable portion of solid carbon (14.4%), whereas rice husk also contains a significant amount of solid carbon (13.9%). Leaves exhibit a fixed carbon content of 10.6%. Fixed carbon content is a critical factor in evaluating the energy potential and applicability of these materials in different industries. Fixed carbon refers to the stable carbonaceous material remaining within a substance after the removal of volatile matter and ash during combustion [62]. It represents the carbon component that remains in solid form during heating. Higher fixed carbon content indicates better energy yields during combustion or conversion processes, whereas lower levels may lead to alternative uses, such as in agriculture or composting.

5.2. Ultimate Analysis

Figure 5 shows that face masks possess a high carbon content of 73.8%. This observation suggests that a significant proportion of the mask's weight comprises carbon, commonly found in synthetic materials like polypropylene or polyethylene. EFB contains a carbon content of 43.3%, whereas rice husk contains 35.8% carbon, with leaves exhibiting the lowest carbon content of 31.8%. Carbon content is a critical factor for assessing energy potential. Materials with higher carbon content typically yield more energy during combustion [21]. The hydrogen, nitrogen, and sulphur content in these samples is relatively low. The low hydrogen content implies that the samples produce less heat energy, but this can be balanced with oxygen levels [23].

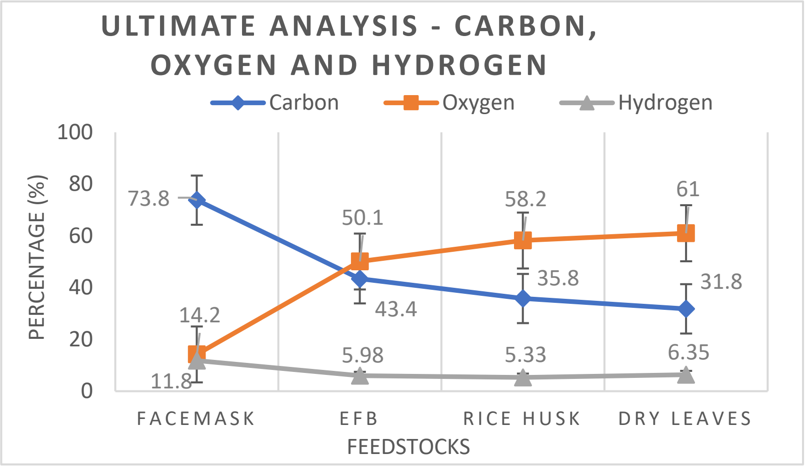

Figure 5. Carbon, Oxygen, and Hydrogen.

Materials with low nitrogen and sulphur content have only minimal amounts of these elements, which is advantageous for energy production as it reduces harmful emissions and environmental impacts. Concerning oxygen levels, face masks exhibit the lowest value at 14.2%, whereas EFB has a high oxygen content of 50.1%, followed by rice husk at 58.2%, and leaves at 61.0%. The higher oxygen content in the biomass samples may be attributed to their origin from agricultural residue, which often contains cellulose and hemicellulose. Having high oxygen content in biomass materials is beneficial, as it leads to clean combustion and reduces harmful emissions like carbon monoxide and soot [63].

5.3. Calorific Value

Calorific value, also known as the heating value, denotes the amount of heat energy released when a specific quantity of a substance undergoes complete combustion. It is measured in kcal/kg and plays an important role in evaluating the energy content of unconventional materials. As indicated in Figure 6, face masks exhibit a high calorific value of 9310 kcal/kg, indicating a substantial energy content, making them a potentially valuable energy source. EFB demonstrates a moderate calorific value of 4113 kcal/kg, rendering it a suitable option for energy generation, especially given its abundant availability as a by-product of the palm oil industry.

The calorific value of rice husk is 3411 kcal/kg, whereas leaves have a calorific value of 2955 kcal/kg, offering a reasonable energy content and making them a practical choice as a renewable energy source through combustion or gasification techniques. Higher calorific values in materials render them more favourable for energy production, as they provide greater heat energy per unit [62]. This knowledge facilitates the optimised selection and utilisation of materials for specific energy applications, promoting efficient resource management. A higher calorific value results in a stronger energy release during combustion [63]. For example, the face mask boasts the highest calorific value at 9310 kcal/kg, surpassing EFB, rice husk, and leaves, thereby potentially offering the most significant energy output.

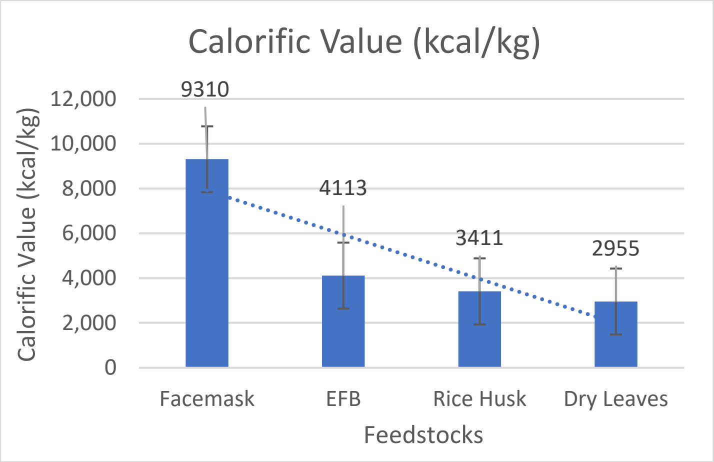

Figure 6. Calorific value.

5.4. Biochar Yield Results

Biochar yield, which is the amount of biochar produced through the pyrolysis process, is a critical parameter often associated with the carbonisation of organic materials. Biochar production is usually quantified in terms of weight or volume. Factors such as the type of biomass used, pyrolysis conditions, and the equipment employed can influence the actual quantity generated. Analysing biochar yield is pivotal for assessing the effectiveness and success of biochar production. Biochar yield is computed using the formula:

$$\text{Biochar yield }(\%) = \left[\frac{\text{Weight of biochar}}{\text{Weight of total feedstocks}}\right] \times 100$$

Table 3 presents the results of biochar yield from samples subjected to co-pyrolysis. The outcome for leaves with a face mask biochar is noteworthy, indicating the potential effectiveness of the co-pyrolysis method in achieving a substantial biochar yield. The absence of results for EFB with a face mask and rice husk with a face mask is a matter for future research. Table 3 underscores how well the process transforms the starting materials into biochar, demonstrating its practical and efficient use in biomass.

Table 3. Biochar yield results.

Feedstocks	Biochar Yield (%)
Face Mask	27.08 [64]
EFB	34.27 [65]
EFB + Face Mask	-
Rice Husk	33.07 [66]
Rice Husk + Face Mask	-
Leaves	32.87 [9]
Leaves + Face Mask	40.20 [9]

Table 4 outlines the roadmap for the future phases of this study, delineating the anticipated outcomes. These projections are based on insights from prior research in the field, supported by logical analytical calculations and sound assumptions. The expected values were derived from the lowest and highest yield results obtained from various research efforts. This table serves as a guide for the upcoming work, providing direction towards an in-depth understanding of the subject matter.

Table 4. Expected biochar yield results.

Feedstocks	Biochar Yield (%)
Face Mask	25–35
EFB	28–38
Rice Husk	30–43
Leaves	28–38
Leaves + Face Mask	30–45

6. Conclusions

The results were meticulously examined, and a comprehensive evaluation of the selected samples for both biomass and plastic materials was conducted. This study primarily focused on the comparison of feedstock samples for the production of biochar through the co-pyrolysis process, both individually and in combination. The paper draws upon existing research and proposes an alternative approach to generate solid fuel for energy from waste management processes. Given the considerable amount of agricultural waste globally, co-pyrolysis holds significant potential for further development and could make a substantial impact in addressing the issue of environmental waste pollution.

The findings have unveiled the elemental composition of certain samples in terms of percentage, assisting in determining the most suitable composition for use in the co-pyrolysis process. Regarding ultimate carbon analysis, face masks exhibit over 70% carbon content when compared with EFB. Notably, face masks also boast a calorific value exceeding 126% when compared with the second highest, which was EFB. The pivotal benchmark here is the calorific value, as face masks display a calorific value twice as high as other feedstocks. This implies that face mask raw samples can potentially contribute more energy during combustion and may result in a higher energy content in biochar, a crucial factor for achieving an enhanced biochar yield.

In addition to their low moisture content, face masks offer significant potential as a feedstock for energy compared with other feedstocks. With the right ratios of feedstocks and heating rates, they ensure a higher yield of char. Furthermore, the synergy achieved by combining these two distinct materials may lead to an improved quality and yield of oil and char. The biochar yield results demonstrate that the hybrid biochar of leaves with a face mask exhibits a higher yield at 40.20% compared with the second-highest yield of EFB at 34.27%. This finding underscores the potential for an enhanced biochar yield through the synergy of combining face masks with agricultural waste. However, much research needs to be conducted because of the lack of results for rice husk with a face mask and EFB with a face mask.

Currently, scientific laboratories worldwide are actively engaged in developing innovative technologies and conducting studies to further enhance the quality of bio-products. This paper also discusses pilot-scale studies previously reported in the academic literature, emphasising the need for additional research to achieve the best results and optimal outcomes. There is a crucial need to delve deeper into the dynamics of the reactions, as they play a pivotal role in obtaining the desired output and ensuring the efficient operation of the co-pyrolysis process.

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