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Feasibility of Bio-Coal Production from Hydrothermal Carbonization (HTC) Technology Using Food Waste in Malaysia

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Abstract: The alarming rise of food waste all over the world due to population and economic growth must be tackled with better waste management and treatment methods. The current practice of landfilling has been scientifically proven to adversely impact environmental and societal health. A relatively new technology called hydrothermal carbonization (HTC) has the potential to solve this problem. It takes in high-moisture-content material, like food waste, and converts it into bio-coal with a heating value similar to normal coal. The present study explored the feasibility of HTC technology and bio-coal production in Malaysia. An in-depth study via desk research was conducted by implementing Porter's five forces analysis to evaluate the feasibility of the bio-coal production project. A survey involving 215 respondents from different households that represent the average demography of Malaysia was also conducted to understand the behaviors and attitudes of different households towards food waste. The present study found that a typical Malaysian household disposes mostly of meal leftovers, with an average of 926 g of food waste per day. In addition, the 3 highest food categories that were disposed of were rice or noodles or pasta (13.0%), vegetables (12.2%) and curry and soup (10.1%). Meal leftovers such as curry and soup are high in moisture content, which is suitable for HTC. The survey on household waste provided adequate information to support the availability of a sufficient quantity of food waste in the country to sustain the raw material for the bio-coal project in Malaysia. Furthermore, a consumer survey involving seven industrial firms was conducted to determine the potential buyers of bio-coal. The responses from the industrial firms show that a bio-alternative for coal is important, and they are willing to transition to greener technologies. However, five out of seven firms stated that the main hurdle in adopting bio-coal is the high cost of production and incompatibility with existing industrial processes. Finally, interviews were conducted with key players in the industry to evaluate the adoptability of bio-coal into the wider market. The findings from the desk research and the primary research show that the outlook for bio-coal in the market is quite positive. In the long run, HTC is certainly profitable, but for immediate benefits, adequate government support and policy in favour of the use of HTC bio-coal in power plants are required.

Keywords: HTC; food waste; bio-coal; market feasibility

1. Introduction

Malaysia has experienced rapid urbanization, economic and population growth in recent years. Even though the growth brings Malaysia closer to the goal of becoming a developed country, it does leave a very worrisome problem of waste and waste management to society and its impact on the environment. One of the major waste management companies in Malaysia, SWCorp, estimated that Malaysia produced 17,000 tonnes of waste per day in 2020, which is equivalent to 6.205 million tonnes per year. In addition, about one-third of waste is food, which was estimated to be at least 2.761 million tonnes per annum across the country [1].

Food waste can be defined as edible food products for human consumption left uneaten, either lost or disposed of along the food supply chain from production to the consumer end. Food waste is also often called biowaste or kitchen waste [2]. Food waste not only negatively affects the availability of food for others but can also adversely affect the environment if not managed and treated properly. Thus, efforts to reduce food waste along the food supply chain must be paired with better food waste treatment and management methods.

In the Eleventh Malaysia Plan (MP 11) for 2016−2020, the government revisited the Solid Waste and Public Cleansing Management Act 2007 (Act 672) to strengthen the institutional framework and reinforce coordination among relevant ministries and agencies. As stated in the MP 11, the government's target was to achieve a 22% recycling rate among households in Malaysia before 2020. However, the recycling rate has remained low (22%), with the remaining 53.2% of waste ending up in unsanitary landfills [3]. Landfills generate huge amounts of greenhouse gases (i.e., carbon dioxide (CO_2); methane (CH_4); nitrous oxide (N_2O)), heavy metals, and toxic leachates that collectively contribute to global warming [4]. Furthermore, a report by the National Solid Waste Management Department shows that out of 176 landfills in operation, about 65% had been shut down based on sanitary inadequacy [5]. Coupled with rapid urban area expansion, reports show that Malaysian communities are not willing to accept the operation of new landfill sites near their residence, citing health risks associated with the sites [6]. Therefore, alternative novel solutions to food waste management are required. Hydrothermal carbonization (HTC) could be the answer to the waste management problem. It is an energy-efficient process to produce a high-energy bio-coal that burns clean and takes a few hours to produce [2,7,8].

Hydrothermal carbonization (HTC) is a thermo-chemical process that has received increasing attention. It accepts high-moisture biomass, which does not require an additional drying process prior to feeding, as raw materials. Besides, HTC requires lower energy intensity than other thermochemical processes such as gasification and liquefaction because it is usually operated at a relatively low-temperature range of 200−225 °C. In addition, operating in this low-temperature range eliminates safety concerns significantly [9].

The HTC process consists of a series of concurring reactions, namely hydrolysis, dehydration, decarboxylation, polymerization, and aromatization reactions [10]. As a result, the wet feedstock is converted into value-added solid and liquid forms. The solid is known as either bio-coal or hydrochar, and it has the potential to replace normal coal for power generation, as its heating value is very similar to normal coal [11]. Hence, HTC could potentially solve the food waste problem because food waste normally contains high moisture. Even though HTC has been experimented with and practiced in many other countries, Malaysia has yet to set up its first HTC plant, specifically for treating food waste. As HTC is considered a new technology in Malaysia, detailed process intensification and integration are needed to improve the limited industrial batch scale HTC process to improve the economic and environmental benefits of the HTC process. Hence, this study investigated the feasibility of the possible utilization of bio-coal by consumers in Malaysia. Potential consumers of bio-coal in the industry were surveyed to understand their willingness to adopt/transition from the current practice to bio-coal. In addition to the adoption of bio-coal as an alternative to normal coal, the present study evaluated the availability of raw material to ensure continuous supply and the viability of the HTC project. The present study also evaluated the amount of food waste produced by common Malaysian households and explored their attitudes and behaviours towards food waste and their willingness to adopt new methods of waste management and utilization.

2. Methodology

This section covers the market feasibility of the bio-coal product produced via HTC technology. The market feasibility section takes a wider view by examining direct and indirect stakeholders in the bio-coal market in the country via an industry analysis and by focusing on food waste quantity and composition, followed by an in-depth understanding of potential consumers in terms of the adoption of bio-coal. The present study utilized Porter's five forces model, which analyses the industry and direct stakeholders (or competitive forces) that impact the industry performance and entry of a new product, which in this instance is bio-coal made from food waste [12–14].

2.1. Porter's Five Forces Analysis Model

The sustainability of a pioneer project in an established industry is dependent on multiple factors such as competition from rivals, profitability and consumer sentiment. Desk research via Porter's five forces analysis model was employed to carry out an in-depth analysis of the current position of the bio-coal industry in the Malaysian market. Porter's five forces analysis (developed by Michael Porter in 1980) represents a model of competitive strategy to indicate the position of an industry in a complex and competitive environment [15]. The five forces of the model include the threat of new entrants, threat of substitutes, bargaining power of suppliers, bargaining power of customers and rivalry among existing firms [16]. Figure 1 below represents the general framework of Porter's five forces analysis. Supplier bargaining power provides an assessment of how easily the suppliers can drive the prices up. This may depend on the quantity of suppliers available in the market, the uniqueness of the service provided by the suppliers, the market capitalization of the supplier and the cost of switching between suppliers. Customer bargaining power is an assessment of how effectively the buyers can cause the drop in prices. This depends on the number of buyers available in the market, the significance of each individual buyer to the supplier and the cost of customers to switch between available suppliers. For example, if the business had only a select number of powerful customers, they would be able to dictate the terms of purchase. Internal rivalry is dependent on how well the organization can thrive amidst the capability of existing competitors. The threat of substitutes happens when there are better alternatives in the market; this causes consumers to switch due to an increase in prices. This will affect the attractiveness of the market and the supplier's bargaining power significantly. In a new highly profitable market, new entrants may emerge to capitalize on the profitability of the market. The emergence of entrants will be affected by the scale of capital required, government regulations, etc. By evaluating these five forces, the potential of the HTC bio-coal production project to thrive in the market may be evaluated.

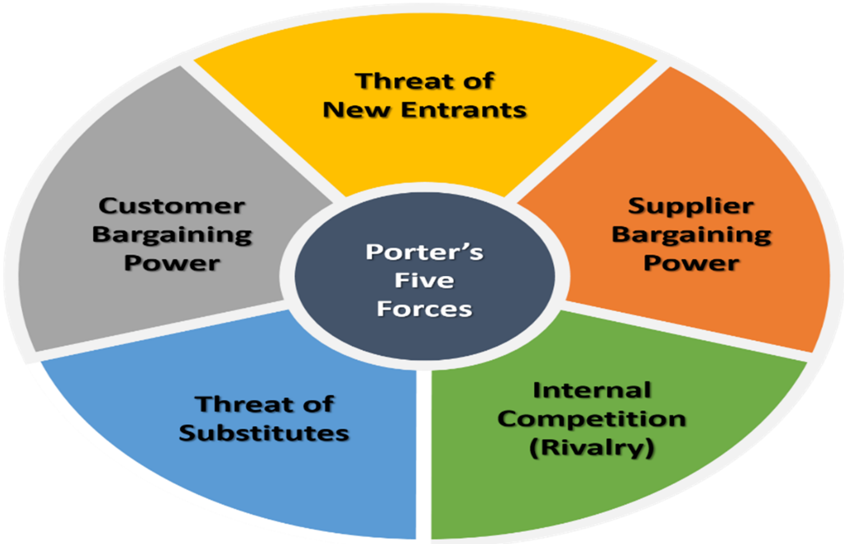


Figure 1. Five forces of Porter's analysis model [16].

2.2. Data Sources, Sampling Method and Survey Design

To evaluate the potential of HTC being adopted as a feasible solution to convert food waste into bio-coal, it is important to understand the sentiment of the general food consumer towards the disposal of leftover food. As Malaysian households consist of various ethnic groups, the amount and type of food waste disposed of may vary significantly depending on the population. Hence, it is important to obtain a group of respondents that reflect the general population of Malaysia.

A survey was conducted to understand households' behaviors and attitudes towards waste products, as well as the types, composition, and quantity of household food waste they produced. The survey was conducted via convenience sampling using the snowballing method [12]. Convenience sampling is a type of non-probability sampling method where individuals from the target population who meet specific criteria are included to participate in the study [12]. On the other hand, snowball sampling is used when it is difficult to access the subjects with target criteria. The existing subjects will recruit new subjects among their networks [13]. A web-based self-reported questionnaire was created and designed in the form of Google forms. A uniform resource locator (URL) of the Google form containing the questionnaire was sent to the first batch of participants, who were chosen through convenience sampling, and they were asked to send the URL to their friends and acquaintances who also met the target characteristics. The data were collected for two months, from June to July 2020. In this research, people who lived in Malaysia and regarded themselves as being responsible for making calls in purchasing food, preparation, storage and disposal were chosen and invited to involve in the survey.

The questions or information asked in the survey included household demographics, type and quantity of food waste, thoughts on the food waste, separation of discarded food, availability of a food waste management facility near their household, and willingness to separate food waste if it would be used to generate electricity. The questions were rated on a five-point Likert scale, for which the value of the continuous variables represented the respondent's attitudes and opinions [14]. In this survey, 1 represented "strongly disagree", while 5 represented "strongly agree".

Additionally, a survey of industries was conducted using the same method as the household survey. A web-based questionnaire was developed and sent to the potential consumers of bio-coal. The aim of this industry survey was to identify potential consumers or markets for bio-coal and to establish the main factors that could lead to or hinder the adoption of bio-coal.

Finally, expert interviews were conducted with key industrial players. The interviews were semi-structured, where guide questions were posted and followed by additional questions based on the responses from the respondents.

2.3. Statistical Analysis

Data from the Google Forms survey were retrieved from the Google Sheets interface and saved in the comma-separated values (.CSV) format. Data were analyzed using SPSS 26 software. Data coding was carried out directly in SPSS 26 software by arranging the questions in the column of the spreadsheet and arranging the 215 respondents in the subsequent rows. Simple descriptive statistics (frequencies, mean, median, mode), where relevant to describe behaviours and gauge disposal patterns, were obtained.

2.4. Case Study of Existing Waste Treatment Methods

In Malaysia, food waste is considered a part of municipal solid waste (MSW). Waste management in Malaysia is handled by private sectors under the purview of the government [2]. Throughout the years, many methods (see Table 1) have been used to treat MSW, but conventional landfills or open dumping areas are the most prevalent because the tipping fees for landfills are relatively low and one faces no technical challenge in dumping MSW in landfills. Practicing landfilling brings a number of adverse impacts on the environment, including surface and groundwater contamination through leachate, the spread of diseases by different vectors, odours, and many more problems. Besides, the food waste undergoes biological degradation at the open dumping areas, producing a mixture of greenhouse gases consisting of methane and carbon dioxide. On top of that, the service of waste collection only covers about 66% of the population in rural areas, causing waste to be dumped directly on the streets or in the drains [7]. Throughout the years, Malaysia has tried to integrate different methods in waste management, as shown in Table 1.

Table 1. Existing waste management methods in Malaysia [7].

Treatment Method	Percentage of Waste Disposed (%)		
	2002	**2006**	**2020**
Recycling	5.0	5.5	22.0
Composting	0.0	1.0	8.0
Incineration	0.0	0.0	16.8
Inert landfill	0.0	3.2	9.1
Sanitary landfill	5.0	30.9	44.1
Other disposal sites	90.0	59.4	0.0

Since the landfills are not environmentally friendly, many other food valorization methods have been studied, such as composting, anaerobic digestion, and thermochemical processes. Each of them has their own advantages and limitations. In Malaysia, composting and anaerobic digestion have been practiced in recent years, and the number of applications is gradually increasing every year. However, thermochemical processes receive relatively less attention. This is mainly due to the high moisture content in food waste, as thermochemical processes such as pyrolysis and gasification prefer dry feedstock [8]. Hence, the adoption of HTC is a step forward in waste management, as an increasing amount of food waste produced is suitable as raw material.

3. Results

3.1. Porter's Five Forces Analysis

Based on the desk research conducted, the competition among existing firms is considered low. This is owing to the fact that there are no direct competitors for the bio-coal project. Currently, there is no waste to energy (WTE) facility in Malaysia which utilizes HTC technology to convert municipal solid waste, particularly food waste, into bio-coal. The country mainly relies on sanitary landfills and incineration plants [17]. Even though the Housing and Local Government Ministry plans to set up six more WTE facilities by 2025, none of them utilize HTC technology. Additionally, the progress on this endeavor has been delayed significantly due to the COVID-19 pandemic and movement restriction order [18]. Thus, this bio-coal project can be categorized as a new industry in Malaysia with no direct competitors, and it brings first-mover advantage in gaining customers and leapfrogging other potential competitors in establishing a foothold in the market.

The threat of new entrants in this industry is moderate to high. This is mainly due to global pressures and government initiatives on the use of renewable energy sources to reduce carbon footprints. Malaysia has agreed and pledged to decrease its greenhouse gas emissions intensity of gross domestic product (GDP) by 45% by 2030 relative to 2005 [19]. Besides Malaysia, there are 196 more countries participating in the well-known Paris Agreement, which aims to reduce greenhouse gas emission and keep the global temperature increase at not more than 2 °C relative to preindustrial levels [20]. However, as mentioned before, the COVID-19 pandemic has delayed the progress as well as reduced or delayed private investment in this industry, which eventually prevents the entry of new entrants into this industry. Thus, it is a positive factor for the current bio-coal project to position itself firmly as a pioneer among other renewable energy efforts because new entrants are not expected to grow significantly soon, as they all are still in the planning stage now.

Next, the key substitutes for bio-coal are solar energy or photovoltaic energy, agricultural waste, biogas and hydropower. The threat of substitute products is only limited to the energy generation industry, as it is the largest and main consumer of coal in Malaysia. Figure 2 shows the annual electricity generation from renewable energy in Malaysia. Even though the main renewable energy source in Malaysia is solar energy, and solid waste constitutes only a very small part of it, the industry is moving in a positive direction as the country starts to embark on different kinds of renewable energy sources. As can be observed from the chart, the power generation of other renewable energy resources is gradually increasing and catching up with solar PV [21].

The following force is the bargaining power of suppliers. In this context, the supplier simply means waste collection companies as they collect food waste from households, restaurants, hotels and many more locations and send this waste to the waste management facility. Waste collection in the target area of Putrajaya is handled by two companies, namely SWCorp and Alam Flora, which in turn are under the Ministry of Housing and Local Government. Thus, the bargaining power of suppliers is considered moderate to high, as they can directly affect the performance of the project with the supply of food waste. Recently, SWCorp has agreed to be involved in this bio-coal project, which indicates the project is moving in a positive direction, as the supply of raw materials is almost guaranteed. Further engagement with the ministry and Alam Flora is anticipated. Furthermore, the facility is recommended to be built close to the collection areas to save transportation costs.

The last and final force of the bargaining power of buyers is considered high as well because coal is highly required in various major industries, especially the power generation industry. The electricity industry consists of major power generation companies such as Tenaga Nasional Berhad (TNB) and Sarawak Energy (SE), who are independent power generators and produce renewable energy [22]. TNB generates and distributes electricity throughout Penisular Malaysia and the state of Sabah, while SE handles the state of Sarawak. Other industries which greatly utilize coal are the cement, steel and aluminum industries. A modern cement plant consumes about 110 to 120 kWh per ton of cement, which is highly energy-intensive [23]. In addition, cement production in Malaysia has risen from around

20 million tons in 2011 to 40.2 million tons in 2017 [23,24]. Currently, there are 8 cement manufacturers with 18 plants across the nation. Regarding the steel industry, there were 12 manufacturers with 18 plants located all around the country, with an average annual production capacity of 15.6 million tons [24]. It is obvious that these industries are huge in Malaysia, and their adoption of bio-coal will directly impact the market feasibility of the bio-coal project.

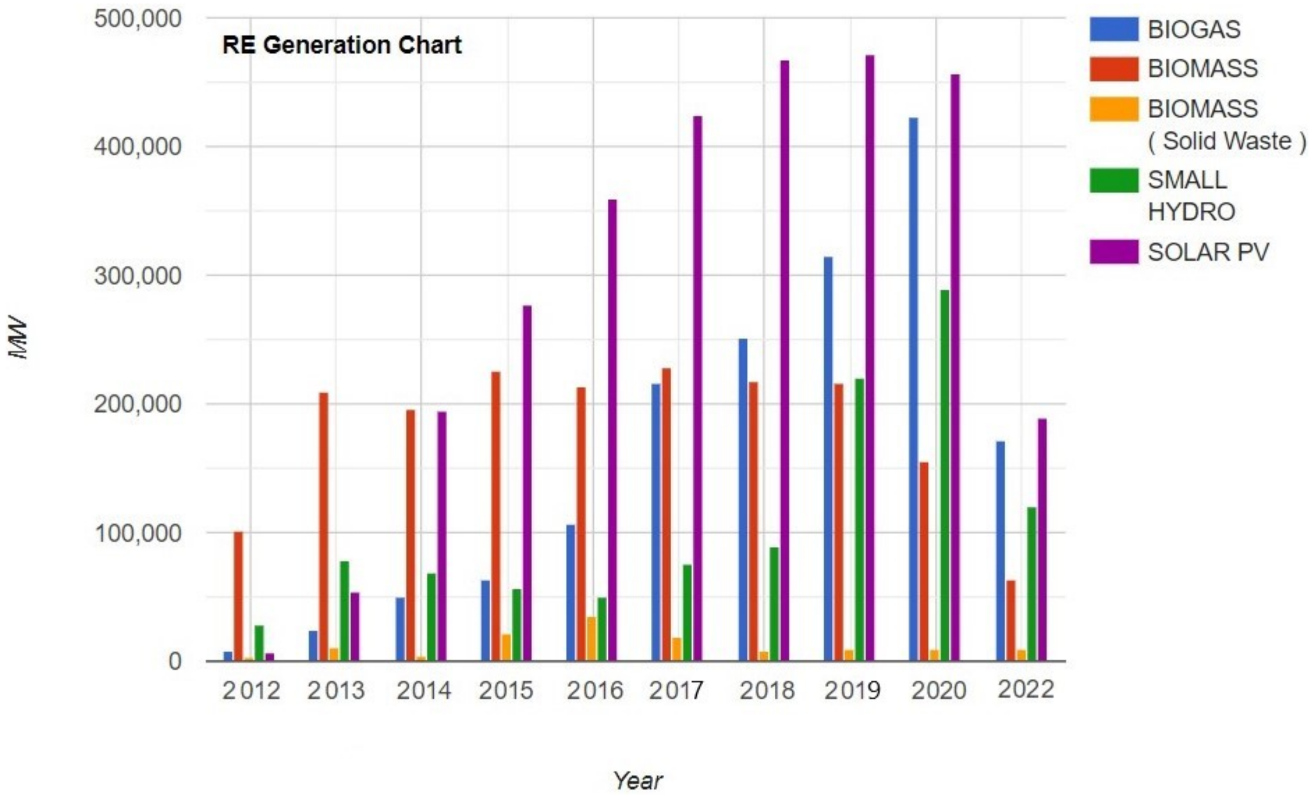


Figure 2. Annual power generation capacity of various renewable energy sources in Malaysia [21].

It is important to note that the influence of policies by indirect stakeholders such as the government and regulatory bodies may arguably act as an additional force in Porter's five forces analysis for many industries. Malaysia's participation in the Paris Agreement 2015 under the United Nations Framework Convention on Climate Change (UNFCCC) resulted in the establishment of several organizations, acts, and policies to support and encourage the development of renewable energy resources in the country. Malaysia also aims to increase renewable energy in its energy generation mix to 20% by the year 2025 [25].

There are several regulatory bodies and authorities taking care of the renewable energy industry in Malaysia, including the Ministry of Science, Technology and Innovation (MOSTI) [25]. Furthermore, the Sustainable Energy Development Authority Malaysia (SEDA) is a statutory body established under the SEDA Act of 2011 to promote the development of renewable energy and to administer and monitor the Feed-in Tariff (FiT) programme in the country [26]. The energy sector in Malaysia is mainly regulated by the Energy Commission, which was established under the Energy Commission Act of 2001. It aims to provide a reliable electricity and gas supply to the people in Peninsular Malaysia and Sabah state at reasonable costs and safety. It has three main roles, which are economic regulation, technical regulation and safety regulation [27].

Apart from bodies and authorities, several legislations have been established to govern the renewable energy industry in Malaysia. In 2011, the Renewable Energy Act was established to implement and regulate the FiT scheme, which incentivizes renewable energy generation projects with capacities of up to 30 megawatts. Besides, the Electricity Supply Act (Amendment) of 2015 and the Energy Commission Act of 2001 regulate renewable energy matters regarding safety, implementation and technical aspects [28]. The SEDA Act was also established in 2011 to aid in the establishment of SEDA and to carry out its roles and functions [25].

Various policies have introduced by the government to stimulate the growth of the renewable energy industry in Malaysia. Among them, the National Renewable Energy Policy (NREP) is the most popular one. Table 2 shows the objectives and vision of the policy.

Table 2. The objectives and vision of NREP [21].

Objective	Vision
To facilitate the growth of the renewable energy industry	To achieve a 20% renewable energy capacity mix by 2025
To ensure reasonable renewable energy generation costs	
To increase renewable energy in the national power generation mix	
To conserve the environment	
To enhance the awareness and importance of renewable energy	

Furthermore, a roadmap called the Renewable Energy Transition Roadmap (RETR) 2035 is being developed by SEDA alongside industry stakeholders to outline strategies and plans to meet the renewable energy targets and policies in Malaysia. The roadmap will form a big part of the 12th Malaysian Plan (2021–2025), which further proves the determination of the government to encourage the use of renewable energy in the country [25]. Moreover, the National Green Technology Policy (NGTP) was launched in July 2009 to act as a driver to promote the sustainable development of renewable energy and accelerate the country's economy [29]. In other words, it integrates various factors such as environment, energy, economy and social aspects in order to achieve sustainable growth and development [26].

Apart from renewable energy legislation and policies, the government's regulations on food waste collection will also affect the performance of the bio-coal project. As mentioned before, the collection of waste in the district of Putrajaya is handled by SWCorp and Alam Flora under the purview of the Ministry of Housing and Local Government. The actions of waste collection are placed under the Solid Waste and Public Cleansing Management Act of 2007. The act aims to regulate the management of solid waste and public cleansing in order to maintain proper sanitation [30]. Unfortunately, there was no legislation specifically established for food waste management until 2010, when the Malaysia Government collaborated with the Ministry of the Environment of Japan (MOEJ) to develop a National Strategic Plan for Food Waste Management in Malaysia. The plan focuses on the 3Rs (reduce, reuse, and recycle) [31]. It consists of six strategies and outlines the roles of different players along the whole food supply chain, including food waste segregation and good food disposal habits, as shown in Figure 3 [32]. Furthermore, under the act, households have been required to separate their food waste from other wastes since September 2015; however, this has not been a success [32]. Nonetheless, the government has demonstrated great efforts and is continuously promoting and encouraging food waste segregation. The inclusion of SWCorp in the project also secures a food waste supply for the facility.

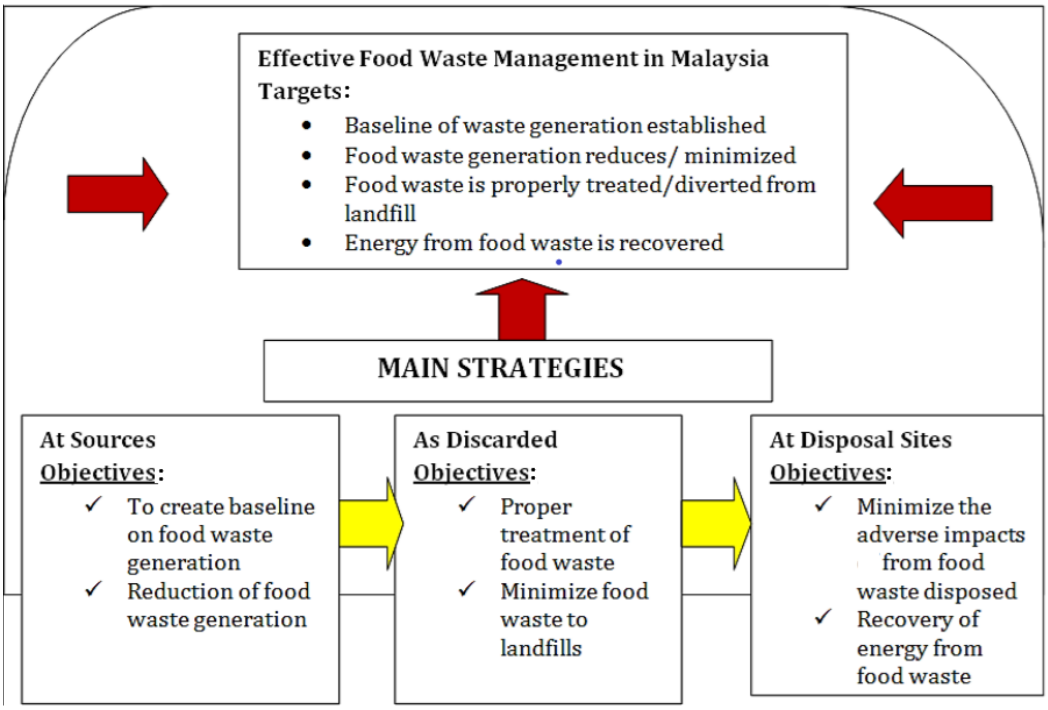


Figure 3. The National Strategic Plan for Food Waste Management in Malaysia [31].

3.2. Survey Results of Household Attitudes and Behaviours towards Food Waste

The study of households' attitudes and behaviors towards waste products plays a very vital role in the market feasibility analysis, as the project highly requires cooperation from households. A total of 215 households provided responses to the survey, and the data were analyzed using descriptive analysis. Table 3 summarizes the demography of the respondents in the study.

Table 3. Demography of the respondents in this study.

	Parameter	Attribute	Frequency	Mass Percentage (%)
1.	Gender	Male	95	44.2
		Female	117	54.4
		Prefer not to say	3	1.4
2.	Ethnicity	Malay	94	44.1
		Chinese	71	33.3
		Indian	36	16.9
		Others	12	5.6
3.	Age group	Less than 20	30	14.0
		21–30	51	23.7
		31–40	61	28.4
		41–50	38	17.7
		51–60	26	12.1
		More than 61	9	4.2
4.	Highest level of education	Secondary	28	13.1
		Diploma	23	10.7
		Bachelors	87	40.7
		Masters and above	76	35.5

Table 3. *Cont.*

	Parameter	Attribute	Frequency	Mass Percentage (%)
5.	Monthly household income	2500 and below	31	14.6
		2501–5000	43	20.3
		5001–10,000	66	31.1
		10,001–15,000	33	15.6
		15,001 and above	39	18.4
6.	Residential area type	Urban	119	55.6
		Suburban	82	38.3
		Rural	13	6.1

There were 95 males and 117 females who participated in this study. The highest number of participants were Malay, followed by Chinese, Indian and other ethnicities. In comparing the age groups, the respondents were relatively diversified, with most of them from the age group of 31 to 40 years old. Most of the participants achieved a bachelor's degree, and more than 50% of the respondents were living in urban environments. According to the data obtained from the Department of Statistics of Malaysia, the sex ratio of the population in Malaysia is 1.06, which means there are 1060 males per 1000 females. Furthermore, the urban population is 76.2% of the country, and the average household income is around MYR 8600 [33]. With this backdrop, it is suitable to conclude that the participants involved in this study somewhat represented the population of Malaysia, as the demography of the respondents was in an acceptable range and resembled the data from the Department of Statistics of Malaysia. The size of a household was also studied. The median family size was 4 persons, with 10 as the largest family size and 1 being the lowest.

Households were then asked to predict the amount of food that they disposed of daily. They were given a list of food categories in the survey form to ease their estimation and the analysis task later. Table 4 shows the percentage and ranking of each food category discarded by Malaysian households on an average day, while Figure 4 shows the average amount. It is obvious that rice, noodles, or pasta is the highest food category disposed of at 13%, which is slightly higher than vegetables at 12.2%, followed by curry and soups at 10.1%. The two lowest food categories disposed of are spreads and preserved seafood and meats. A notable mention is that 5.4% of the respondents stated that they did not throw away or waste any food. Liquids or drinks also contribute to a large extent of domestic waste, with approximately 167 g of drinks disposed of per household per day. Overall, the data collected indicated that almost 1 kg (926 g, to be precise) of edible food is thrown away on an average day per Malaysian household.

The households were then asked to state the conditions of the food when disposed of. The food conditions were split into four groups, namely leftover after storing, meal leftovers, completely unused food, and partly used food. The findings show that large quantities of bread and dairy products were disposed of as leftovers after storing. Rice, noodles, pasta, and fresh food products such as cooked meat and vegetables were disposed of as meal leftovers. In addition, curry and soups were also considered to be disposed of as meal leftovers. Next, the drinks and beverages, which were also discarded in large amounts, can be referred to in the category of partly used food. The findings emphasise that typical Malaysian households throw away meal leftovers the most, and this partly indicates the habits of over-preparing and poor meal planning. Meal leftovers usually contain higher moisture content than uncooked food, especially soups and curry, which means the food waste in Malaysia is very suitable to be used as raw material for HTC to produce bio-coal, as the technology prefers high-moisture feedstocks. Figure 5 reveals the conditions of food disposed of by Malaysian households on an average day by food type.

Table 4. Ranking and percentage of food disposed of according to category.

Food Category	Ranking	Percentage (%)
Rice or noodles or pasta	1	13.0
Vegetables	2	12.2
Curry and soups	3	10.1
Sauces (soya sauce, tomato or chilli sauce, etc.)	4	7.9
Breads (including roti jala, roti canai and chapati)	5	6.6
Fresh fruit or preserved fruits	6	6.5
Fresh meat or cooked meat	7	6.0
Dairy and dairy products (milk, yoghurt, ghee, cheese, butter, etc.)	8	5.3
Fresh or cooked fish and other seafood	9	5.1
Drinks	10	4.3
Spreads (jams, margarine, kaya, etc.)	11	2.3
Eggs	12	3.9
Cakes, ice cream or any type of dessert	13	3.4
Cereals (cornflakes, muesli, barley, millet, etc.)	14	2.9
Beans and nuts (dahls, lentils, chickpeas, groundnuts etc.)	14	2.9
Spreads (jams, margarine, kaya, etc.)	15	2.3
Preserved or dried fish, seafood, or meats	16	2.2

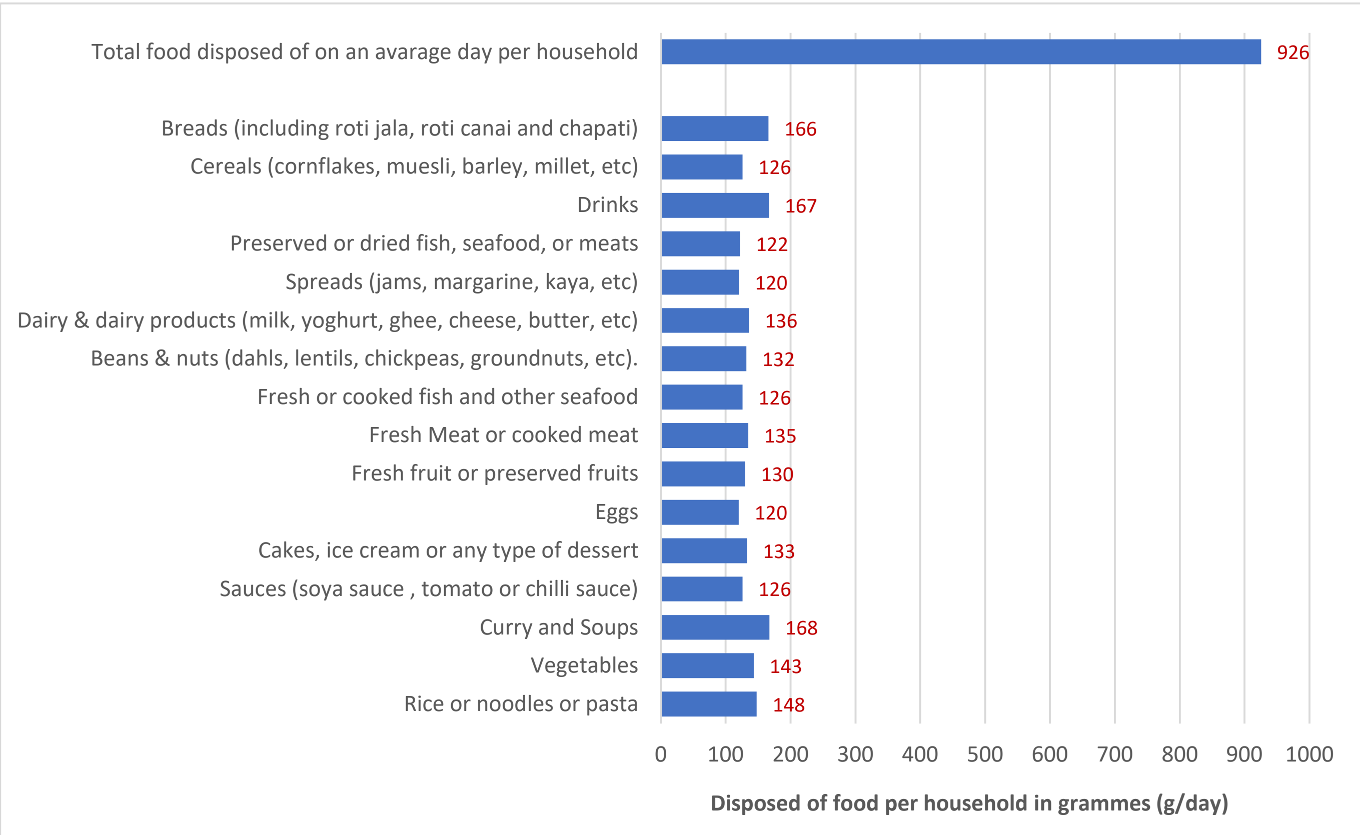


Figure 4. Average amount of food disposed of per household per day according to food category.

After studying the composition and quantity of food waste, the behaviors and attitudes of the respondents were also studied. The respondents were asked if there was any facility for food waste management around their living area, as illustrated in Figure 6. As expected, the majority of respondents reported that there are no facilities for food waste management in their living area, while only 12.1% of the participants reported "yes". This is because food waste management is still a very nascent industry in Malaysia, and it is still very new to the residents like the participants in this study. Nonetheless, it represents a golden opportunity from the market feasibility perspective, as there is no direct competitor. Next, the respondents were asked to report if they practiced food waste segregation in their daily life, as shown in Figure 7. Unfortunately, only 56.3% of the respondents separate food waste, while the remaining 43.7% do not. The willingness of the households to practice food waste segregation will directly affect the feasibility of the bio-coal project, as it will significantly ease up the process of supplying feed to the reactor. The operators do not need to separate food waste with high moisture content prior to reactor feeding. This study also presents the urgency to educate, encourage and spread food waste separation knowledge among households.

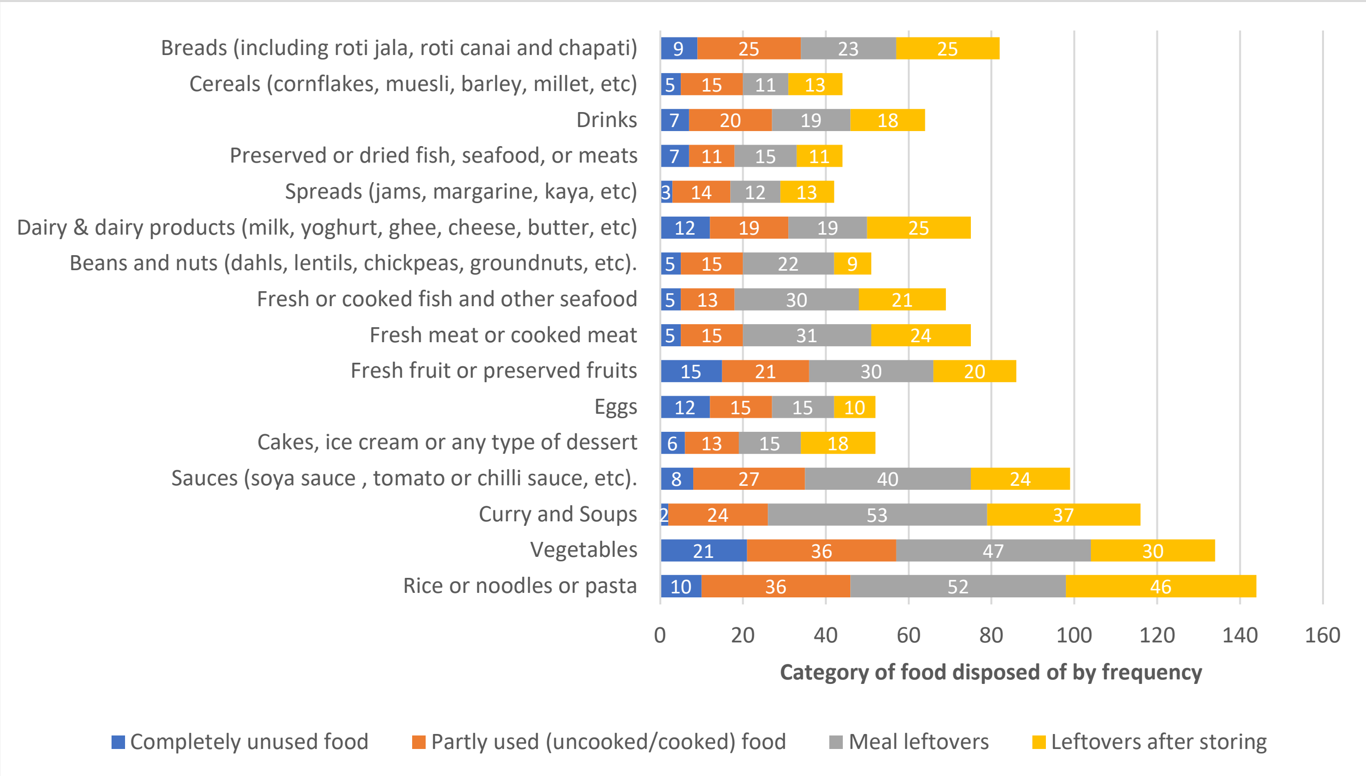


Figure 5. Food conditions when disposed of by Malaysian households on an average day.

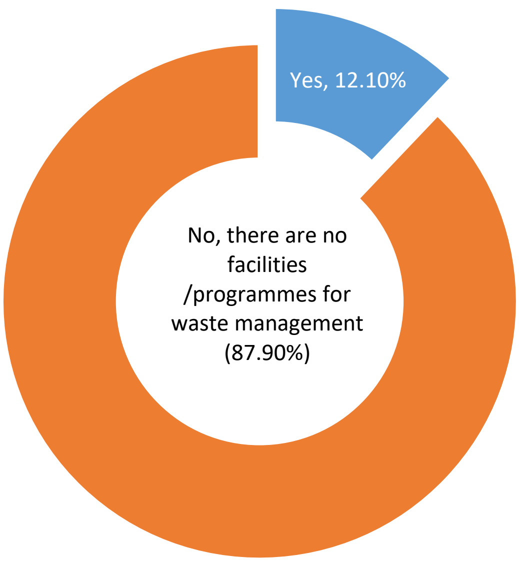


Figure 6. Facilities for food waste management nearby living area.

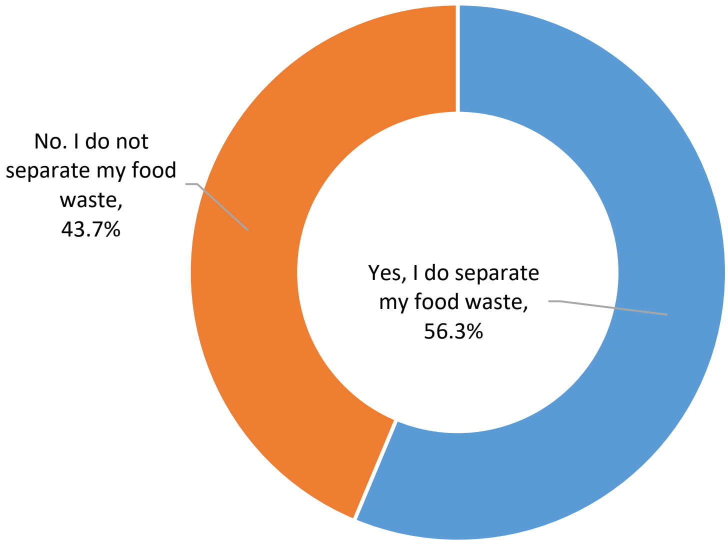


Figure 7. Percentage of households that separate food waste.

The respondents then encountered a follow-up question regarding their feelings about food waste, as shown in Figure 8. Even though most respondents do not separate food waste from other solid wastes, 21.6% of the participants emphasized that they buy and cook just enough food so that the food is not wasted and thrown away. Another 36.9% of participants stated that they always try their best not to throw away food or food items. A total of 8.0% of participants would like to donate edible foods to others, while 16.8% would like to provide those leftover foods to animals. Although these respondents are trying to make some good use of the "unwanted food", meaning food that is still edible but that they choose not to finish, they should change their behaviors to start conserving food and not wasting it.

Furthermore, as shown in Figure 9, 51.2% of the respondents reported that their disposed food ended up in the landfills, while some recycled their food waste for home composting for gardening (19.8%) and animal feed (24.4%). Other responses include sharing the food to other schemes (3.4%) and donating to food charities (1.2%).

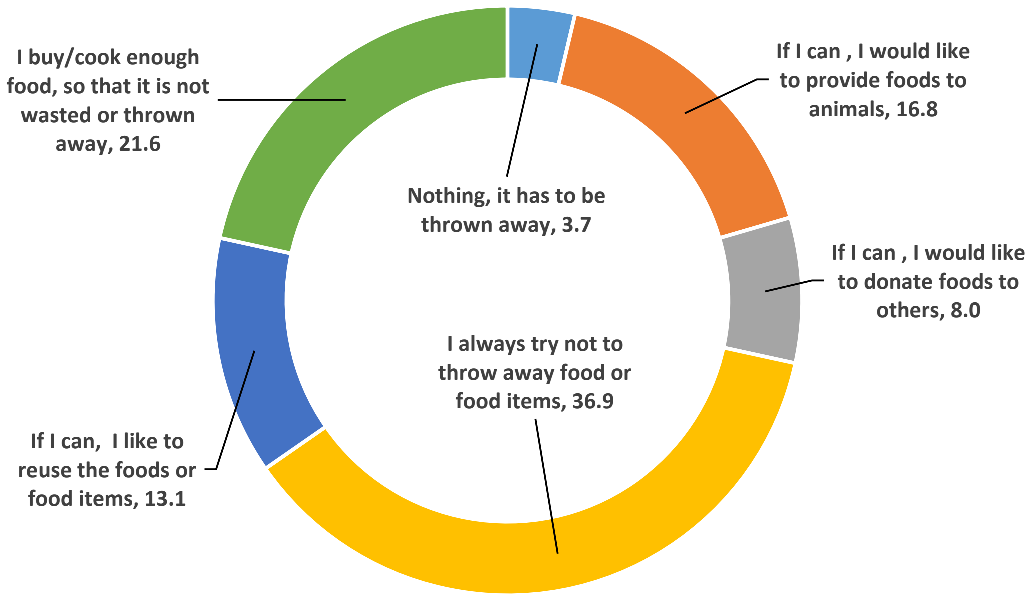


Figure 8. Feelings about food waste amongst Malaysian households.

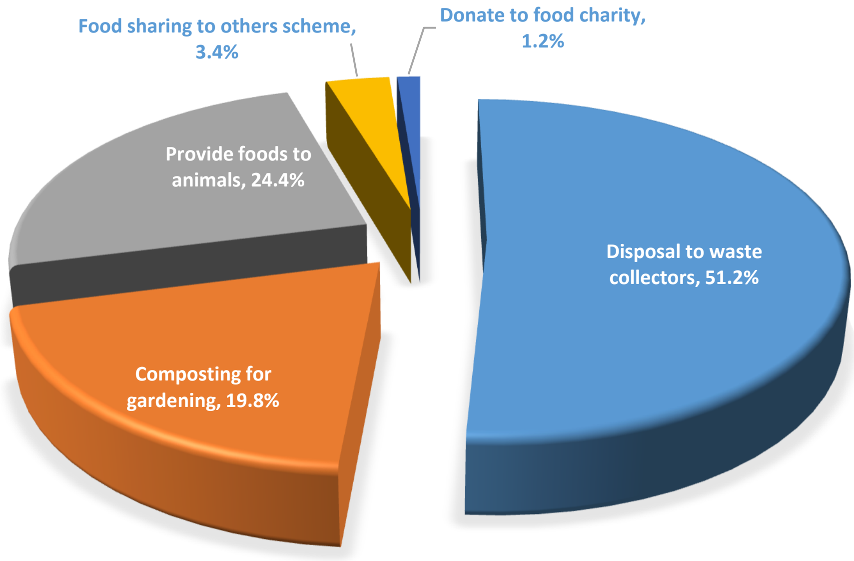


Figure 9. Fate of disposed-of food in Malaysian households.

After knowing the behaviors of the households towards food waste, a very critical question was asked. The question was intended to ascertain the willingness of households to separate their food waste if utilized for power generation, as shown in Figure 10. Surprisingly, almost all the respondents would consider starting to separate food waste if the food waste could be used to generate power (97.7%), with only 2.3% insisting that they will not practice food waste segregation. This proves the potential of increasing food waste separation in Malaysia, as the households appreciate the efforts of converting waste into power, and it increases the feasibility of the bio-coal project.

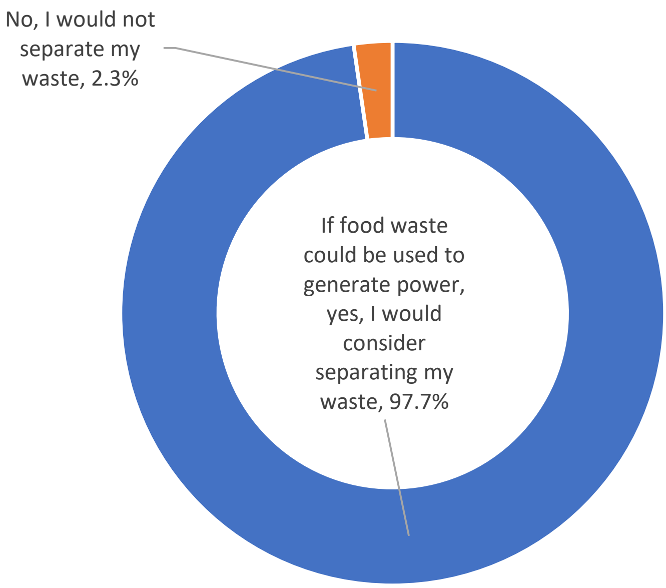
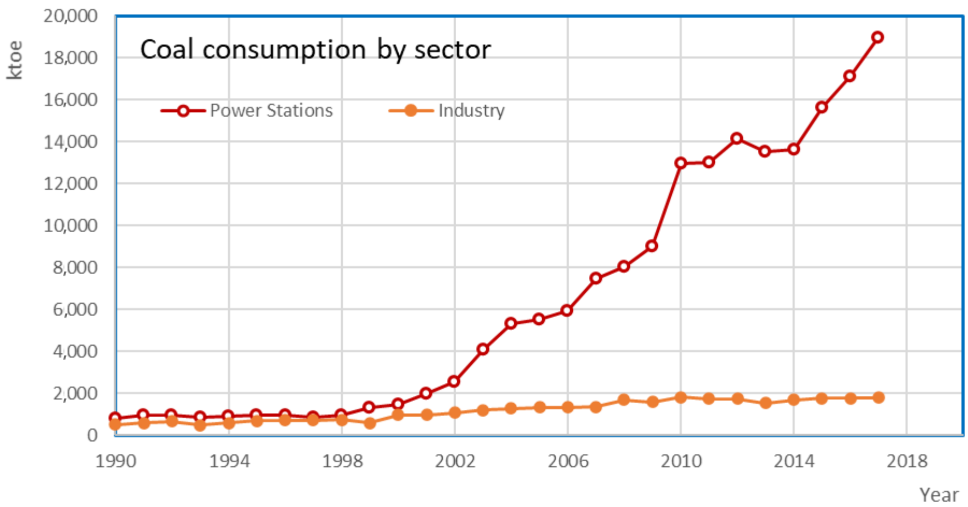


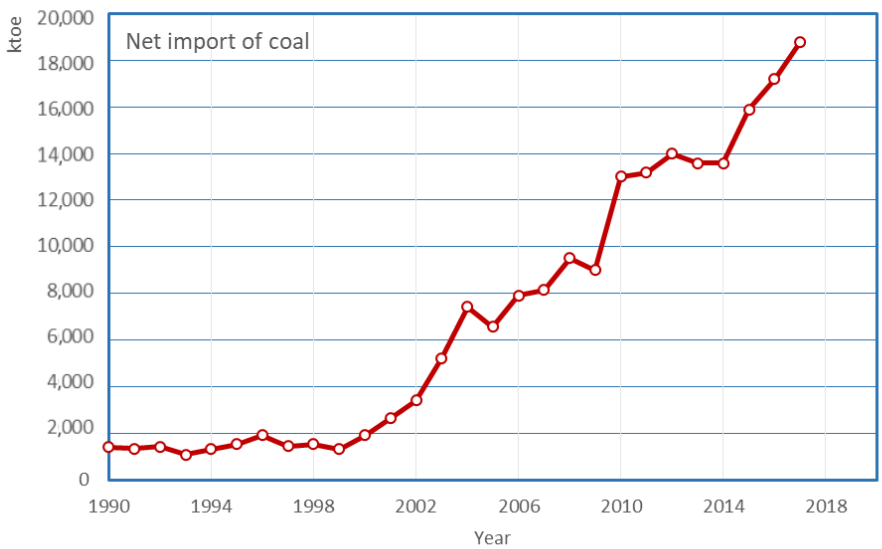
Figure 10. Percentage of households willing to separate food waste if utilized for power generation.

3.3. Survey of Industrial Bio-Coal Consumers

Households' behaviors and attitudes towards food waste, especially food waste separation, can guarantee a source of raw material; however, it does not represent the profitability and feasibility of the project. Thus, the potential consumers and markets for bio-coal as a substitute for power generation were studied. As mentioned before, the key consumers of coal are the power generation industry, cement manufacturers and steel producers in the country. Besides, the average consumption of coal in Malaysia is increasing every year, which represents a great opportunity for bio-coal, provided that its composition and heating value have similar values when compared to conventional coal. Figure 11a shows coal consumption by sector, where power stations consume almost 10 times more coal in the country compared to other industries [34]. The country is also a net importer of coal, as can be viewed from Figure 11b. This means that the country is still very dependent on fossil fuel, creating many opportunities for renewable energy sources to replace or reduce the use of coal. Hence, the opinions of industrial users and key players were collected through questionnaires and interviews to uncover the factors that lead to the adoption of bio-coal and the concerns that prevent its adoption.



(**a**)



(**b**)

Figure 11. (**a**) Malaysia's coal consumption by sector. (**b**) Net import of coal (source: power utilities, IPPs, cement, iron and steel manufacturers) (note: measurement in ktoe is based on the Energy Commission's calculation).

The details of the respondents for this consumer survey are presented in Table 5. There were a total of 7 respondents from 5 organizations, with 3 respondents using coal for power generation. The respondents were then given a list of factors and the advantages of HTC that led to the adoption of bio-coal. It is noted that the quality of the HTC bio-coal is comparable to, if not better (HHV of 21–31 MJ/kg) than, that of natural fossil coal (HHV of 25 MJ/kg) [35,36].

They were asked to rate the importance of each factor using the scale of "not important", "somewhat important", "important", "very important", and "extremely important". Figure 12 summarizes the findings of the rating. Lower production costs receive three "extremely important", two "very important" and two "important" votes from the respondents, which establishes it as one of the key factors. This is because lower production costs usually guarantee a higher return on investment (ROI) and higher profitability. The performance or efficacy of bio-coal is highlighted, as six out of seven respondents rated it as either "very important" or "extremely important". Bio-coal at least must meet the same capability of coal, if not exceed coal, so that the quality of the product, such as electricity, is not affected. Next, the ability of the bio-coal production process or HTC technology to reduce pollutants in the environment is also a key driver for the adoption of bio-coal. The firms are keen to look for alternatives that can perform the same function as coal while being environmentally friendly, unlike conventional coal. Apart from that, tax-free status, incentives and government regulations on bio-coal are also highlighted. Even though most respondents rated these facts between "important" and "very important", there were two respondents who rated government regulations only as "somewhat important". Government regulations and incentives can encourage investment in this industry and can also increase publicity and attract the public's attention to the bio-coal industry, which is very important for the growth and development of bio-coal in Malaysia. The next highlighted factor is the influence of shareholders, which received two "very important" and five "important" votes. The bio-coal project meets the demands of some shareholders who are keen on environmentally friendly practices in their businesses.

Some other factors that were listed in the survey form but did not receive many important votes include customer influence, aesthetics, potential to attract new customers, recognition from global and local agencies, positive public image of bio-coal and use by other firms in the same industry.

Table 5. Details of the respondents.

Parameter	Attribute	Freq	%
Name of organization	Cenergi SEA—Renewable Energy	2	28.6
	Tex Cycle—Scheduled Waste Management & Renewable Energy	1	14.3
	Mukah Power Generation—Coal-Fired Power Plant	1	14.3
	Havys Oil Mill	1	14.3
	TNB	2	28.6
Position/post in organization	Executive	2	28.6
	Technical Engineer	1	14.3
	Station Manager	1	14.3
	Project Researcher	1	14.3
	Head of Section	2	28.6
Number of employees	Full-time employees from 5 to less than 75	1	14.3
	Full-time employees from 75 to not exceeding 200	4	57.1
	Full-time employees of 200 and above	2	28.6
Why does your organization purchase coal?	Electricity	3	75.0

Table 5. *Cont.*

Parameter	Attribute	Freq	%
	Boiler	1	25.0
Would your organization buy bio-coal for your business operations and/or to generate energy/fuel for your key processes in the short term?	Maybe	7	100
	Yes	0	0
	No	0	0
Would your organization buy bio-coal for your business operations and/or to generate energy/fuel for your key processes in the longer term (2 years or more)?	Maybe	7	100
	Yes	0	0
	No	0	0

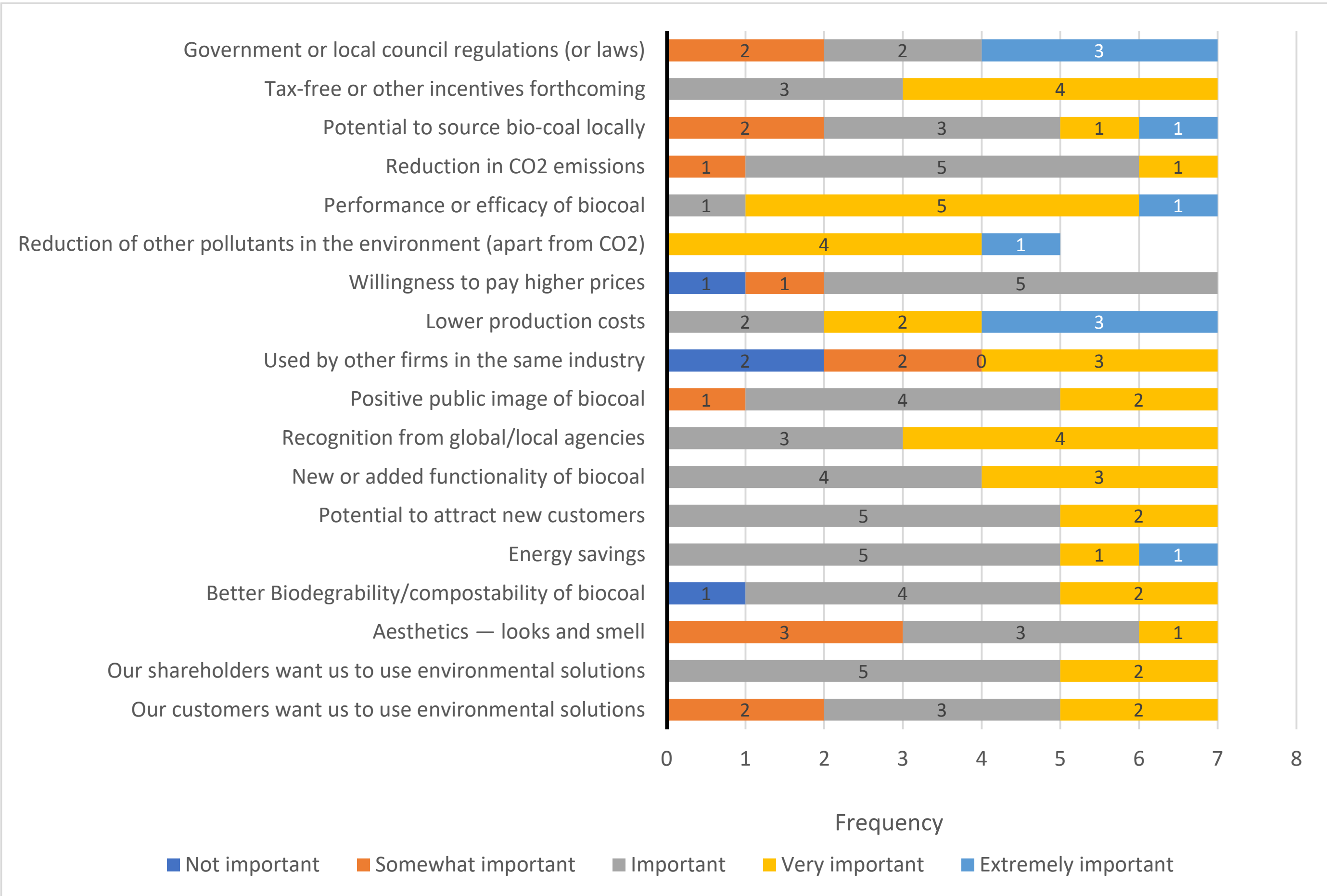


Figure 12. Ratings of various factors in terms of importance to accept bio-coal as an alternative to coal.

Apart from the factors listed in Figure 12, the respondents also mentioned a few additional factors that they thought would play very important roles in encouraging industrial users to adopt bio-coal for their processes. Two respondents highlighted that technical hurdles should be given more attention, for example, the production rate and consistency of energy value. The operating cost and return on investment (ROI) were also mentioned.

Similar to factors that encourage the adoption of bio-coal, a list of factors that potentially prevent the utilization of bio-coal was rated by the respondents, as shown in Figure 13. As mentioned before, lower production costs are one of the key factors for the adoption of bio-coal; thus, a higher cost of production becomes one of the largest hurdles that prevent its adoption. It received five "extremely important" votes out of seven respondents. Besides, the industrial users are also worried that the price of bio-coal is much higher as compared to normal coal, which reduces their profitability significantly. Next, they also raised their concerns on the uncertain performance and efficacy of bio-coal. Incompatibility with existing processes or current industry practice may also hinder its adoption, as the firms or industries might need to make huge investments to make modifications to the existing plants. Five respondents rated it as "extremely important", whilst the remaining two rated it as "important." Unsupportive government or local regulations and lack of any incentive are also factors that prevent the adoption of bio-coal by industrial users.

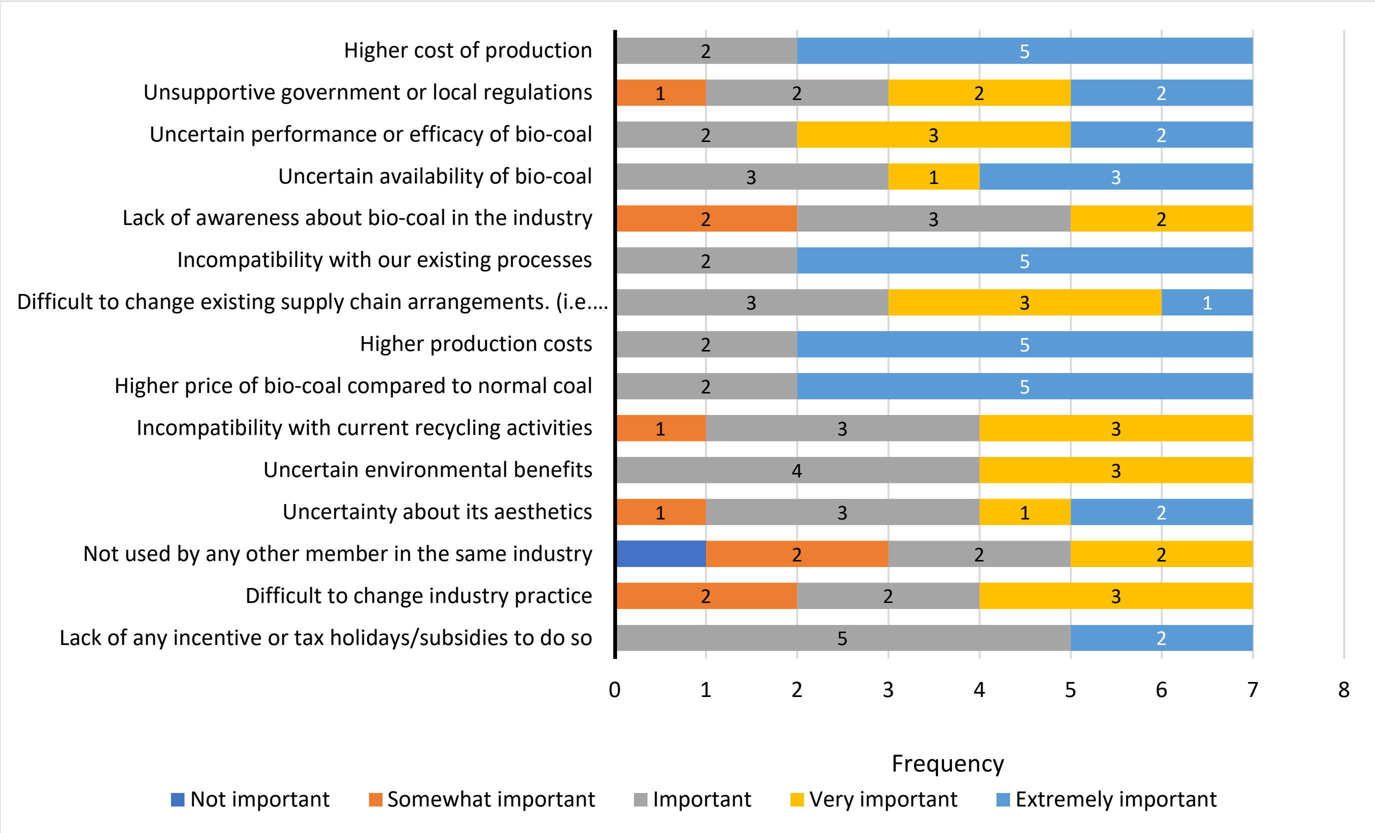


Figure 13. Industry ratings of important factors preventing the adoption of bio-coal.

Two respondents also highlighted an additional concern of their firms regarding bio-coal, which is its scale and capacity. They were also worried about the reliability of the bio-coal production process. As mentioned before, it is still in its nascent stage, and little information and few details can be studied, especially in the country of Malaysia, where there is no bio-coal project so far.

The respondents were then asked to indicate the type of information that they or their firms would require for them to consider purchasing bio-coal for their operations. Five types of information were presented to them, and they ranked the information according to their importance, as shown in Table 6. Overall, the buyers are concerned about the calorific value and energy efficiency of bio-coal. They are keen to know if the heat value or energy value of bio-coal is comparable to conventional coal, as this will affect the outcome of their operations directly. Furthermore, they would like to know the emissions of the bio-coal process and the reduction in environmental pollutants. These important features will definitely increase the market prospect of bio-coal. The biodegradability of bio-coal was ranked as the least important aspect.

Table 6. Ranking of key information on bio-coal.

Ranking	Item
1	Heat/energy/calorific value (most important)
2	Information on energy efficiency
3	Emissions
3	Reduction of environmental pollutants
4	Biodegradability (least important)

In the final section of the consumer survey questionnaire, the respondents were instructed to provide an overview of them or their firms towards green products. As a result, most firms were found to be more than willing to support the global call of reducing emissions and adopting greener practices in their operations. Besides, they are also happy to consider a green alternative and use an energy substitute that utilizes existing waste products, like bio-coal, which utilizes food waste and can substitute coal for power generation. However, they are not very interested if the substitute costs more, even though the adoption of it is good for the environment.

3.4. Interview with Key Industry Players

Besides the consumer survey, interviews were conducted with key players of the industry to find more about their perceptions towards the bio-coal project. Two interviews were held with senior staff members of TNB and the Director of SEDA, respectively.

The senior staff members of TNB emphasized that authorities like SEDA and the Energy Commission have a very important role in directing the energy industry into using more renewable energy sources. They gave a very good suggestion, which was to cease the licenses of coal-powered energy generation plants. They mentioned that TNB is very supportive of the use of renewable energy sources, and in fact, they are now focusing on gas-powered plants and solar energy. However, some independent power producers across the country are still utilizing coal to generate electricity. TNB has several renewable energy strategies to gradually reduce and remove coal from its power generation mix, and it aims to terminate all coal-powered plants in the next decade. Furthermore, TNB is also considering embarking on a bio-coal project which utilizes food waste, but they still have a few concerns which remain unsolved. The concerns are the stability of power generation capabilities, compatibility with current plants, reliability of the power generated, costs and, most importantly, safety. They also mentioned that the adoption of bio-coal will be seriously considered if it can be blended with the currently used coal.

Overall, TNB has been putting a lot of effort into renewable energy sources, especially solar energy. As a major player in the power generation industry in Malaysia, the adoption of bio-coal by TNB will create positive impacts for the development and growth of bio-coal as an alternative for coal in Malaysia. Hence, many independent power producers will be convinced to follow TNB's footsteps in utilizing bio-coal for power generation.

The Director of SEDA emphasized that the renewable energy industry in the country is experiencing growth in recent years; however, the progress is very slow. The contribution of renewable energy to the total energy requirement is still insufficient. He also shared that costs and ROI are the key considerations for most players in the industry. Since coal-powered plants are still very efficient in generating power and very profitable, it somehow slows down the development of the renewable energy industry, including TNB.

Apart from selling bio-coal to local industries, there is also a possibility that it can be sold to other countries in the ASEAN region. The energy requirement in the ASEAN region has experienced a rise by 80% since the year 2000, with renewable energy only satisfying 15% of the demand [37]. Therefore, it is obvious that ASEAN countries require sustainable clean energy; thus, it could potentially be a great opportunity for the use of bio-coal throughout the ASEAN region.

3.5. Summary and Limitations

HTC is a simple and stable process that uses superheated water under pressure to produce a carbon-rich solid product (bio-coal) and gaseous and liquid by-products. On the other hand, anaerobic digestion (AD) involves microorganisms in the process of degradation of organic compounds and releases biogas without oxygen present. As reported by Pontoni et al. [38], the process is rather complex and is completed in several stages involving physicochemical and biochemical reactions in sequential and parallel pathways. HTC offers a shorter reaction time to process food waste compared to AD biological processes. More importantly, bio-coal produced from HTC was reported to have an energy content and composition equivalent to lignite coal, which could be easily stored and used as a substitute fuel in energy generation [39]. However, the presence of an amorphous secondary char on the surface of the bio-coal may make such direct fuel substitutions unfeasible. As carbonization conditions become harsher (e.g., as temperature and time increase), the as-carbonized bio-coal will have lower heating values. Therefore, the design of HTC systems for food waste to direct coal-substitute fuels may need to include an extraction step, whereby the primary char is recovered for combustion, and the extracted secondary char can potentially be used as a source of biochemical and fuels [40].

Overall, the market is positive for the growth of the bio-coal industry and bio-coal project specifically as a renewable energy source to substitute or to be used with coal in various industries. This is because of the following reasons:

1. The industry is still very nascent in terms of using bio-waste based on household waste as an energy resource;
2. There are no competitors, thus giving the bio-coal project a first-mover advantage in the market. The closest competitor is currently being planned but is not yet operationalised. The Ministry of Housing and Local Government is planning six waste-to-energy plants for the year 2022, which utilise the same raw material for energy generation;
3. One of the key factors facilitating the growth of the industry is the household food waste quantity and components. The survey on household waste has provided adequate information to support the availability of a sufficient quantity of food waste in the country to sustain the flow of raw material for the bio-coal project. However, the consistency in the supply of food waste feedstock is of utmost importance to keep the bio-coal production steady and the HTC plant profitable. Any fluctuation in the supply of food waste would greatly reduce the plant's efficiency, hence leading to technical and economic issues. As such, the uptake of the HTC technology is encouraged by the fact that the system can integrate food waste with other sources of wet waste from industry (pulp and paper mill waste), agriculture (palm oil residue) or live-stock farming (animal manure). This can greatly reduce HTC's susceptibility to fluctuating waste resources;
4. The key consumer for coal in the country is the energy sector. Surveys and three separate interview sessions with key role players in the sector have provided valuable inputs on key industry priorities for energy generation. Overall, the findings suggest that consumers prioritise the costs and performance of bio-coal, with positive prospects if both are proven to be within an acceptable range;
5. HTC has the potential to reduce the amount of food waste that ends up in landfill sites. HTC not only provides the best waste-to-energy technology in dealing with high-moisture-content food waste bound for landfills but also produces useful end-products (i.e., solid (bio-coal) and liquid (process water) phases). These can be used to generate a cleaner energy source (either through sole usage or by blending with fossil fuels), thereby drastically reducing greenhouse gas emissions, which would otherwise

be hazardous to the environment if unmanaged. In addition, the liquid phase, i.e., HTC slurries, could be processed to produce bio-fertilizer for agricultural purposes. Besides, it also could be used as a source of biogas in an anaerobic digestion plant [41], thereby closing the loop and providing a circular renewable energy economy.

However, a few limitations of the present study should also be considered. Firstly, the study of the influence of direct and indirect stakeholders was conducted through desk research, which is mainly based on local and global publications, with some inputs from the interviews conducted. Desk research may be limited in terms of biased reporting and inaccuracies, as the data might not reflect current needs [42]. There are many websites that provide information on the Internet, but these could not be considered reliable information sources, as some of them contained incorrect information. Furthermore, data published on the Internet can become outdated very quickly due to the pace of change within the industry. The information sources should be carefully analyzed and crosschecked with data from various sources to validate their accuracy, which requires a significant amount of effort, patience, extreme care and skill to gather useful information. Therefore, it is suggested to use various Internet tools and search engine techniques to find qualified data and utilize it for research.

Besides, the survey of households to consider waste amounts and behaviors or attitudes were self-reported. The main disadvantage of a self-reported questionnaire is the possibility of providing inaccurate answers. This is because respondents may be underreporting or over-reporting quantities of waste based on memory and recollection that may be flawed. The respondents may not answer truthfully, especially on sensitive questions. This phenomenon can be known as social desirability bias, in which the respondents tend to answer in a socially acceptable manner [43]. For example, they may pretend they separate their food waste. Besides, the survey results showing the average amount of food disposed of per household per day could be estimated in a more accurate manner by sampling real municipal solid wastes.

There is also a need for more data and extensive surveys in the future. Therefore, it is suggested to allow the survey method and online method of distribution to be easily accessed by mobile phones, tablets, or desktops in order to allow more people to participate. Due to COVID-19, the number of responses was low, and the survey of firms had only 7 respondents, consisting of 5 companies based on the network of the researchers via the convenience sampling and snowballing approach. Additional interviews could be conducted with the key consumers and regulatory body to provide further insights into their perceptions towards the bio-coal project in terms of cost and safety aspects.

4. Conclusions

Desk research examining the influence of direct stakeholders on the performance of a bio-coal project was conducted using Porter's five forces analysis model. From the research conducted, it is evident that there will be an adequate supply of raw materials for the HTC process from participating households. The buyers of bio-coal can be very low or very high, as the main consumer of coal in Malaysia is the power generation industry, and the industry is dominated by TNB. Thus, the adoption of bio-coal by TNB will directly affect the market of bio-coal and increase the bargaining power of buyers. While key players in the industry are open to the adoption of bio-coal produced from HTC, there are some challenges to overcome, such as the performance, compatibility and cost of bio-coal production, which become key factors for adoption. The outlook for bio-coal in the market is quite positive, as the government is continuously promoting and encouraging the use of renewable energy through policies developed by SEDA over the years. The energy sector specifically has policies to develop the use of renewable energy via the Energy Commission.

In conclusion, the market feasibility of bio-coal in Malaysia is relatively positive. However, this research was only limited to food waste produced by the average Malaysian household; thus, the major contributors of food waste, such as restaurants and cafes, were not taken into consideration. By investigating the production levels of food waste in the commercial sector, the economic analysis and long-term sustainability of the HTC process could be evaluated to a better extent.

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Institutional Review Board Statement: The study was conducted in accordance with the approval by the Science & Engineering Research Ethics Committee of University of Nottingham (AS150720) on 21 July 2020.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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