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Evaluating Sustainable Options for Valorization of Rice By-Products in Sri Lanka: An Approach for a Circular Business Model

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Abstract: Due to the significant quantities of waste generated by the Sri Lankan rice industry, circular bioeconomy methodologies were applied to examine value-adding entrepreneurial activities for rice industry by-products (RIB). The study was conceived after scouring the existing literature on agricultural waste management and interviewing experts in the field and the rice industry. In the first phase, the suitability of valorizing alternatives for RIB was considered via a multi-criteria decision-making method. Valorization options, such as biochar production, energy purposes, composting, and other activities, were evaluated using an analytical hierarchy process (AHP) based on four criteria, namely environmental, social, technical, and economic issues. The results indicated that the highest priority should be given to environmental, social, and economic considerations, with local priority vectors of 0.5887, 0.2552, and 0.0955, respectively. It was found that biochar production is the optimal valorization strategy for managing RIB in Sri Lanka. From these findings, the development of a sustainable business model for making biochar out of RIB was done based on commercial motivations and value addition in biochar manufacturing processes. The Business Model Canvas elements played a vital role in categorizing and interpreting the case study data. Though the RIB seems undervalued at present, it was found that as a direct result of environmental concerns, several stakeholders have developed RIB valorization with an emphasis on bioenergy generation and biochar production. Adequate subsidies (technology and knowledge), standard regulations, more collective actions for creating economies of scale, and marketing strategies (consumer awareness) are all necessary for the successful implementation of sustainable circular business models.

Keywords: rice husk; rice straw; MCDA; AHP; circular business model; biochar; green economy; valorization

Citation: Illankoon, W.A.M.A.N.; Milanese, C.; Karunarathna, A.K.; Liyanage, K.D.H.E.; Alahakoon, A.M.Y.W.; Rathnasiri, P.G.; Collivignarelli, M.C.; Sorlini, S. Evaluating Sustainable Options for Valorization of Rice By-Products in Sri Lanka: An Approach for a Circular Business Model. *Agronomy* **2023**, *13*, 803. https://doi.org/10.3390/agronomy13030803

Academic Editors: Niccolò Pampuro, Eugenio Cavallo and Lucia Vigoroso

Received: 16 February 2023
Revised: 6 March 2023
Accepted: 7 March 2023
Published: 9 March 2023

1. Introduction

Sri Lanka is an island with an agricultural economy with a significant amount of agricultural waste generated in each region [1,2]. In order to prepare their fields for the next farming season, farmers often fire or discard crop refuse in open fields [3]. These unsustainable options create immense environmental pollution and adverse health effects for humans and animals. By contemplating the valorization process for these prospective feedstocks and using them as a valuable resource for the country's economic system, reducing these negative impacts is feasible [4,5]. Based on the massive quantity of different types of agricultural waste, Sri Lanka has significant potential for generating energy, extracting nutrition, value-added biomaterials, and biochemicals through different valorization processes [1,2,4,6,7]. Nonetheless, their potential has yet to be fully realized because of problems with their supply chain, suitable tools for pre-treatment, economically viable techniques, and practical business structures to enable the valorization of agricultural waste in Sri Lanka [6].

According to the Sri Lankan Rice Research Center, approximately 34% (0.77 million hectares) of Sri Lanka's farmland is dedicated to growing rice, which is the country's primary crop and a food source for the majority of the population. The average yearly amount of rice cultivated is around 870,000 hectares, with the main cultivation season (Maha) accounting for about 560,000 hectares and the second cultivation season (Yala) for about 310,000 hectares. Across the island, nearly 1.8 million agricultural households are involved in growing paddy. Currently, Sri Lanka is nearly self-sufficient in terms of rice, producing 2.45 million MT of raw rice annually. The average Sri Lankan gets 40% of his daily protein needs and 45% of their daily calorie needs from rice [8,9]. Depending on the cost of rice, bread, and wheat flour, the annual per capita consumption of rice ranges from 106 to 114 kg [9]. It is expected that annual rice consumption will rise by 1.1%, requiring an annual growth in rice output of 2.9% [9]. To meet these output goals, intensifying cropping and raising the national average yield are viable strategies. Large-scale rice production results in significant waste production, leading to the loss of valuable materials and posing serious economic and environmental management problems [10,11]. However, many of these by-products can be used in alternative manufacturing methods, such as biorefineries [12–16].

The term "rice straw" refers to the components of the rice plant that are green and leafy (*Oryza sativa* L.). When rice is harvested or milled, the byproduct is rice husk. Several studies have shown that 1.5 kg of rice straw is produced for every kilogram of rice grain [1,17]. Previous research has indicated that 0.10 kg of rice bran is produced for every kilogram of rice. Several researchers have shown that adding 20–28 wt % of rice husk results in 1 kg of rice [1,17]. Abbas and Ansumali [18] found that half of the rice mill's husk is burnt to generate steam. Some sources estimate that around 25% of rice husk ash was produced throughout the burning process. Figure 1 shows the total amount of rice straw, rice husk, and available amount of rice husk that Sri Lanka produced during the 2019 Yala season, as determined by data from the Sri Lanka Rice Research Center. Rice production varies across districts due to localized effects of climate and other factors. Therefore, this research mainly focused on the valorization of rice straw and rice husk since rice bran is already being utilized in many economic sectors in the country. The excess amount of rice straw and rice husk in each district changes and is not constant throughout the country (Figure 1) owing to their different cultivation practices, as shown by information acquired from stakeholders working with the production process and prior studies on the rice industry. A total of 216,615 hectares (27.9%) was discovered to be dependent on rainfall, 203,168 hectares (26.2%) were stated to be under small irrigation systems, and 356,063 hectares (45.9%) were supposed to be under large irrigation systems in 2021/2022 Maha season [19].

According to Sri Lankan millers, more than 60% of the rice husk generated in processing plants is used to generate power for parboiling and dehydrating in the same mill [1,20]. As the rice mill is primarily responsible for parboiling and drying rice, its operations will directly impact the levels of local surplus rice husk. According to some farmers, the whole amount of rice straw produced after harvesting is dumped back into the field. Therefore, some rice straw will decompose in the same area, some are utilized to feed livestock, and the rest is burnt to prepare the land for the subsequent crop.

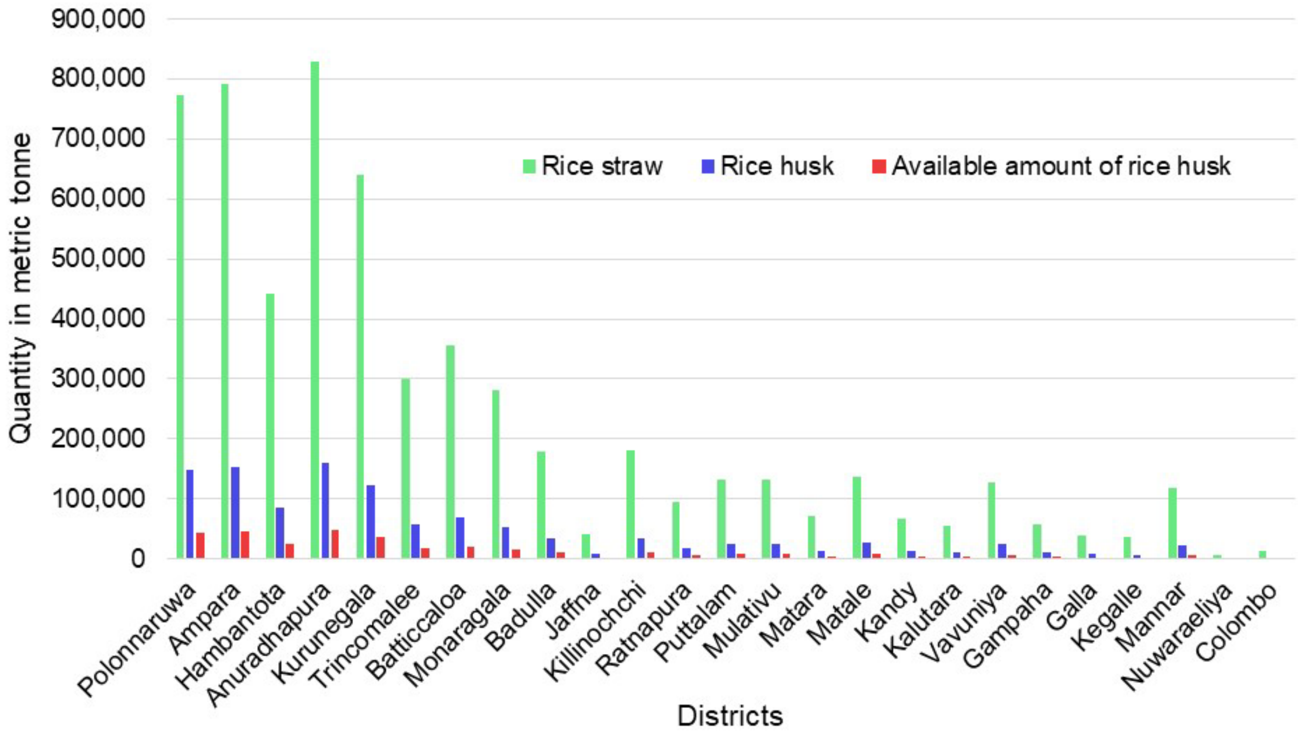

Figure 1. Amount of rice industry by-products in Sri Lanka.

Many criteria and aspects, such as public health, ecological, sociological, cultural, political, technical, and economic issues, must be considered when deciding the appropriate method for managing agricultural waste [21]. Adopting an efficient and effective disposal or treatment method may positively affect the environment while conserving resources and money. This will protect human health and societal benefits while reducing environmental risks (including water, air, land, vegetation, and wildlife). This research will investigate sustainable techniques of valorizing rice husk and rice straw that have been recommended and already adopted in Sri Lankan society, such as biochar production, thermal energy recovery (electricity and heat), composting, and other miscellaneous activities like animal feed, craft works, paper manufacturing, as a building material by using multi-criteria decision analysis (MCDA) incorporated with an analytical hierarchy process (AHP). Additional considerations beyond the ecological implications are needed to address matters such as waste disposal methods and proper business infrastructure. Because maximizing one advantage may entail reducing another, decision-makers must weigh various competing considerations to ensure these facilities' long-term viability. As such, the suggested framework is an optimization method for minimizing stakeholder conflicts and incorporating environmental, sociocultural, political, technological, and economic factors.

According to the MCDA's optimal valuation option, major social transformations and adjustments to every aspect of the economy, including production and consumption, are necessary to achieve a circular economy [22,23]. This transformation has fundamentally altered the way agricultural waste is handled, with stakeholders in that field playing a crucial role [24]. In the past few years, a higher number of investigations have been conducted on sustainable and/or circular business models that seek to increase economic development while avoiding adverse effects on the environment and society [25–29]. These "new business models" provide various interdependent benefits, including social, ecological, and financial use [30]. The issues of how to generate, distribute, and collect value with closed material loops are addressed through circular business models [31].

Circular Business Model

Recognizing the potential of agricultural waste, finding new uses for them, recycling nutrients, and reducing waste generation in agrifood systems may be aided by using circular economy methods, which encourage more environmentally responsible and economically effective production and consumption patterns [32]. Recycling and reusing materials and components while avoiding waste is at the foundation of the circular economy, which has been advocated globally for some years. The circular economy aims to optimize resource usage and achieve equilibrium among the economy, environment, and society by supporting closed manufacturing processes [33]. Focusing primarily on the economic and environmental components, it is considered a unique approach to balance economic expansion while conserving natural resources and establishing long-term economic systems [34–37]. However, although the importance of the circular economy to the agrifood system has been emphasized in many recent studies [32,38–40], there are still significant research gaps, particularly in management science [35,41]. However, in order to make the change from a linear to a circular economy, new business models are required. These models must be flexible in terms of resources and management skills [42], as well as be able to combine technical and organizational innovation [43]. Furthermore, these emerging circular business models seek to integrate commercial value generation with resource efficiency measures by reducing and terminating resource flows [44–46].

Generally, a business model outlines how a company conducts its operations. The term “business logic” describes a company’s perspective, processes, and the benefits it generates for its stakeholders. Osterwalder and Pigneur’s business model canvas is the most often used conceptual tool for creating and evaluating new business models. It comprises nine distinct components, such as value proposition, cost, revenues, channels, customer relationships, customer segments, key activities, key resources, key partners, or building blocks, that span the four major sectors of a company (Figure 2).

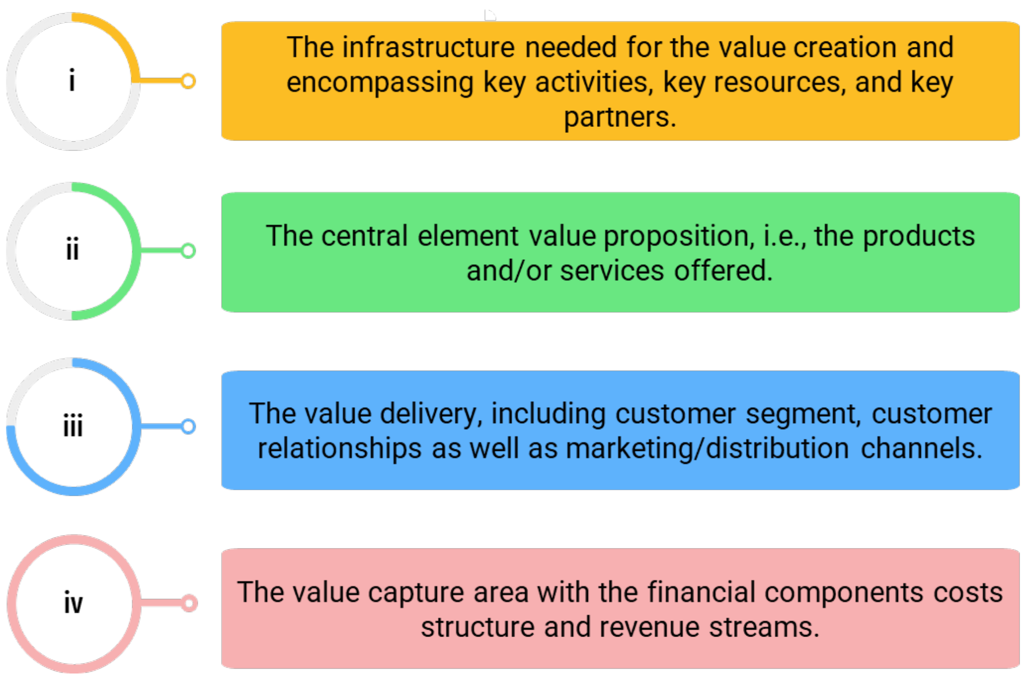

Figure 2. Four major sectors of the business model canvas adopted from [40–44].

Both circular and sustainable approaches to a business aim to maximize mutual advantages across economic, environmental, and societal spheres [43]. These two varieties are closely connected and form a subset of business approaches [25]. Moreover, circular business models offer fresh perspectives by outlining strategies to stop, strengthen, slow down, dematerialize, or limit resource cycles [47–49]. Following the Ellen MacArthur

Foundation's description of the circular economy, Mentink [31] describes a circular business approach as "the reasoning of how a company develops, distributes, and captures value with and inside closed material loops". Both Micheaux and Aggeri [50] agree that the primary goal of a circular business model is not to maximize short-term profits but to secure the company's long-term existence by minimizing energy and material waste. According to Lewandowski [26], there is a lack of research focusing on frameworks for circular business models. Using the ideas of the circular economy, he incorporated them into the business model canvas developed by Osterwalder and Pigneur and expanded on it by adding two more rows such as:

I. "Take-back system", which incorporates the concept of "material loops," in which items, parts, or substances are recovered from consumers and then reused.
II. "Adoption factors", which assume that multiple existing management skills and external (technical, political, societal, and economic) elements are necessary for a successful shift towards circular business models.

According to Antikainen and Valkokari [25], the "business ecosystem level" is crucial as it refers to the trends and causes as well as the engagement of stakeholders that affect the business model. Even further, Stal and Corvellec [51] argue that adopting a circular business model is mandated by the new institutional environment of the circular economy, which includes regulations, conventions, and beliefs.

The research objective of our work was to investigate and find the most appropriate valorization option based on environmental, social, technical, and economic issues. Subsequently, the drivers and characteristics of the circular business model for valorization options found through the MCDA are analyzed. Therefore, this research addresses the potential and necessary improvements to implement these options in a real-world situation.

2. Materials and Methods

Choosing the right valorization strategy for farm refuse is a difficult and time-consuming process [52]. Criteria and factors linked to public health, the environment, community, culture, politics, science, and economics play a major role. Several favorable outcomes result from selecting the most economical and effective valorization choice, such as reduced expenditures and minimal environmental impact. It will protect human health and societal benefits while reducing water, air, soil, vegetation, and wildlife risks. In order to determine which alternative is ideal, it is necessary to make comparisons between them and give each of them weight-based criteria on the factors used. Additional considerations beyond the environmental consequences are required in order to carry out and provide such valorization options and facilities. Before implementing this kind of solution in the actual world, it is also crucial to have a firm grasp of fundamental business issues. The study was conducted after searching existing literature on agricultural waste management and interviewing stakeholders and experts in the field and in the rice industry. This literature and data proved that preferred valorization options required a commercialization strategy. As a result, the methodology was devised with meticulous attention to achieving the ultimate research objective, considering the facts mentioned above.

2.1. Hierarchy Model

According to Figure 3, at first, the issue is built into a hierarchical framework. The hierarchy was divided into three sections: first, second, and third. The first section describes the purpose of the problem, the second section details the criteria considered in the study, and the third section indicates the alternatives used for the analysis.

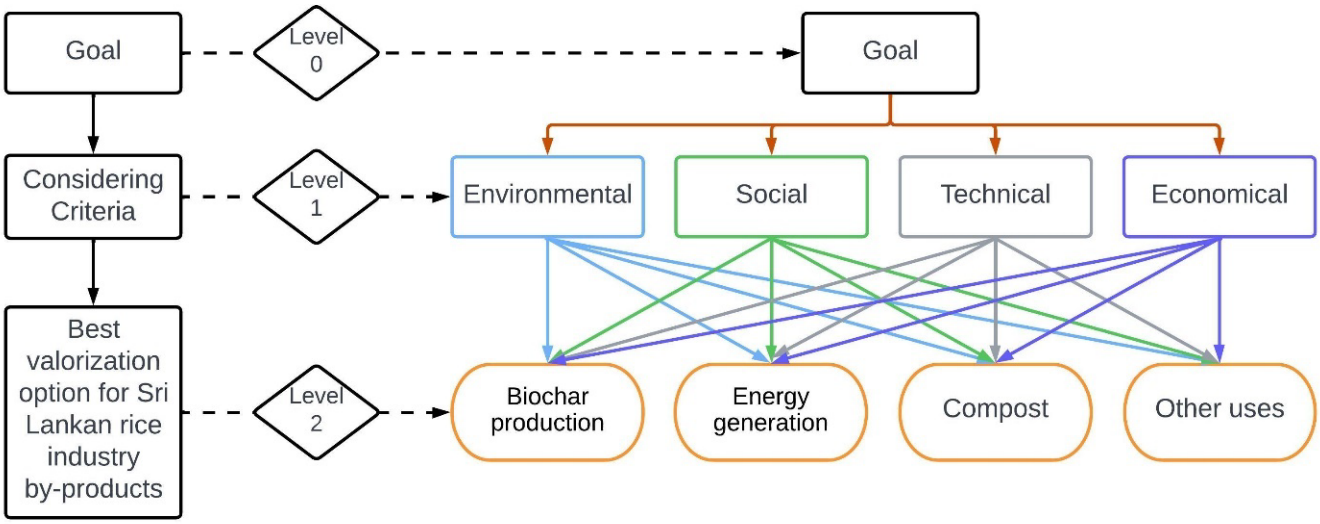

Figure 3. Hierarchy model representing considered criteria and waste-to-energy options.

2.2. Make a Pair-Wise Comparison to Generate a Matrix

After developing the hierarchical model, each level was compared in pairs. Initially, a pairwise comparison between considered criteria with respect to the goal of the study was carried out, followed by a pairwise comparison between valorizing options with respect to considered criteria was performed, which drives the build-up of judgmental matrices. According to a nine-point measure, from 1 to 9, which is shown in Table 1, the evaluations and their weights were made [52–54]. Furthermore, the AHP approach was used to determine the priority vectors of valorizing options. The local priority vector (W) for the matrix judgment was obtained by normalizing the vectors in each column of the matrix and calculating the average of the resulting matrix rows. Each option was evaluated by synthesizing local priorities rather than a global priority hierarchy.

Table 1. Nine-point Weight of Pairwise Comparison.

Weight of Pairwise Comparison	Status
1	Equally: Two technologies contribute to equal weight
3	Slightly favor: One technology is slightly more important than another
5	Strongly favor: One technology is more strongly important than another
7	Very strongly favor: One technology is more strongly important than another
9	Extremely favor: Evidence proof of importance over another
2, 4, 6, 8	Intermediate values: When further analysis is needed

Consistency Check

After weighing, each option relevant to the considered criteria was incorporated into a model. Equation (1) was used to calculate priorities if the built matrix is consistent.

$$AW = \lambda_{max} W \quad (1)$$

where A, W, and λ_{max} are denoted as comparison matrix, priority vector, and principal eigenvalue, respectively. Equation (2) was used to calculate the consistency ratio (CR). CR was useful in making the final decision of input weighted value.

$$CR = \frac{CI}{RI} \quad (2)$$

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (3)$$

where CI (finding through Equation (3)), RI, and n are denoted as consistency index, ratio index, or random consistency index and size of the comparison matrix, respectively. The size of the comparison matrix depends on the number of options used for the study. Table 2 represents the number of comparisons.

Table 2. Number of comparisons.

Number of Options	1	2	3	4	5	6	7	n
Number of comparisons	0	1	3	6	10	15	21	$\frac{n\,(n-1)}{2}$

According to Table 3, the average of the consistency index of 500 randomly generated matrices was used as the Random Consistency index (RI) [53,54]. According to the consistency ratio, matrices were defined as consistent or not. If the calculated matrix was lower than 0.1, the matrix was considered consistent, and if it was greater than 0.1, it was considered an inconsistent matrix. Further, some modifications were made to minimize the inconsistency.

Table 3. Random consistency index (RI).

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

2.3. AHP Model Development

The primary goal of this research is to identify the most viable valorizing choice for managing agricultural by-products in Sri Lanka and to offer a long-term answer for those involved in the rice business. In order to implement AHP technology, an expert consulting system was set up to identify and formulate possible waste management alternative components that would influence their selection. Following an in-depth review of the literature, an interview process was conducted with experts working in the fields of agricultural waste management, environmental consultation, energy generation, local government bodies, the rice industry and research organizations in Sri Lanka. Subsequently, according to the AHP approach, each level of the hierarchy was constructed by defining valorizing options and considering the criteria, as shown in Figure 3. In addition, ten different criteria were identified, such as environmental, social, technological, political, cost (capital, operation and maintenance), rules and regulations, public health, land use, economic and cultural. After several discussions with national and international waste management experts, ten different criteria were concentrated into four categories: environmental, social, technological and economic. Therefore, it was easier to conduct the evaluation process.

Definitions of Criteria: To Be Shorten and Made without Repetitions

Improper waste management negatively impacts the environment, animals, and humans. In addition, waste disposal has a wide range of effects on the ecosystem and may lead to significant health issues. As a result, all solutions were ranked according to the following list of consequences, and only those with the most significant potential to lessen environmental impacts were ultimately chosen (Figure 4). The socioeconomic structure and behaviors of the population often influence waste management. Campaigns, educational initiatives, and increased public awareness have a beneficial impact on how people perceive waste. These criteria support the objective of enhancing working conditions, incomes, and accessibility to social services. When choosing between different waste handling methods, technical aspects are essential. Their significance is often based on the expected growth in the average daily volume of waste materials that the facility will need to handle to accommodate more processing capacity. Based on these factors, appropriate tools and knowledge are identified for refuse management work. Economic assessment plays a significant role in strategic planning and investment programming for each waste disposal plant. Budgeting for the original expenditure requires an understanding of the ongoing costs associated with the different waste management operations. The willingness and ability of the general population to contribute to the operation were also evaluated. The assessment was conducted using the elements shown in Figure 4.

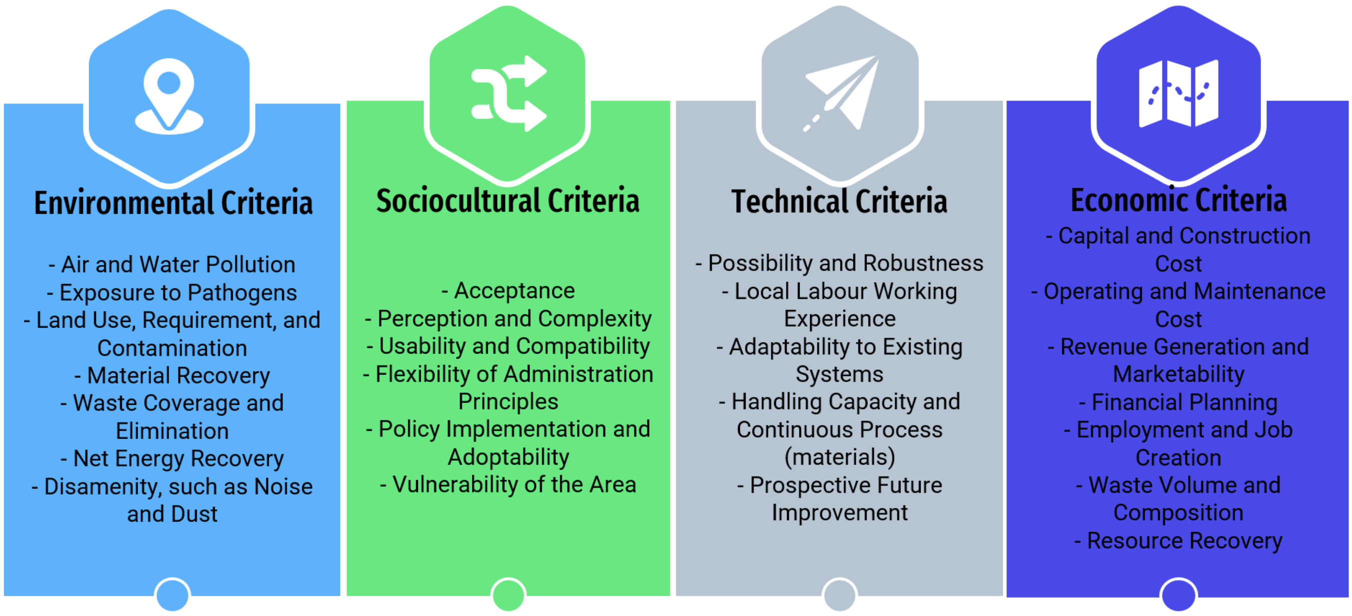

Figure 4. Main considered criteria for AHP analysis.

The AHP methodology evaluates and compares four valorizing options, including biochar production, combustion or incineration for energy purposes, composting, and other miscellaneous activities, and discusses their feasibility based on four environmental, social, technological, and economic criteria. The options consisted of some thermal and biological treatments for waste.

After building the hierarchical model (Figure 3), the first step was to create a comparative matrix in pairs for all the criteria used in this study. This hierarchical model was used to determine what valorizing option would be viable for the agricultural waste (rice industry by-products) management system in Sri Lanka. To establish relative weight, either of the two basic approaches was used, group decision-making (standard experts/decision-makers) or individual decision-making (individual decision-maker or author judgment) [52–56]. In any case, the judgment should be based on the pairing of each component that corresponds to different components at the same level in a given hierarchical model (Figure 3).

In general, estimates depend on a numerical scale that indicates how often one factor is more important than another factor in relation to the general objective rule [52,53]. With respect to the above realities, the values of the pair model are given in Tables 4–8, based on the technical guidelines on solid waste management in Sri Lanka. To build a comparison between the criteria and the valorizing options, the questions asked were based on the following:

- Regarding the object of the study: "What factors are considered significantly robust criteria in implementing and proposing the best valorization option for the Sri Lankan agricultural waste management system"?
- Four main criteria were considered for each of the four valorizing options according to their level of significance. The interrogation was (for each valorizing option): "How

much more robust or highly significant are one considered criteria over another in the valorizing options for agricultural management"?

Table 4. Pairwise comparison matrix of the considered criteria with regards to the goal.

Criteria	Environmental	Social	Technical	Economical	Priority Vector
Environmental	1	3	7	7	0.5887
Social	0.33	1	5	3	0.2552
Technical	0.14	0.20	1	0.33	0.0606
Economical	0.14	0.33	3	1	0.0955
Note: λ_{max} = 4.1177	CI = $(\lambda_{max} - n)/(n - 1)$ = 0.0392			CR = CI/RI = 0.0436 < 0.1	

Table 5. Pairwise comparison matrix for the valorizing options with regards to environmental criteria.

Criteria	Biochar Production	Energy Purposes	Composting	Other	Priority Vector
Biochar production	1	3	3	5	0.4994
Energy purposes	0.33	1	2	3	0.2306
Composting	0.33	5	1	5	0.2001
Other	0.2	0.33	0.2	1	0.0699
Note: λ_{max} = 4.2666	CI = $(\lambda_{max} - n)/(n - 1)$ = 0.0888			CR = CI/RI = 0.0987 < 0.1	

Table 6. Pairwise comparison matrix for the valorizing options with regards to social criteria.

Criteria	Biochar Production	Energy Purposes	Composting	Other	Priority Vector
Biochar production	1	5	3	9	0.5444
Energy purposes	0.2	1	2	3	0.0688
Composting	0.33	0.5	1	3	0.1934
Other	0.11	0.33	0.33	1	0.1934
Note: λ_{max} = 4.2039	CI = $(\lambda_{max} - n)/(n - 1)$ = 0.068			CR = CI/RI = 0.0755 < 0.1	

Table 7. Pairwise comparison matrix for the valorizing options with regards to technical criteria.

Criteria	Biochar Production	Energy Purposes	Composting	Other	Priority Vector
Biochar production	1	3	0.33	0.14	0.0974
Energy purposes	0.33	1	0.11	0.11	0.0425
Composting	3.00	9	1	0.33	0.2772
Other	7.00	9	3	1	0.5829
Note: λ_{max} = 4.1954	CI = $(\lambda_{max} - n)/(n - 1)$ = 0.0651		CR = CI/RI = 0.072376897 < 0.1		

Table 8. Pairwise comparison matrix for the valorizing options with regards to economic criteria.

Criteria	Biochar Production	Energy Purposes	Composting	Other	Priority Vector
Biochar production	1	5	2	0.33	0.2251
Energy purposes	0.2	1	0.14	0.11	0.0354
Composting	0.5	7	1	0.33	0.2251
Other	3	9	3	1	0.5145
Note: λ_{max} = 4.1981	CI = $(\lambda_{max} - n)/(n - 1)$ = 0.0660		CR = CI/RI = 0.0733 < 0.1		

2.4. Circular Business Model

After identifying the best agricultural waste valorization option, a circular business model was implemented to evaluate the criteria for a sustainable agricultural waste management system related to the rice industry by-products waste in Sri Lanka. As an analytical framework, Osterwalder and Pigneur's business model canvas was used to analyze and evaluate new business models for the agricultural waste management system.

3. Results and Discussion

In total, five pairwise matrices were up throughout this study. The first matrix shown in Table 4 represents the considered criteria related to the goal. When the second-level criteria are linked to the third-level valorization choices, the remaining four paired matrices (Tables 5–8) depict the four valorization possibilities for those criteria (Figure 3). All weights that were used for the comparisons are consistent because the CR of all comparisons was under 0.1.

3.1. Preference Order of Valorization Options

Table 9 displays the relative positions of the valorization alternatives with respect to the four factors that were taken into account at the second level (Figure 3). Then, the final priority vector was obtained by multiplying the ranking of every criterion by the prioritization vector, then aggregating the values obtained for each valorization choice.

Table 9. Composite values for all considered criteria: integrating to get the conclusive outcomes.

Valorization Options	Criteria				
	Environmental	Social	Technical	Economical	Overall Priority
Biochar production	0.2940	0.1516	0.0059	0.0227	0.4742
Energy purposes	0.1357	0.0492	0.0026	0.0041	0.1917
Composting	0.1178	0.0396	0.0168	0.0185	0.1927
Other	0.0412	0.0148	0.0353	0.0501	0.1414
Note: $\overline{\text{CI}} = 0.1163$		$\overline{\text{RI}} = 1.8$		$\overline{\text{CR}} = 0.0646 < 0.1$	

The overall consistency ratio ($\overline{\text{CR}}$)was calculated by using the following Equation (4), and it was given as 0.0646, which is less than 0.1. Hence, the overall priority proves a consistency (Table 10) similar to other literature studies [52–55].

$$\overline{\text{CR}} = \frac{\overline{\text{CI}}}{\overline{\overline{\text{RI}}}} = \frac{\sum_{i=1}^{n} \text{WiCI}}{\sum_{i=1}^{n} \text{WiRI}} \tag{4}$$

where $\overline{\text{CI}}$, $\overline{\text{RI}}$, and Wi are denoted as consistency index in all levels of the hierarchy, ratio index in Table 3, and priority vector regards to the considered criteria. Idealized priorities were calculated by dividing each overall priority by the highest total priority value for the biochar production (0.4742). The outcome is shown in Table 10. The result enables the highest valorization option and obtaining their corresponding values relative to the largest value for other valorization options. Subsequent explanations of the result show that energy generation is about 40.4% of the attraction of biochar production, composting is about 40.6% of the attraction of biochar production, and finally, about 14% of the attraction of biochar production is other miscellaneous activities.

Table 10. Outcomes of normalized priorities and idealized priorities.

Options	Normalized Priority	Idealized Priority
Biochar production	0.47	1
Energy purposes	0.19	0.4042
Composting	0.19	0.4065
Other	0.14	0.2982

According to this analysis, the ideal valorization option for the Sri Lankan agricultural waste management system using the AHP approach was recognized as biochar production, followed by composting and energy generation through combustion and incineration, whereas other miscellaneous activities are the lowest feasible alternative to be considered (Figure 5). In addition, biochar production was found to be the best valorization choice across all parameters (Figure 6).

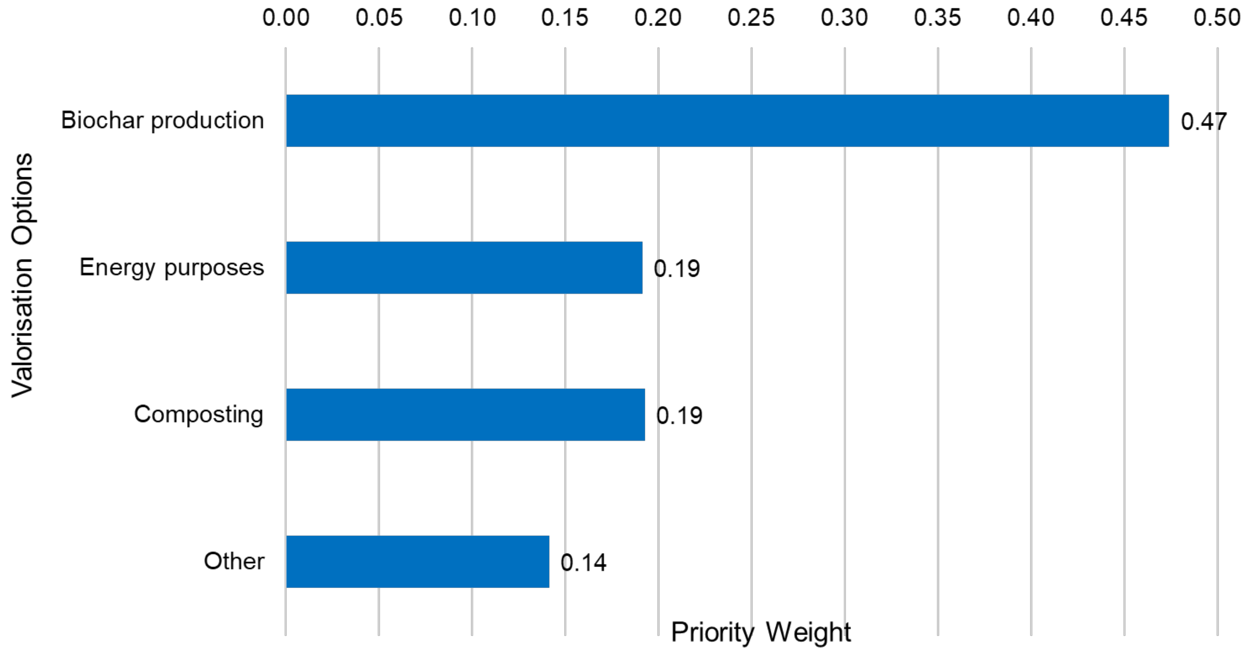

Figure 5. Overall priority of all valorization options.

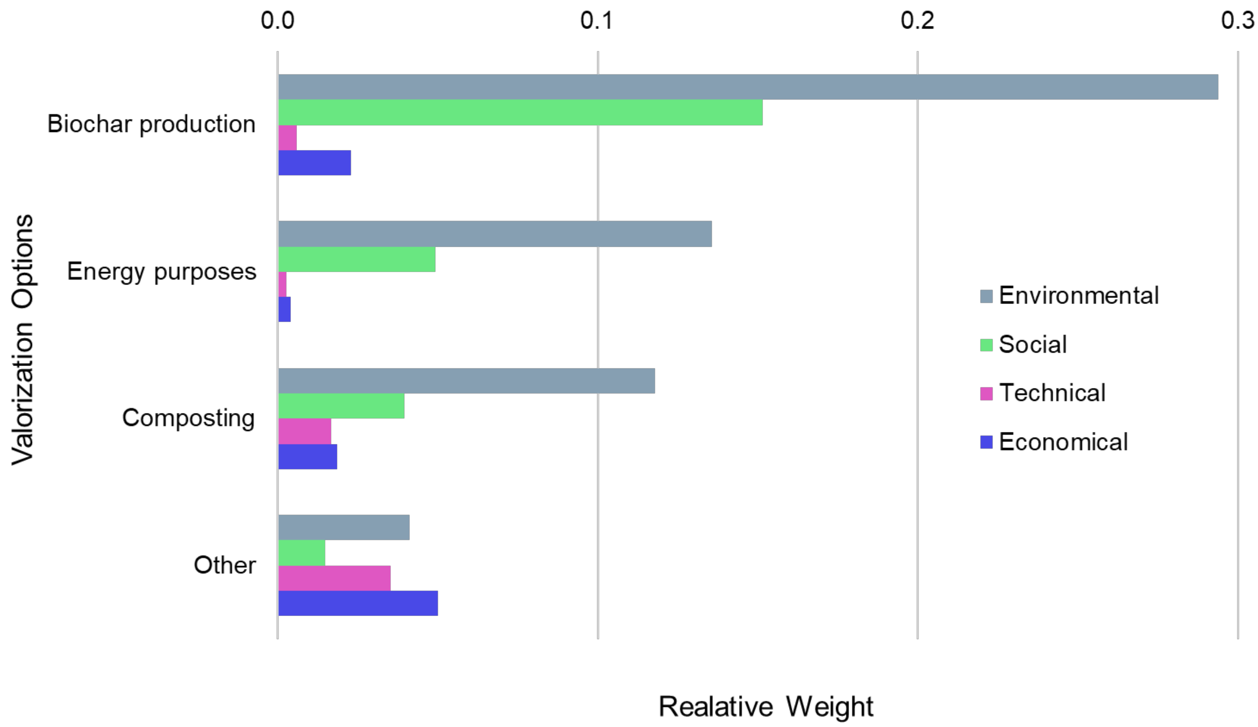

Figure 6. The overall ranking of all valorization options with respect to criteria.

Sensitivity Analysis

As an essential part of MCDA, sensitivity analysis shows how shifting the weights of individual factors at different tiers of the hierarchy can affect the ultimate choice. In addition, this allows for detail of the potential preferences of the decision-makers concerning the applied criteria and how those choices affect the research results. This study was conducted by systematically altering the criteria's relative weights and documenting the resulting shifts in the rankings. This is accomplished by considering four cases:

1. In the first of these four scenarios, three criteria are allocated no relative weight (0), while the remaining criterion receives the full weight (1). Figure 7a displays the analysis results, demonstrating that biochar production is the most effective method for managing rice waste, followed by composting and energy generating via combustion and incineration, and other miscellaneous activities being the least effective method.
2. Two criteria get relative weights of 0.5, while the other two get relative weights of 0; this is one of six possible outcomes, as shown in Figure 7b. Figure 7b suggests that the analytical outcome is consistent with Figure 7a.
3. In the third scenario, three of the four criteria are each given a relative weight of 0.33. In contrast, the remaining criterion is given a relative weight of zero (0), as shown in Figure 7c. Findings also indicate that biochar production, followed by composting, and energy generation, is the most effective strategy, whereas other miscellaneous activities are the least desirable alternative.
4. In the last case, as seen in Figure 7d, all four criteria have an equal weight of 0.25. While both biochar production and other miscellaneous activities were significant in this study, biochar production was found to be somewhat greater than other activities. However, in the Sri Lankan context, producing biochar is the most appropriate use for rice industry by-products, followed by composting and energy generation.

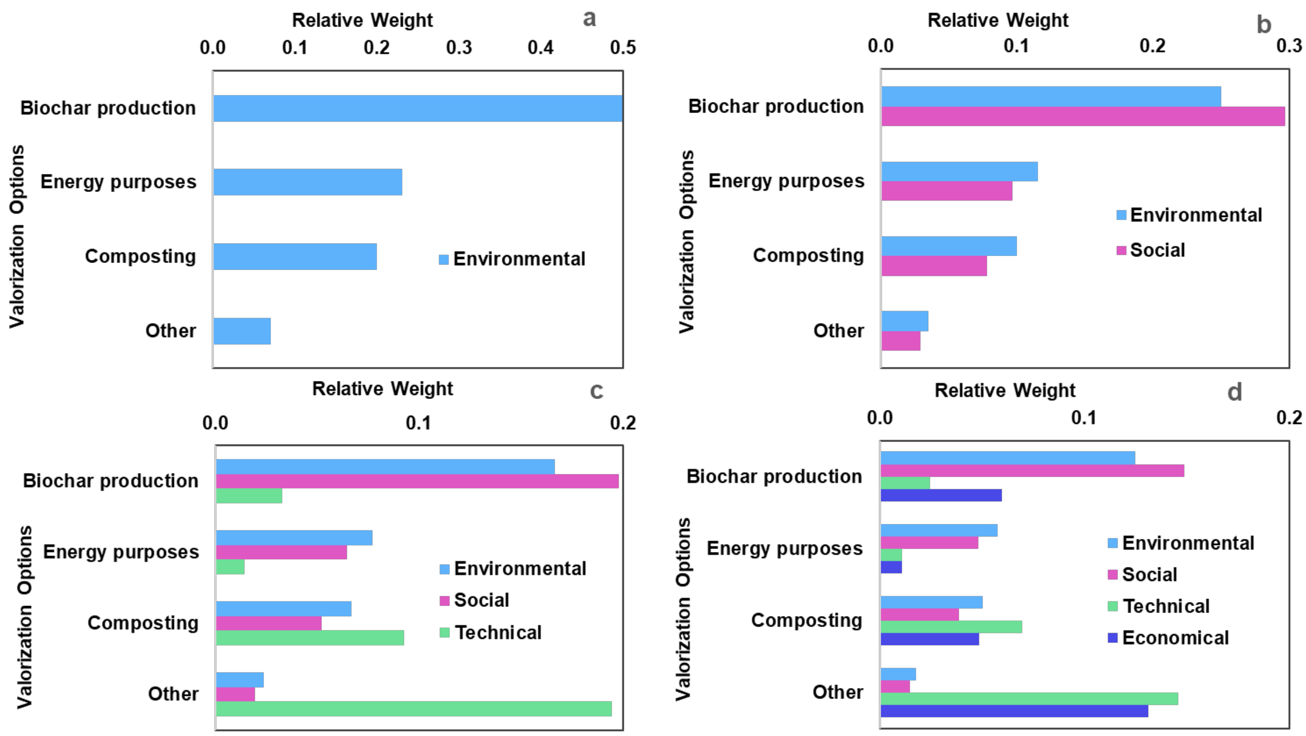

Figure 7. Sensitivity Analysis ((**a**): three criteria are allocated no relative weight 0, while the remaining criterion receives the full weight; (**b**): 2. two criteria get relative weights of 0.5, while the other two get relative weights of 0; (**c**): three of the four criteria are each given a relative weight of 0.33, while the remaining criterion is given a relative weight of 0; (**d**): all four criteria have an equal weight of 0.25).

Figure 7 shows a consistent trend in the sensitivity of the data across all four conditions. It also demonstrates that biochar production is, significantly and alone, the most viable valorizing alternative for rice waste management in Sri Lanka, followed by energy generation by combustion and composting being the clear last alternative. Similar research has been conducted by Yaghoubi and his coworkers as well [56]. They suggested a valorization approach similar to the one discovered in this research for valorizing by-products from the rice industry.

3.2. Development of Circular Business Model for Biochar Production in Sri Lankan Context

Based on the findings of this study, biochar production is the most appropriate valorization option for rice industry by-products in Sri Lanka. For this reason, the concept of a circular bioeconomy via biochar production has been at the forefront of the development of the circular business model. The biochar synthesis process involves the gradual breakdown of organic materials into smaller particles, which are then discharged from the process stream as gases, condensable vapors (oils), and solid charcoal [57–62]. There is a direct correlation between the inputs (temperature, time, heating rate, weight, precursor types, and reactor design) and the outputs (product amounts). Therefore, it has a wide range of possible economic application, depending on the nature of the final products [63–66]. The use of thermochemical technologies for biochar production, especially in remote areas, will support regional economic growth by enabling small and medium-sized businesses to produce enough energy, increasing farming revenue, and streamlining agricultural waste management [62]. Biochar production from agricultural waste permits the formation of closed system models in which waste from one process is utilized as an input to another process, thereby contributing to the social, economic, and environmental benefits of the circular economy at a small scale [60,67,68].

Similar interactions between various biochar production processes and waste reuse are necessary to develop new prospects. A circular bioeconomy allows for the development of new products and services as well as the opening of new businesses by repurposing waste from one agricultural processing sector to address harmful pollutant issues in another and by-product application to soil [69].

Significant components become fluids at a high moisture content of the feedstock. If there is a low degree of moisture, there is a higher possibility that the method will generate a more significant quantity of solid materials rather than oil [70,71]. At temperatures more than 800 °C, when the warming rate is high, a greater division of debris and vaporous substances is produced [71,72]. Therefore, bio-oil may be provided employing average temperatures and somewhat high heating rates. Discharge rates of unstable elements towards the beginning of the process, at temperatures of about 250–300 °C, are roughly several orders of magnitude higher than the subsequent progress [72]. Recovering the biochar and heat created while also considering technical and budgetary considerations are possible via the integration of methodologies that strike a balance between convenience, energy efficiency, and limited discharges into the local network [73]. The following advantages for the environment may be recognized:

- Decrease in the production and emissions of carbon dioxide and other greenhouse gases.
- Cost savings in waste collection and disposal positively affect the economy.

Implementing this circular economy helps reduce waste in various ways and hence increases the value of waste [37,74]. The problem of recycling agricultural waste, and products and by-products, presents a real opportunity for developing a circular economy (CE) through the use of new methods and promising strategic approaches. The proposed framework can provide a sharply controllable energy base compatible with circular economy guidance in local cultivation networks.

Instead of emphasizing the social advantages of transitioning from a linear to a circular economy, the anaerobic digestion (AD) framework would benefit the surrounding community; because its products, such as gas and slurry, can be efficiently utilized in the nearby communities [75–78]. In addition, one of the main obstacles to using AD for rice husk and rice straw is that these wastes require a pre-treatment process before they can be applied to AD because of their low digestibility characteristics. Approximately 59% cellulose, 18% hemicellulose, and 21% lignin make up the lignocellulose found in rice husks [2,79,80]. It is difficult for microbes to decompose lignocellulosic materials on their own because of their high lignocellulosic content [80]. Rice husk pre-treatments, which entail modifying the cellulose structure of the rice husk, speed up the hydrolysis of cellulose and hemicellulose, resulting in the rapid production of biogas. Mechanical, physical, chemical, and biological pre-treatments are some of the options available [71,79]. Particle size reduction is a crucial physical pre-treatment because it ultimately results in a larger surface area and the release of intracellular components [81,82]. Therefore, it is a disadvantage from an economic and technical point of view. This is one of the main reasons AD is not considered an appropriate option compared to other options in the Sri Lankan context.

3.2.1. Economic Feasibility of Biochar System

As part of a larger portfolio of approaches to climate change, biochar and integrated biochar–bioenergy production systems can develop into viable decentralized industries supporting the region's economy [83,84]. It has been claimed that biochar has been found to function better than compost in various applications [85–87]. Low labor costs in countries like Sri Lanka and other developing nations like Vietnam, Ethiopia, and Nigeria will allow for a net economic advantage to be realized via the employment of simple production processes. As well as in developing country scenarios, using a gasifier system is economically unfeasible [84]. Both low-tech and high-tech alternatives are available for biochar synthesis. Large-scale biochar production is possible with modern technology, but this necessitates substantial investments in both infrastructure and technology.

Currently, a ton of biochar made employing cutting-edge technology can fetch between USD 600 to USD 1200 on the open market [84,88–91]. Many farmers on a low income cannot afford this level of production and pricing. Vice versa, there is an open market for small-scale biochar producers that make good quality biochar, contributing positively to farmers' economic level. In addition, farmers and other stakeholders might adopt simple methods like burning and soil covering techniques or flame curtain pyrolysis kilns to directly use agricultural waste like rice husk and rice straw in biochar manufacturing and employ it for soil improvement. The burning and soil covering method, as shown by Zhou et al. [92] generates high-quality biochar that may be utilized for soil amendment while releasing fewer pollutants than traditional field burning. Those authors proposed that Chinese farmers may benefit from using the burning and soil covering methods. In pyrolysis, the term "flame curtain kiln" refers to a metal kiln or pit in the shape of a conical spire; by using this "flame curtain kiln" process, biomass such as agricultural waste may be converted into high-quality biochar at a cheap cost, with little emissions. Cornelissen et al. [93] have proposed that farmers in both developed and developing nations may use a flame curtain kiln for pyrolysis to treat a wide variety of feedstocks.

3.2.2. Characterization of Biochar Production According to the Business Canvas Model

According to the Business Canvas Model, Figure 8 highlights the key outcomes as regards business traits. However, a vast amount of information is available on the literature and data fronts about key resources and the valuation routes for novel value propositions. Therefore, there is a consequent increase in focus on these elements.

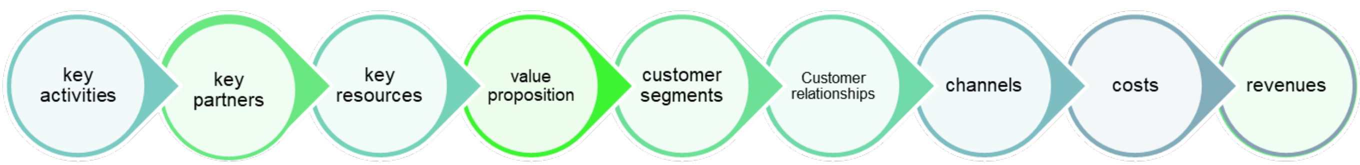

Figure 8. Business Canvas Model order.

Research conducted with rice industry stakeholders in Sri Lanka identified various business models for biochar production. The vast majority is composed of independent organizations, such as rice mills, farms, start-ups, or highly specialized corporations; the rest are public–private alliances, unions, or organizations. Even small-scale producers and companies rely heavily on collaborative efforts to access resources, share information (e.g., with research institutions), and establish reliable distribution channels for their final goods.

There are some companies that specialize in producing biochar exclusively from rice milling waste, while some carry out both rice processing and biochar production. Collecting and transporting rice straw and husk from the field and mills and their treatment are the key activities involved in the conversion of rice waste and by-products. Many different types of partnerships exist, depending on the interests of the many parties involved. For example, some companies collaborate closely with academic institutions, others are founded on government-funded research or public–private partnerships and others are rooted in business-related non-profit organizations. The second point is that private–public partnerships are more common both within (among paddy farmers, millers, and cooperatives) and outside (e.g., poultry farms, bioenergy suppliers, clay bricks and pots makers, paper making or artisanal industry) the rice supply chain.

Concerning the key resources used, besides the rice seeds used for rice production, other parts of the rice plant, including waste generated in the milling process, can be valorized. From the whole value chain of the rice industry, there are many types of waste generated in each stage, such as in cultivation and harvesting; non-harvested paddy, half fill grains, dead grains, straw in retail; low-quality paddy in processing; husk, bran, in distribution; rotten rice, in consumption; processed rice, cooked rice and expired rice. The resources from the rice production process are the dominant resources for valorization. There are many valorization processes for rice bran and husk, and rice bran is completely valorized within the current system. Unfortunately, in many cases, the straw is burnt, and a higher amount of husk is also going to open field burning. Therefore, this case study is mainly focused on rice straw and husk.

According to Figure 9, the outcomes of the assessment processes, i.e., the value proposition in terms of finished goods or raw materials, could be categorized in the order of greatest to least value-added product or utilizations as follows: cosmetic applications and medicine, high-tech industrial materials, food, animal food, water treatment and sanitation, construction, fertilizers, and energy. Many biochar producers produce biochar for fertilizer and energy purposes. Some of them use biochar for construction work and water treatment sectors. However, there are no manufacturers found in Sri Lanka to produce biochar for the specific purpose of use as cosmetic, medical, and high-tech industrial materials.

Biochar has a high carbon content of up to 90% and binds carbon material reliably, long-term, and without adverse side effects. It is characterized by fascinating physical and chemical properties and positively affects biochemical processes. Biochar has proven to improve the quality of construction materials such as concrete or asphalt. It is widely used as a fodder additive for animal health for cleansing air and water; it helps regulate humidity, absorbs toxins, and fosters beneficial microbial life. It can and should be locally sourced from residual material, limiting transportation costs and emissions, and it replaces scarce resources while improving the quality of the end products. These benefits make it a precious resource; therefore, its primary uses are likely gaining higher levels of business importance. The advantages of using biochar in the agricultural sector are shown in Figure 10. Biochar has the potential to enhance processes, reduce emissions of greenhouse gases, and generate carbon sinks in seven different systems of agriculture, as shown in Figure 10.

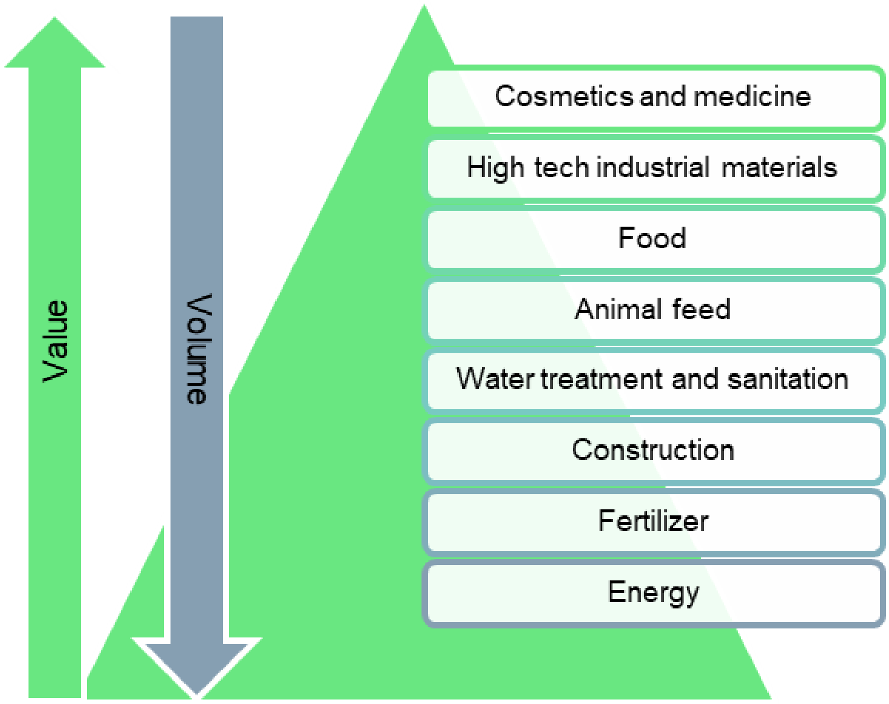

Figure 9. Biochar valorization outputs adapted to the waste valorization pyramid (own design).

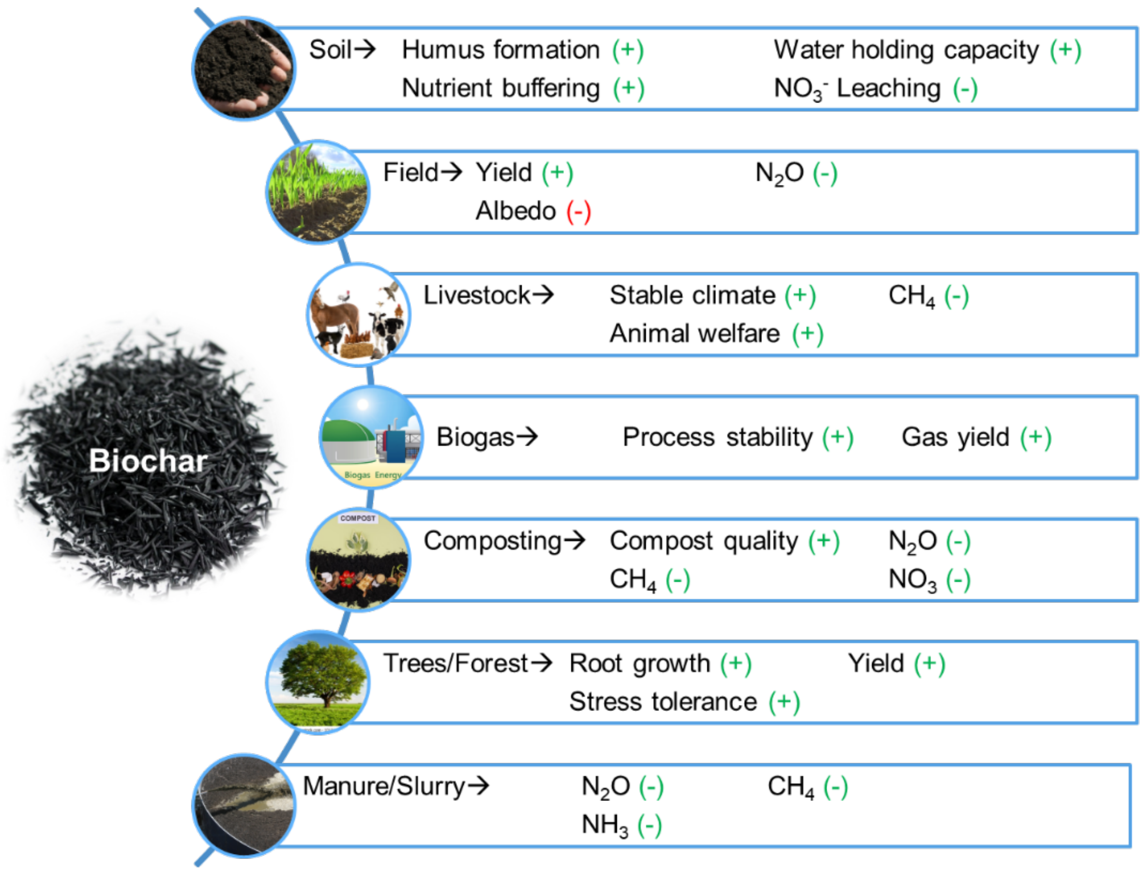

Figure 10. Benefits of biochar application in agriculture: Increases (+) and decreases (−) are visualized as positive (green) or negative (red) effects (own design).

In the study of business models, customers are divided into two groups: business-to-business (B2B) and business-to-consumer (B2C). However, depending on the quality and standard of the final product, customers will differ. Since biochar is a centered raw material, it often deals with B2B. It can also be classified as B2C in terms of some small-scale farmers, bioenergy users, and animal farms. Rather than the traditional customer–producer relationship, circular business models include interactions between several parties. This indicates that both parties share accountability; for example, the customer is somewhat accountable for the quality of goods provided by the producer. In addition, a business model's responsiveness to specific client requirements and close connection to the firm's strategic analysis is necessary for sustained competitive advantage. It is also sometimes unclear how customers feel about bio-based goods, which may vary depending on whether they are aware that the items are made from by-products or waste or how eco-friendly they are. Therefore, consumer behavior studies and increased customer education spending are essential.

Distribution and communication routes have been analyzed to determine the most effective ways. Household and small-scale producers selling their products directly to consumers like farmers and energy generators are only two examples of direct distribution channels. Indirect channels include the likes of merchants and biomass marketplaces. The same is true for long-distance distribution; for example, when biochar is used as animal feed, fertilizer, or in producing high-quality, standardized biochar exported all over the globe. To reach a wider audience, small-scale companies use both conventional and social media, as well as trade shows. However, large-scale companies are increasingly prioritizing online and mobile storefronts above conventional and social media channels to spread the word about their goods. It is fair to acknowledge, nevertheless, that websites often fail to adequately, if at all, explain their practices concerning waste and by-products. Finally, there was a lack of readily available information about the cost and revenue structures of the enterprises. However, managing the perishability, seasonality, and fluctuation of agricultural goods, the costs and accounting efficiency of collecting waste and by-products, and forming lasting relationships with local farmers is challenging. Furthermore, it is clear that certain items in a given category command greater market pricing than others. A summary of the circular business canvas model is shown in Figure 11.

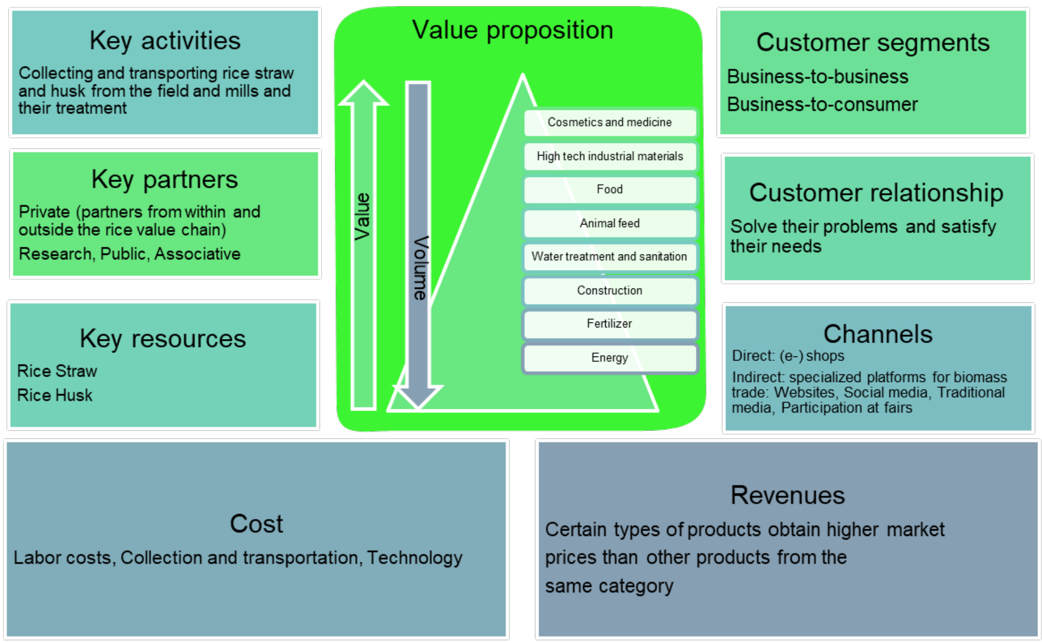

Figure 11. Circular Business Canvas Model for biochar production from rice industry by-products (own design).

4. Key Insights of the Study

I. Public commitment to the environment in the context of wasted and unsustainable waste management in the rice industry is the primary motivator for implementing by-product valorization initiatives in the sector. In South Asia, Sri Lanka is also a major rice husk and straw producer.

II. It is common for companies to focus primarily on the value addition of rice industry by-products. However, the value-adding process may also be a great side business for rice producers.

III. Although some businesses operate as unions, organizations, or public–private alliances, the overwhelming majority is run by sole proprietors who may be either small-scale rice millers, entrepreneurs, or global corporations with specific specializations.

IV. All rice industry by-products have valorization potentials, but complete value-addition activities are often confined to just one or a few resources and practices, only a few valuation options.

V. While there is more potential for effectively marketing high-value-added goods, most rice sector by-products are now turned into low-value-added products (bioenergy or fertilizers).

VI. Appropriate technology is required for environmentally friendly, high-quality biochar production with minimum specific operational and technical requirements that can efficiently operate under field and household conditions.

5. Conclusions

This study focused on the valorization options for review and evaluation with the guidance and assistance of experts in the waste management sectors in Sri Lanka and Italy and accordingly defined the considered criteria and sub-criteria. Furthermore, the results of the AHP analysis show the preferred value of each criterion and demonstrate that the most important decision-making criteria for the implementation of the rice industry by-product valorization in Sri Lanka are the environmental criteria with local priority vector of 0.5887, followed by the social, economic, and technical criteria with local priority vectors of 0.2552, 0.0955, and 0.0606, respectively. According to these four criteria, the preferences of the rice industry by-products management in Sri Lanka are that biochar production is the best-performing valorization option, followed by composting, energy-generating, and other composting activities. The first two choices with the greatest priority vectors can undergo a life cycle assessment to evaluate their environmental impacts.

There is still a substantial knowledge gap about circular business models, particularly in the context of the bioeconomy in the rice industry by-products. The closed-loop and/or cascading techniques inherent in the business models of the circular bioeconomy are novel management solutions to ecological concerns that can be used to develop and market biochar goods or their uses using biomass waste instead of fossil-based resources. However, there are still many risks and obstacles that circular business models must overcome. Several issues prevent bio-based products from becoming mainstream, such as insufficient supportive policies, reliance on incentives, the requirement of significant investment and cooperation with appropriate technologies, price competition for bio-based products, and insufficient consumer communication. We suggest expanding studies focusing on circular business models of biochar production from agricultural waste by paying special attention to business communications, marketing techniques, and value sharing between the major chain players.

Author Contributions: Conceptualization, W.A.M.A.N.I. and S.S.; methodology, W.A.M.A.N.I., A.K.K., K.D.H.E.L., A.M.Y.W.A. and S.S.; software, W.A.M.A.N.I., K.D.H.E.L. and A.M.Y.W.A.; validation, W.A.M.A.N.I., A.K.K., K.D.H.E.L. and C.M.; formal analysis, W.A.M.A.N.I.; investigation, W.A.M.A.N.I., A.K.K., K.D.H.E.L. and A.M.Y.W.A.; data curation, W.A.M.A.N.I., A.K.K. and A.M.Y.W.A.; writing—original draft preparation, W.A.M.A.N.I.; writing—review and editing, W.A.M.A.N.I., C.M., K.D.H.E.L., A.M.Y.W.A., A.K.K., P.G.R., M.C.C. and S.S.; supervision,

C.M., A.K.K., P.G.R., M.C.C. and S.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The authors are grateful to the Department of Agricultural Engineering at the University of Peradeniya, Sri Lanka, and the Postgraduate Institute of Agriculture, University of Peradeniya, Sri Lanka, for providing the necessary facilities. Darusha Vitharana of the Sri Lanka Rice Research Center deserves the deepest thanks for supplying important data and information that helped make this research a success. Nimesh Ariyadasa is acknowledged for his invaluable assistance in bringing together diverse stakeholders in Sri Lanka. All the staff of the Sustainable Agriculture Research & Development Center in Sri Lanka deserve the deepest thanks for supplying important data and information that helped make this research a success. Hashani Ruwanthika Padmasiri is acknowledged for her invaluable assistance in making this research a success.

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

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