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Review

Rice Straw Utilisation for Bioenergy Production: A Brief Overview

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Abstract: Unsustainable rice straw management causes environmental impacts; hence, utilisation of rice straw for bioenergy is a promising strategy for sustainable rice straw management. Although rice straw has a high potential for bioenergy generation, the whole production cycle and application may cause environmental damage that is not fully understood. Hence, environmental performance studies are required to determine the most effective rice straw utilisation options. A comprehensive approach, such as life-cycle assessment (LCA), can give comprehensive information on the possible environmental effects of rice straw utilisation for bioenergy. Therefore, this study briefly overviews the LCA of rice straw utilisation for bioenergy production. It is found that utilisation of rice straw for bioenergy could reduce global warming potential compared to energy production from fossil fuels. However, it is suggested that other impact categories in LCA be evaluated in the bioenergy production from rice straw research to determine the overall sustainability of the production.

Keywords: rice straw; waste management; bioenergy; life-cycle assessment; sustainability

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1. Introduction

Rice is a staple food for many countries in the world; hence, this sector plays a critical role in achieving Sustainable Development Goal 2 (Zero Hunger). Global environmental issues such as global warming contribute to the negative impacts on rice production and consequently threaten food security. Rice production has increased tremendously over the years, and its demand is expected to increase by 28% by 2050 due to the increasing world population [1–3]. Figure 1 illustrates the increase in global rice production from the year 2012 until 2021, with the Asian region as the largest producer based on reports from the FAO [4]. The Asian region contributes approximately 90.5% of global rice production.

The increasing demand for and production of rice led to an increase in rice straw production. Rice straw is a rice plant's stalk, which is produced as an agricultural by-product upon harvesting the rice grain. Rice straw contains about 40 to 60% of the rice plant's gross weight [5]. Rice straw is lignocellulosic biomass composed of 43% cellulose, 25% hemicellulose, and 12% lignin [6,7]. The rapid development of rice agricultural methods and technologies, such as the intensification of rice-cropping systems and the use of combined harvesters, has resulted in a rise in the quantity of straw left in the field.

The growing concern regarding global environmental issues such as climate change and fossil fuel depletion has led to other alternative energy sources. Many countries worldwide are aiming to reduce GHG emissions intensity per unit of GDP by 2030 compared to 2005. Hence, exploring a more sustainable energy source is crucial to fulfilling energy demand [8,9]. Therefore, renewable energy has become one of the options to reduce dependency on fossil fuels and contribute to mitigating greenhouse gas (GHG) emissions [10–13]. Biomass is among the most sustainable and cost-effective renewable sources of energy. Compared to fossil fuels, biomass is a more sustainable alternative fuel and can be converted into biomethane gas, potentially replacing natural gas [14,15].

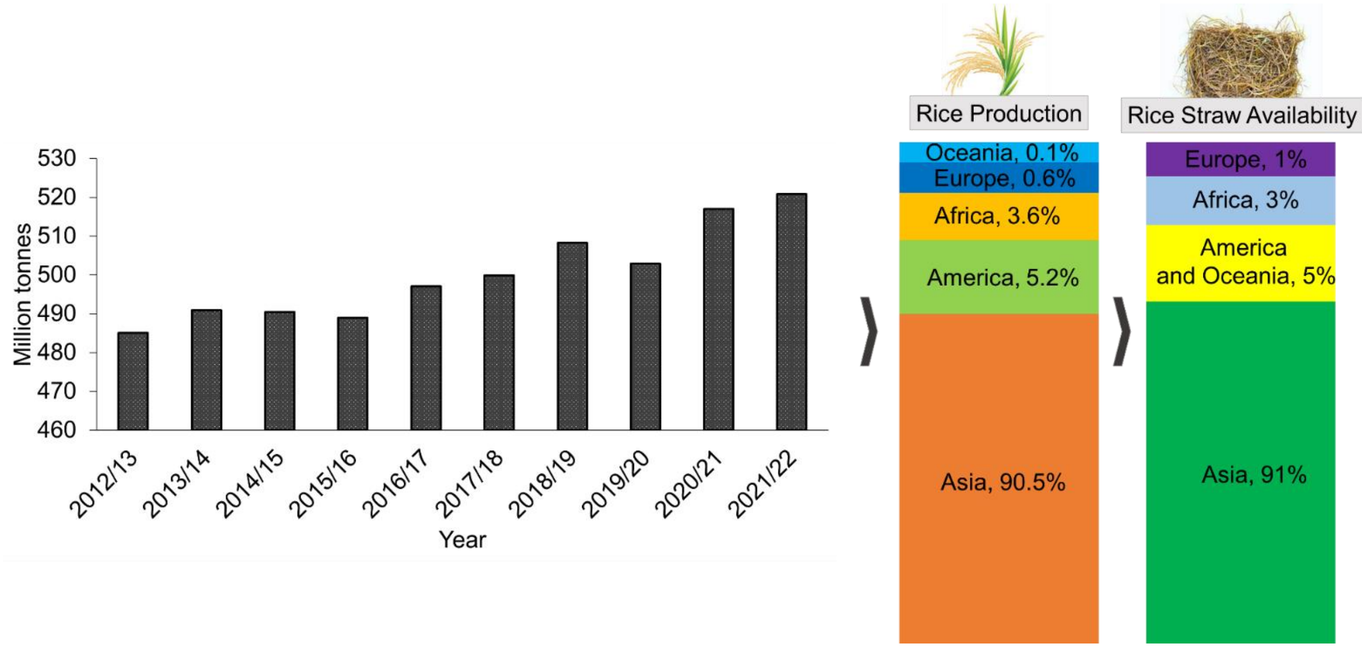

Figure 1. Global rice production [3,16].

Agricultural waste is an attractive feedstock for an alternate bioenergy source. Many European countries encourage bioenergy production and usage since it promotes the diffusion of a circular economy [17]. The circular economy strives to reduce or eliminate the use of fossil or non-renewable input resources in a manufacturing system while maximising their reuse within the same system [18,19]. Hence, bioenergy can contribute significantly to circular economy practices. In addition, the use of agricultural residue in energy production could mitigate gaseous emissions such as CO_2, SO_x, and NO_x due to the low amount of S and N in the agricultural residue [20,21]. Agricultural residues such as rice husk, rice straw, and sugarcane bagasse, among others, have been utilised worldwide to produce renewable energy. Rice straw constitutes almost half of the paddy plant's weight and is considered one of the important agricultural wastes for bioenergy utilisation [5].

Utilisation of rice straws for bioenergy purposes has been attractive in recent years. Various studies have been conducted to see the potential of rice straw to be utilised as a bioenergy resource. Multiple studies have been reported on rice straw utilisation. For instance, Dash et al. [22] conducted a study on the utilisation of rice straw for bioenergy by focusing on methods for developing rice genotypes for higher yield and greater biofuel production. On the other hand, Idris and Hashim [23] conducted a study on renewable energy transformation in Malaysia through bioenergy production, and Rosmiza et al. [24] evaluated the potential of rice straw in agricultural activities in the MADA region of Kedah, Malaysia. Although rice straw has great potential for bioenergy production, the full cycle of the production process and application might exhibit potential environmental pollution that may not yet be completely understood. Studies on environmental performance are essential for understanding the best-practise technologies for rice straw utilisation from environmental perspectives. In addition, information on the source of emissions is important to be investigated to determine the environmental hotspot of the process. Hence, some improvements can be made, particularly on the inputs of the material used.

A comprehensive technique and tool such as the life-cycle assessment (LCA) that could provide a thorough understanding of the potential environmental effects and assure the environmental sustainability of rice straw utilisation for bioenergy are necessary [25]. LCA is a comprehensive assessment to evaluate the environmental performance and identify a product's or system's environmental hotspots throughout its entire life cycle [10,26,27]. LCA is a holistic approach that takes into account all the inputs and outputs involved in the production of a product or system. LCA is based on the International Organization for Standardization (ISO) 14040 series (ISO 2006; 2006; 2006d) and ISO 14044 (2006) [28,29], which consists of four phases, namely goal and scope definition, life-cycle inventory (LCI), life-cycle impact assessment (LCIA), and interpretation. LCA results can be implemented for various purposes, including policy making, product development, or improvement. The present study provided a brief overview on the LCA of rice straw utilisation for bioenergy to provide references for future research and practise in rice straw utilisation for bioenergy.

2. Rice Straw Composition and Management Practice

Annual rice straw production on a global scale is roughly 800 to 1000 million tons, with about 91% of the straw produced in Asia as shown in Figure 1. Rice straw production is rapidly increasing due to the shorter turnaround times needed for intensified rice cropping. Rice straw has the potential to be processed and utilised in agriculture for a range of purposes, including the improvement of soil quality through carbonisation and composting, the production of bioenergy, and the production of industrial products, such as bio-fibre and silica [30,31]. However, from an economic point of view, not all of the options are good because the costs of materials made from rice straw, including the cost of transportation, are still higher than the costs of materials made from other traditional feedstocks or feedstocks that already exist [32–34].

2.1. Rice Straw Composition

The components of rice straw include panicle rachis, leaf blades, leaf sheaths, and stems [24,35,36]. As mentioned earlier, rice straw is a lignocellulosic biomass consisting of cellulose, hemicellulose, and lignin. Cellulose consists of monomeric D-glucose subunits connected by glycosidic linkages and is categorised as crystalline or amorphous [37,38]. Hemicellulose contains pentose, hexose, uronic acids, etc. [39]. Hemicellulose holds lignin and cellulose molecules together for tensile strength [40]. Lignin protects the monolignol (p-coumaryl, coniferyl, sinapyl) mosaic structure [41]. Table 1 shows the composition of rice straw.

Table 1. Composition of rice straw [6].

Component	Quantity (wt %)
Cellulose	43
Hemicellulose	25
Lignin	12
Ash and silica	34–44

2.2. Rice Straw Management Options

Figure 2 shows the various techniques for rice straw management. Rice straw management practises are divided into in- and off-field options. In-filed options include open field burning, mulching, and incorporating straw into the field. Open field burning is a common technique used in most producing countries for a variety of reasons, including high labour costs for manual straw collection, soil incorporation challenges due to multiple cropping rotations per year, insufficient decomposition time, and so forth [42,43]. Rice straw used to be manually gathered and utilised as a raw material in the production of paper, fertiliser, and animal feed. With the advancement of rice straw vaporisation technology, rice straw collection has become laborious and expensive. Therefore, it is not profitable for farmers to collect rice straws manually. Due to the lack of time required for the decomposition of rice straw, the incorporation of rice straw into intensive systems with two to three cropping cycles per year presents various obstacles. Due to these reasons, rice straw field burning practices have increased rapidly. The rice straw open field burning practise has negative environmental consequences such as GHG emissions and suspended particulate matter. On the other hand, incorporating rice straw into paddy soil may maintain and improve soil fertility.

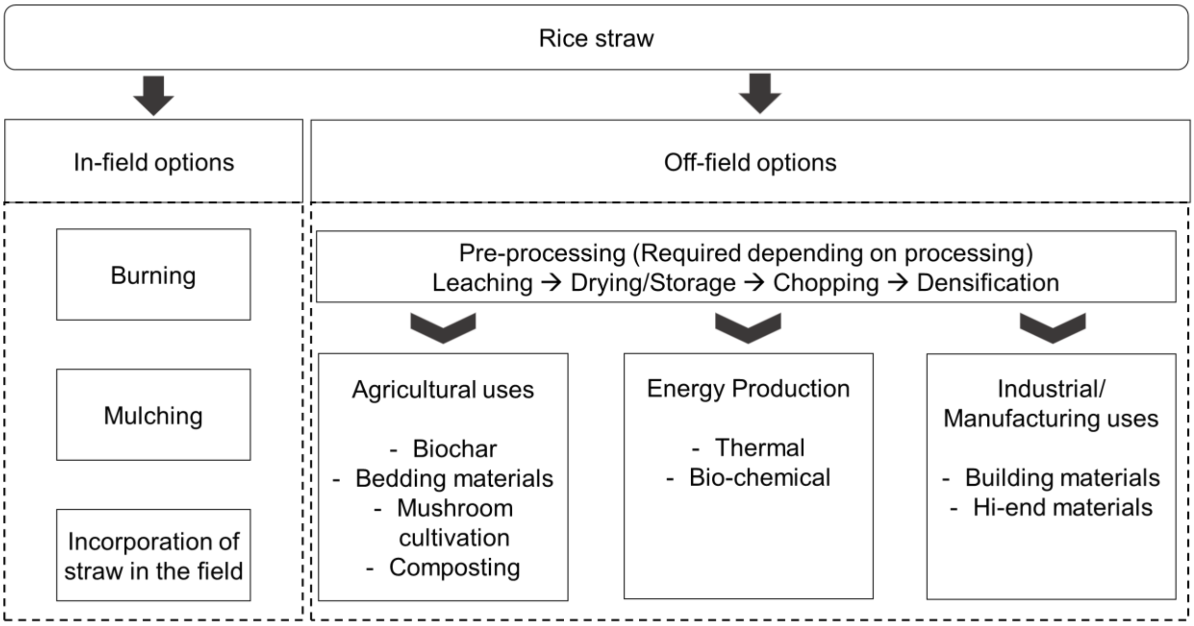

Figure 2. Overview of rice straw management options.

However, inefficient straw integration management may lead to decreased production efficiency and higher greenhouse gas emissions. After incorporating straw into the soil, appropriate management considerations for greenhouse gas emissions (GHG) must be considered [44]. The slow decomposition rate of rice straw is one of the main reasons some farmers avoid incorporating it into the soil, particularly in intensive cropping systems with a 3-week intermission. Regarding total carbon dioxide equivalent (CO_2-eq) per hectare transformed from CH_4 and N_2O, recent IRRI research revealed that rice straw soil integration emitted between 3500 and 4500 kg CO_2-eq ha^1 [45], which is 1.5–2.0 times greater than when rice straw was removed. Thus, removing the straw from rice fields can prevent open field burning and significantly help in reducing GHG emissions from the rice production cycle [46].

Off-field options for rice straw management were divided into three sub-categories: Agricultural uses, energy production, and industrial/manufacturing uses. Most of the rice-producing countries use rice straw for agricultural uses such as biochar, bedding materials, mushroom cultivation, composting, and livestock feed. Rice straw has also been used in industrial sectors, such as to produce roof insulation [47] and rice straw particleboards [48]. As the world focuses on reducing its dependency on fossil fuels for energy production, biomass from rice straw has gained attraction for bioenergy production. Table 2 shows the rice straw utilisation for bioenergy in Asia. China is the leading country that utilises rice straw for bioenergy. A total of 53.6% of rice straw production has been used in China for rural energy generation. Bioenergy production from rice straw involves various technologies discussed in the next section.

Table 2. Rice straw utilisation for bioenergy in Asia [24,49,50].

Country	Rice Straw Utilisation	Percent (%)
Thailand	Biofuel	0.2
China	Rural energy	53.6
Japan	Combustion	4.6
India	Biogas	28.0

3. Technologies in Rice Straw Utilisation for Bioenergy

Rice straw has the potential to be an essential resource for various sectors as it is widely available and renewable. It can be converted into heat, steam, coal, methanol, ethanol, biodiesel, and raw materials [51,52]. This is in line with the principles emphasised by the United Nations' Sustainable Development Goals (SDGs), namely the optimal use of resources and responsible use of resources within the concept of a circular economy. Therefore, recycling agricultural waste and converting waste to other economic sources is an excellent initiative to manage growing rice straw production.

Several technological approaches can be used for the conversion of rice straw for bioenergy, as shown in Figure 3. The conversion technologies are divided into two: thermochemical conversion (combustion, gasification, and pyrolysis) and biological conversion (fermentation and anaerobic digestion). The combustion method is widely used because it is easy to implement. The combustion process through furnaces, turbines, boilers, and so on can convert the chemical energy inherent in biomass into thermal or electrical mechanical energy [53]. Gasification is the conversion of biomass to a mixture of flammable gases that occurs at high temperatures between 800 and 1100 °C under controlled oxidation of biomass [54]. The gasification process involves intermediate processes, including drying, pyrolysis, combustion, and reduction. Among the resulting gases are carbon monoxide, nitrogen, methane, and hydrogen [55]. They can be used directly for thermal applications or as a fuel in internal combustion engines to generate mechanical or electrical power. Pyrolysis is the process of converting biomass into non-condensable solids, liquids, and gases, which occurs at high temperatures in the range of 300–800 °C in the absence of oxygen [56]. Products produced through pyrolysis include biochar, bio-oil, and gases such as H_2, CH_4, CO, CO_2, N, and others [57].

Biochemical technology is a network of technologies used to produce chemicals and products through the biological transformation of bio-based and renewable materials [58]. Fermentation is a process used to produce bioethanol. The fermentation process involves the breaking down of biomass and converting starch to sugar by enzymes. Then, ethanol is produced by the method of converting sugar to ethanol by yeast. Fermentation usually uses glucose from sugar (molasses, sugar cane), starch (wheat, corn, cereals), or cellulose (wood, grass) [59]. On the other hand, anaerobic digestion is the degradation of organic matter such as animal waste, food waste, and agricultural waste to produce biogas in the absence of air [60]. There are four main processes in the anaerobic digestion process: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Using agricultural waste for anaerobic digestion processes requires pretreatment of the waste. Anaerobic digestion technology is a technology that produces the lowest environmental loads such as greenhouse gas emissions and air pollutants compared to other technologies [53,61,62].

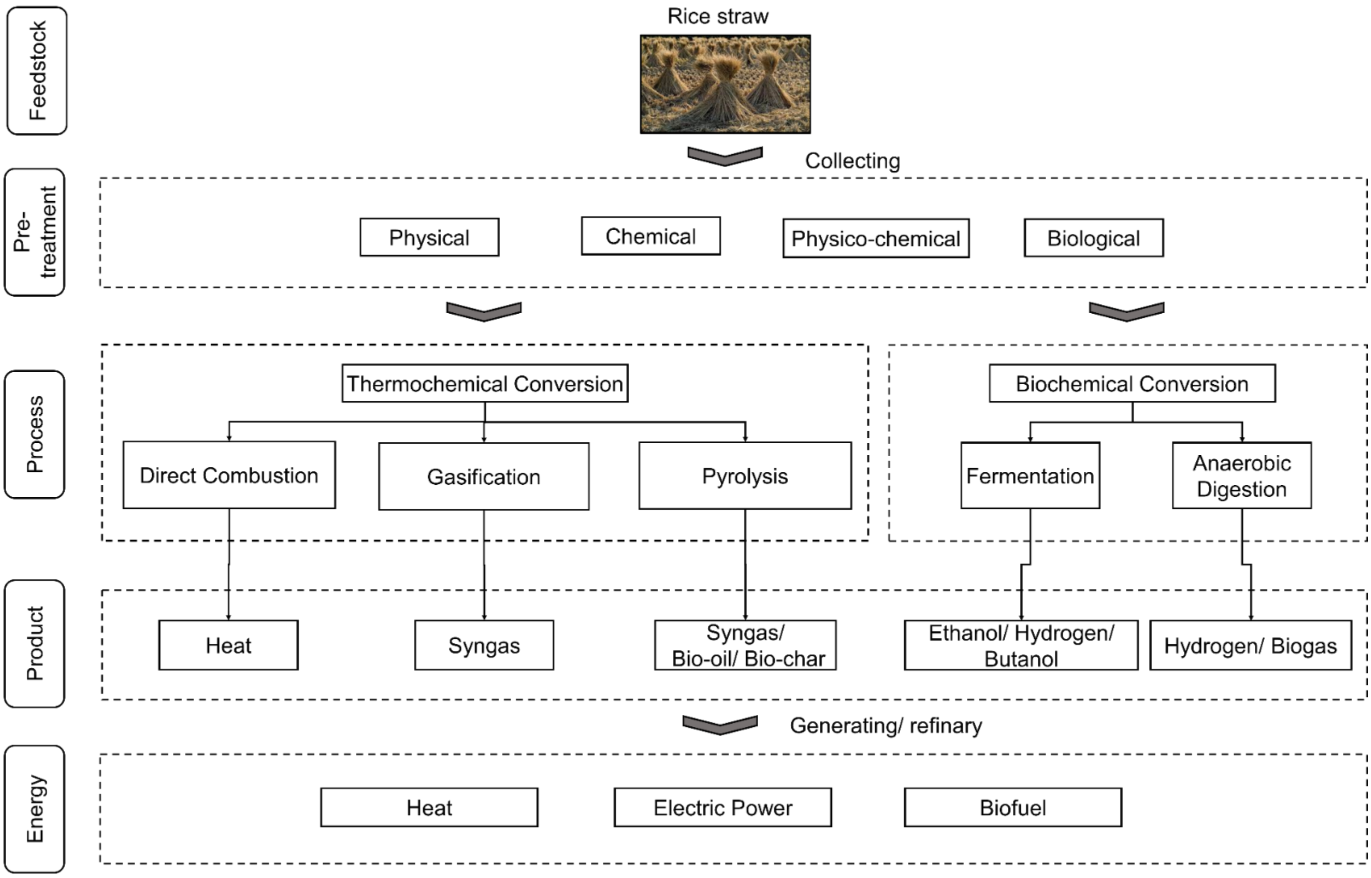

Figure 3. Technologies for conversion of rice straw to bioenergy.

4. Circular Economy Concept

Many countries strive to identify alternative energy sources to incorporate or replace fossil fuels and mitigate global warming. Utilising renewable energy sources for energy production, such as biomass, is a strategic approach to achieving sustainable development goals (SDGs), particularly SDG7, by providing access to clean, secure, reliable, and affordable energy [63–65]. In addition, SDG targets encourage the optimum and responsible utilisation of resources, resulting in a compelling transition to a circular economy. The significant negative effects of landfilling, the dependence of national economies on resource extraction and recovery, and the rapid emergence of urban business models that compete with traditional recycling firms pose major obstacles to the emerging adoption of the concept of a circular economy.

The circular economy concept involves the production and consumption systems with low material and energy losses through extensive reuse, recycling, and recovery [66,67]. Therefore, extensive product and business process transformation are needed to successfully shift to the circular economy. The concept of a circular economy has gained a lot of support globally. Many countries have taken steps to shift from a linear economy to a recycling and circular economy. It is predicted that the circular economy will become the dominant economic model in the future. Figure 4 explains the difference between linear economy, recycling economy, and circular economy.

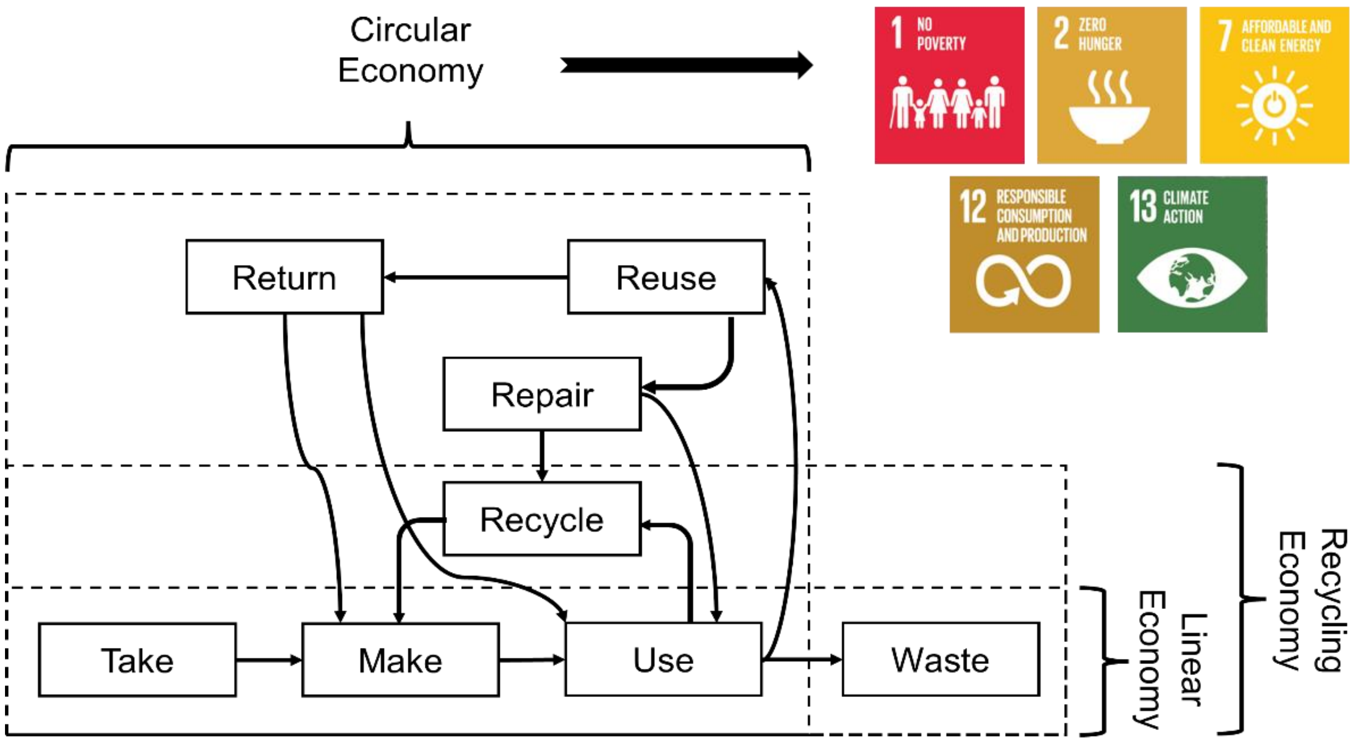

Figure 4. Circular economy approach.

Agricultural waste valorisation for bioenergy has gained attention and interest in recent years. Many studies have reported that the anaerobic digestion technology is the most cost-effective and environmentally beneficial way to convert agricultural waste to energy due to GHG reduction [53]. However, transitioning successfully to a circular economy would require strategies for balancing industrial and economic growth, environmental protection and preservation, and resource-efficient measures [68]. Furthermore, the environmental performance of agricultural waste should be analysed throughout its whole life cycle because agricultural production phases have also led to adverse environmental impacts, such as GHG emissions. As a result, the overall impact of the full supply chain process of the agricultural waste valorisation for bioenergy could be assessed following the circular economy approach. The use of LCA in the field of circular economy is therefore appropriate for evaluating the environmental performance of circular product designs as well as large-scale changes, such as the shift toward a more circular economy [67,69]. LCA and the circular economy concept share the ultimate objective of reducing environmental consequences. When LCA results contradict circular economy principles, circularity should not be imposed. Therefore, bioenergy is one of the circular economy action areas requiring detailed evaluation [18,70].

5. Environmental Performance of Bioenergy Production from Rice Straw

The life-cycle assessment (LCA) is a tool to assess the environmental performance of a product or process by measuring energy and material use from the collection of raw materials phase until the end-product life cycle [28]. Moreover, LCA enables the identification of possibilities to enhance the process of environmental sustainability over the whole life cycle [21,71]. This evaluation is beneficial for computing and modelling energy balance and the environmental impacts, including climate change, ozone depletion, acidification of terrestrial land, and eutrophication of freshwater and marine environments. The LCA assessment is divided into four phases. The first is objective and scope definition, which specifies the research's goal and scope, system boundary, and functional unit [72,73]. The second phase is life-cycle inventory (LCI), which models a product's life cycle by examining its inputs and outputs. The third phase is known as life-cycle inventory analysis

(LCIA), and it assesses the environmental performance of a product's full inputs and outputs. The results of the investigation are evaluated and concluded in the fourth phase (interpretation) by identifying feasible solutions to lessen the environmental burdens [26,74]. Figure 5 depicts the overview of phases in LCA assessment.

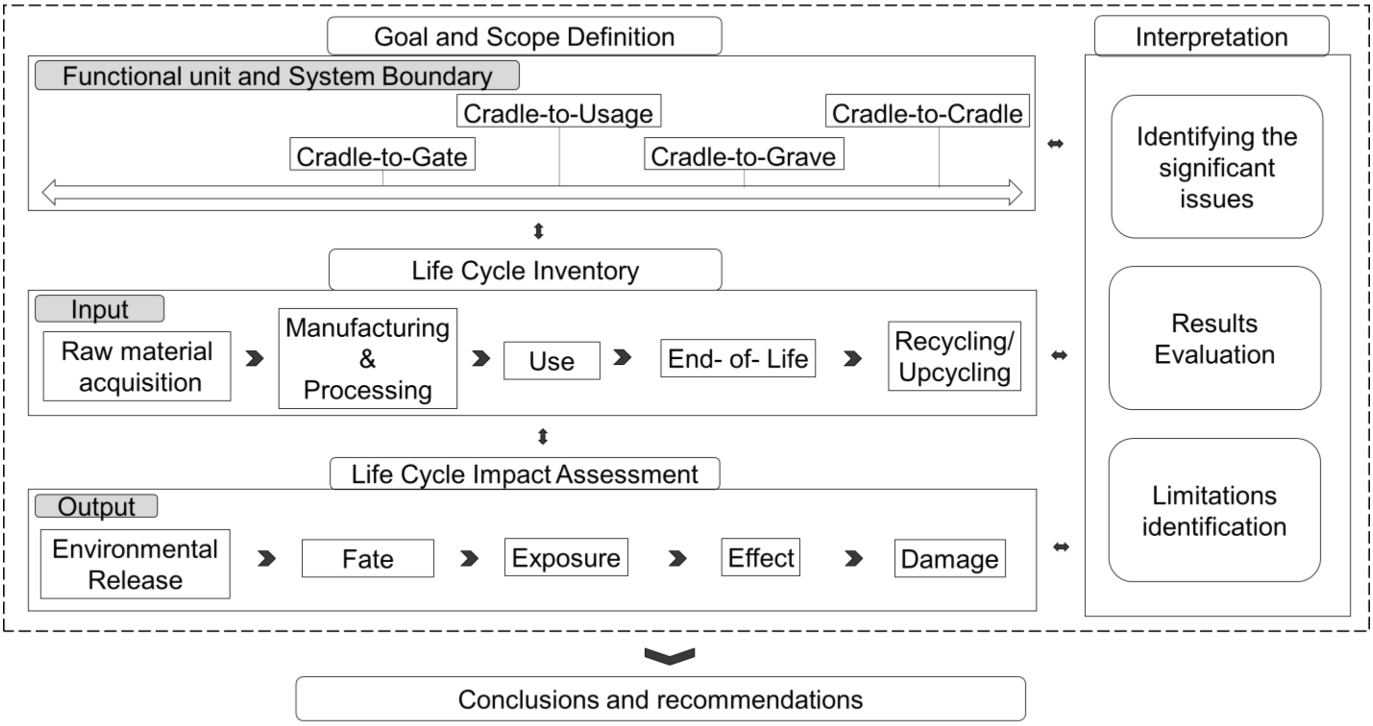

Figure 5. Overview of the four phases in LCA assessment.

Table 3 shows the LCA studies on the utilisation of rice straw for bioenergy production. Most of the studies were carried out in Asia because Asian countries are major global rice producers and consumers. In general, the environmental performance, specifically GHG emissions of bioenergy production from rice straw, is lower compared to fossil fuels [75]. The environmental performance of bioenergy production from rice straw is affected by several factors, for instance, conversion technologies, transportation fuel, impact assessment, etc. [74,76]. Cherubini [77] reported that the generation of heat and power from biomass offers more GHG emissions reduction and energy-saving benefits than biofuel production. Prasad et al. [21] and Muench [78] suggested that deploying dedicated and non-dedicated lignocellulosic biomass for energy generation with thermochemical conversion can cut more GHG emissions than direct burning of lignocellulosic biomass.

Table 4 shows the percentage comparison of agricultural waste reduction, air pollution, and global warming potential between the conversion technologies. Percent of agricultural waste reduction represents the reduction of the agricultural waste amount that needs to be disposed of. It is reported that thermochemical conversion could contribute to a high percentage of agricultural waste reduction (75–90%) compared to biochemical conversion technologies that contribute to a 45–50% reduction. However, anaerobic digestion contributed very little to air pollution and global warming potential compared to thermochemical conversion technologies [53,92,93]. The classification of air pollution has been reported by a previous study [93] that compared the emissions of air pollutants such as carbon dioxide and methane from bioenergy conversion technologies using a weightage formula and classified them as very low, moderate, high, and very high. Since bioenergy production from rice straw has various conversion technologies and pathways, it is crucial to identify the most sustainable approach for bioenergy generation.

Table 3. Previous studies of LCA of rice straw utilisation for bioenergy.

No.	Year	Author	Location	System Boundaries	Functional Unit	Method/LCA Software	Sensitivity	Impact Categories	Findings
1.	2021	[76]	India	Cradle-to-grave	1 ton of rice straw	NA	NA	Energy GHG	GHG reduction: - Dilute acid (DA) pretreatment = 11,954 kt CO_2 eq - Steam explosion (SE) pretreatments = 14,375 kt CO_2 eq
2.	2019	[2]	China	Cradle-to-grave	1 MJ of electricity output	NA	Yes	Water consumption	- Water consumption = 11.71 L/MJ
3.	2019	[79]	India	Cradle-to-gate	1 ton of rice straw	CML2	Yes	Global warming potential (GWP) Acidification potential (AP) Photochemical oxidants creation potential (POCP) Eutrophication potential (EP)	- The highest GWP reduction is gasification = 1343 kg CO_2 eq./tonne - The incineration and gasification reduce the total SO_2 eq. by 10.09 and 10.70 kg/tonne, respectively - For POCP, incineration and gasification reduce 1.33 and 1.14 kg C_2H_4 eq./tonne, respectively - EP = incineration and gasification reduce 0.71 and 0.74 kg PO_4 eq./tonne - Gasification is best to improve the overall environmental impact
4.	2018	[80]	India	Well-to-gate	1 L ethanol produced	CML 2	NA	GWP AP EP POCP	Overall LCA results reveal that performance of modified pretreatment (MP) 2, MP3, and MP4 is on the negative side in all the environmental impact categories as compared to conventional pretreatment (CP)
5.	2018	[81]	Thailand	Cradle-to-gate	1000 L bioethanol at 99.7 vol % purity	ReCiPe/SimaPro 8.2	Yes	Mid-point	Bioethanol from cassava shows the best values of net energy ratio (1.34), renewability (5.16), and reduced greenhouse gas emissions (410 kg CO_2 eq/1000 L)

Table 3. *Cont.*

No.	Year	Author	Location	System Boundaries	Functional Unit	Method/LCA Software	Sensitivity	Impact Categories	Findings
6.	2017	[82]	India	Cradle-to-gate	1 MJ of exergy output	CML 2001/Eco-indicator 99	Yes	Mid-point and end-point	Polygeneration with surplus rice straw is more environment-friendly than conventional stand-alone generation of same utilities
7.	2017	[75]	India	Cradle-to-gate	1 ton of dry rice straw	CML2	Yes	GWP EP AP POCP	GWP, AP, and POCP emissions reduction of 1471 and 1023 kg CO_2 eq., 15.0 and 3.4 kg SO_2 eq., and 6.7 and 7.1 kg C_2H_6 eq.
8.	2017	[83]	China	Cradle-to-gate	1 MJSNG	LCSoft version 6.1/SimaPro	Yes	GWP AP Chinese abiotic depletion potential (CADP) Respiratory inorganic (RI)	- GWP = 3.77×10^9 kg CO_2 eq. - AP = 3.64×10^{10} kg SO_2 eq. - CADP = 1.55×10^{13} kg Coal-R eq. - RI = 4.34×10^9 kg $PM_{2.5}$ eq.
9.	2016	[84]		Cradle-to-gate	1 Nm^3	SimaPro 8.0.2/ReCiPe 2008 v.1.09	NA	Mid-point End-point	Human toxicity and marine ecotoxicity were the most significant causes in mid-point category, while human health experienced the highest impact at end-point level
10.	2016	[85]	India	Cradle-to-grave	1 ton of rice straw	IMPACT 2002+	Yes	GWP Energy reduction	Processing of 1 ton of straw to electricity and biogas resulted in net reduction of 1471 and 1023 kg CO_2 eq., 15.0 and 3.4 kg SO_2 eq., and 6.7 and 7.1 kg C_2H_6 eq. emissions in global warming, acidification, and photochemical oxidation creation potential, respectively
11.	2014	[86]	Malaysia	Cradle-to-gate	1 kWh of electricitygenerated	CML 2001	Yes	GWP EP AP Toxicity	Rice straw power generation can save GHG (greenhouse gas) emissions of about 1.79 kg CO_2 eq/kW

Table 3. *Cont.*

No.	Year	Author	Location	System Boundaries	Functional Unit	Method/LCA Software	Sensitivity	Impact Categories	Findings
12.	2013	[87]	Taiwan	Cradle-to-grave	Kilowatt hour	IMPACT 2002+/Simapro 7.2	Yes	GWP Aquatic ecotoxicity Terrestrial ecotoxicity Land occupation Non-renewable energy	- Carbon reduction = 0.04 and 0.09 kg CO_2 eq per kWh electricity generated and 0.36 and 0.39 kg CO_2 eq per kg rice straw at 10% and 20% cofiring ratios
13.	2013	[88]	Thailand	Cradle-to-grave	1 ton of dry rice straw	CML2	NA	GWP	GHG reduction = 35 g CO_2 equiv./MJ or 60% GHG emission reduction as compared to conventional gasoline
14.	2013	[89]	Thailand	Cradle-to-gate	per MJ basis	NA	Yes	GWP	GHG reduction of biodiamethyl ether (bio-DME) used for: - Diesel engine = by around 12–60 g CO_2 eq/MJ or 14–70% as compared to the existing diesel fuel used for transport - Liquefied petroleum gas (LPG) supplement for household applications = about 1–49 g CO_2 eq/MJ or 2–66% as compared to LPG at the same performance
15.	2013	[90]	Malaysia	Cradle-to-grave	6,132,000 MWh (Manjung Power Plant, MP) and 2,628,000 MWh (Kapar Power Plant, KP)	CML 2002	NA	GWP EP AP Human toxicity	Overall GHG emissions for rice straw preparation (starting from paddy production until rice straw available at coal power plant, range between 0.4067 and 0.5994 kg CO_2 eq per kg rice straw ready at coal power plant
16.	2012	[91]	Japan	Cradle-to-gate	m^3 anhydrous bioethanol produced	NA	Yes	GWP Energy consumption	- CO_2 emission = −0.5 to 1.6 kg/L - Net energy consumption = 10.0–17.6 MJ/L

Note: CML = Centrum voor Milieukunde Leiden; MJ = MilliJoule; MJSNG = MilliJoule Synthetic Natural Gas; NA = Unavailable.

Table 4. Comparison of the conversion technologies on the percentage reduction of agricultural waste, air pollution, and global warming potential [53,92,93].

Parameter	Combustion	Gasification	Pyrolysis	Fermentation	Anaerobic Digestion
Percent of agricultural waste reduction	75–90%	75–90%	75–90%	45–50%	45–50%
Air pollution	Very high	Moderate	High	Very low	Very low
Global warming potential (kg CO_2 equivalent per unit MWh electricity generation)	424	412	412	NA	222

Note: NA = Unavailable data.

The impact categories reported in previous studies are varied. Some studies performed complete LCA, while others focused on GHG emissions or energy balance. For instance, Parvez et al. [84] and Jana and De [85] conducted studies covering the mid-point and end-point impact categories, while Hassan et al. [76], Soam et al. [85], Shafie et al. [90], and Roy et al. [91] focused on energy consumption and GHG emissions. On the other hand, Silalertruksa and Gheewala's [88] and Silalertruksa et al. [89] study focus was limited to GHG emissions. Global warming potential (GWP) has been included in most of the previous studies. GWP refers to increases in the average temperature caused by increases in global warming potential as an effect of anthropogenic emissions of global warming gases such as CO_2, CH_4, N_2O, and others. The GWP impact category is the focus of attention in most LCA studies on bioenergy production from rice straw. Based on the previous studies, it was found that bioenergy production from rice straw reduced GHG emissions in the range of 1.79 to 14,375 kt CO_2eq, depending on the technologies and pretreatments used. According to Zhu et al. [2], the highest GWP reduction is achieved by the gasification technique, in contrast to the findings of some researchers such as Soam et al. [75] and Rathnayake et al. [81] who reported that anaerobic digestion is a promising technology to reduce GWP in bioenergy production. To conclude, there are numerous approaches and technologies to convert rice straw to bioenergy; hence, a comprehensive environmental impact assessment for the whole life cycle of each bioenergy conversion technology should be investigated.

Besides GWP, other environmental impact categories considered in previous studies include acidification and eutrophication. Intensive agricultural activities such as nitrogen-based fertiliser usage usually affect acidification and eutrophication [94]. In addition, biorefinery systems also have a high potential for eutrophication and acidification [87,95–97]. A study by Zhu et al. [2] evaluated water consumption for bioenergy production from rice straw. Stand-alone impact category assessment could give limitations in sustainability assessment.

Therefore, the other impact categories in LCA should also be included in the bioenergy production studies to identify the sustainability of the production [98,99]. The other impact categories include global warming (GWP), stratospheric ozone depletion (ODP), ionising radiation (IRP), ozone formation (human health) (HOFP), fine particulate matter formation (PMFP), ozone formation (terrestrial ecosystems) (EOFP), terrestrial acidification (TAP), freshwater eutrophication (FEP), terrestrial ecotoxicity (TETP), freshwater ecotoxicity (FETP), marine ecotoxicity (METP), human carcinogenic toxicity (HTPc), human non-carcinogenic toxicity (HTPnc), land use (LOP), mineral resource scarcity (SOP), fossil resource scarcity (FFP), and water consumption (WCP).

The system boundaries for all the reviewed studies are comparable as they start with the harvesting and collection of straw, followed by transport, processing of straw to the end-product, and finally the use phase. System boundary and allocation are important factors affecting the result of the environmental performance of bioenergy production from rice straw [100,101]. Soam et al. [85] conducted a scenario study on ethanol production from rice straw by extending the system boundary to include the rice farming phase and allocating the emissions based on economic allocation. They reported that increased rice straw prices had increased GHG emissions. The rice farming phase contributed a significant number of adverse environmental impacts on soil, air, and water due to the use of energy for machinery, irrigation, land preparation, sowing, harvest, transportation, etc. [26,102]. For instance, the anaerobic condition due to the flooding condition in rice fields has contributed to GHG emissions and high water consumption.

Studies of bioenergy production from rice straw mostly reported a decrease in adverse environmental impacts compared to energy production from fossil fuels [103–105]. However, the application of LCA involves some uncertainties such as the complexity of the bioenergy system (cultivation, logistics, conversion technology, distribution, end-use, etc.), the variability of LCA methods or models, data deficiencies, spatial and temporal variability, impact categories, indirect impacts, transparency, and the reference system [21,106]. Based on the reviewed studies, most of the studies conducted a sensitivity analysis in their assessment to evaluate the biassed settings, especially in data inventory, and to analyse possible improvement possibilities by substituting the process with an alternate process. Hence, false conclusions could be avoided.

6. Conclusions

The increasing demand for rice production has led to an increase in rice straw generation, particularly in rice producer countries such as Asian countries. Rice straw is a notable agricultural waste readily available and has high potential in bioenergy production. However, the utilisation of rice straw could contribute to adverse environmental impacts if not properly managed. The brief review reveals that the valorisation of rice straw for bioenergy based on the circular economy concept has played a significant role in achieving sustainable development goals. The utilisation of rice straw for bioenergy production involves several conversion technologies and routes; thus, it is essential to perform an environmental performance evaluation to determine the most sustainable methods for the conversion of rice straw for bioenergy production. As a result, numerous scientific research studies on the LCA of rice straw valorisation for bioenergy have been reported. However, LCA studies on rice straw valorisation for bioenergy are currently constrained by the knowledge gap concerning the discharge and exposure of the conversion process into the environment.

Based on the findings, some recommendations for LCA practitioners working in bioenergy production to improve consistency, transparency, and completeness are provided. First, it is strongly recommended to utilise a transparent and prudent characterisation model such as land-use change, toxicity, and eutrophication since a lack of characterisation factors will lead to uncertainty in fate, exposure, and effect factors. Second, combining LCA with other environmental performance approaches or tools such as material flow analysis (MFA) or the geographical information system (GIS) is also recommended to improve input and output data collection in the inventory phase. Inadequate data will lead to uncertainties in process inputs, outputs, and final emissions. Hence, MFA could assist in evaluating the energy and material flow of the valorisation of rice straw for bioenergy production. On the other hand, the conventional LCA method could not detect spatial differences due to the use of generic data; thus, integrating LCA with a spatial platform such as GIS could increase assessment accuracy. Third, a full assessment and analysis of the entire life cycle of bioenergy production from rice straw are recommended to avoid invalid assumptions in the interpretation stage.

To conclude, LCA can be explored for sustainable energy generation by evaluating the most sustainable methods and routes for producing bioenergy from rice straw. The LCA evaluation could help as a policy support tool for policymakers and end-users in the sustainability of agricultural waste valorisation for bioenergy. Sufficient usage of transparent and thorough characterisation models in the LCA interpretation phase needs extra effort on the part of practitioners and researchers. Furthermore, other characterisation factor assessments should be thoroughly investigated for a clear and reliable LCA analysis.

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