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# Rice Straw Valorization for Bioenergy Potential in Southeast Asia: A Brief Review on Life Cycle Assessment (LCA) Perspective

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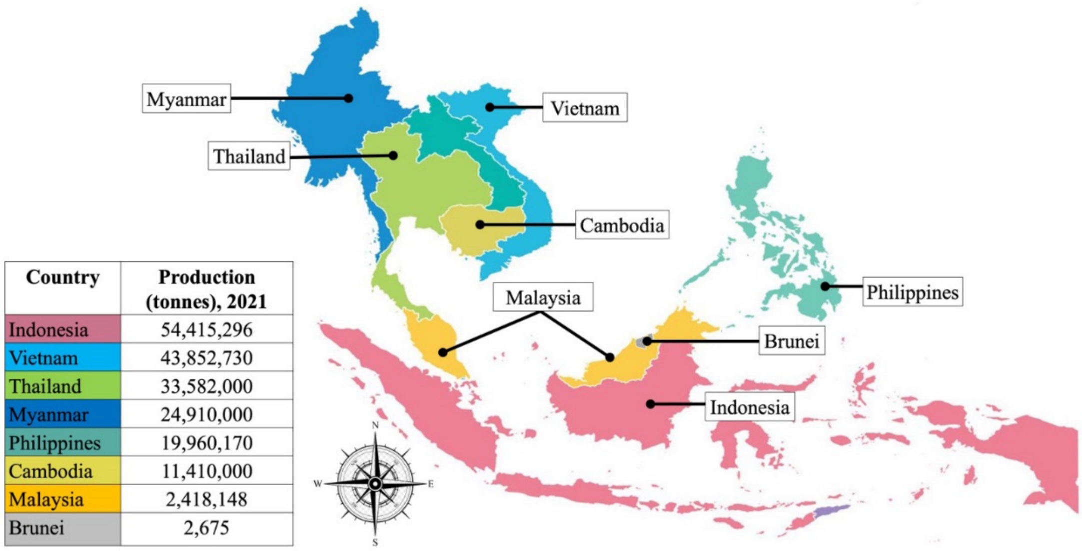
ABSTRACT

*The large amount of rice straw production in Southeast Asia presents both challenges and opportunities for sustainable environmental management. Improper rice straw management poses significant environmental challenges, prompting interest in utilizing it for bioenergy production as a sustainable solution. However, a comprehensive understanding of the environmental implications throughout the entire lifecycle of rice straw utilization is poorly understood. A comprehensive approach of life cycle assessment (LCA) could provide valuable information concerning the environmental impact of rice straw utilisation for bioenergy. Therefore, this study attempts to provide a brief overview of the LCA of rice straw utilisation as a source of bioenergy in Southeast Asia. Several search engines and databases, including Springer, Web of Science, and Scopus, were used to select the articles for this review. These searching strategies involve three main processes: identification, screening, and eligibility. Following those process, a total of 13 articles were included in this review. The findings indicated that biochemical conversion pathways for producing bioethanol and biogas yield the greatest environmental benefits notably through greenhouse gas emissions reduction. This highlights the potential of rice straw bioenergy as a promising avenue for mitigating the impacts of climate change by curbing GHG emissions. In summary, this research underscores the significance of comprehending the holistic environmental implications of rice straw utilization for bioenergy, emphasizing the potential of specific conversion pathways to contribute to sustainable rice straw management and climate change mitigation in Southeast Asia, encouraging further research in this field for practice refinement and widespread adoption.*

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

## INTRODUCTION

The Southeast Asian population heavily relies on rice, a staple food that plays a crucial role in achieving Sustainable Development Goal 2 (Zero Hunger). Globally, rice production reached approximately 787.3 million tonnes in 2021, with Asia dominating this industry. Although China and India are known for their largest rice production, it is important to recognize that Southeast Asia, with countries like Indonesia, Vietnam, Thailand, and Myanmar, also holds a significant position as leading rice producers within the Asian region. In 2021, Southeast Asia collectively produced around 194.5 million tonnes of rice, accounting for 25% of the world's production. Southeast Asia's rice production not only ensures regional food security but also plays an integral role in sustaining the global rice supply chain, representing 40% of global rice exports (Yuan et al. 2022). This highlights its significance in the global rice industry. Figure 1 provides an overview of rice production distribution among Southeast Asian countries as of 2021. According to the Food and Agriculture Organization (FAO) reports, Indonesia leads rice production in Southeast Asia, producing 54.4 million tonnes annually. Vietnam follows as the second-largest producer with 43.9 million tonnes, and Thailand ranks third with 33.6 million tonnes (FAO 2023).




| Country | Production (tonnes), 2021 |
|---|---|
| Indonesia | 54,415,296 |
| Vietnam | 43,852,730 |
| Thailand | 33,582,000 |
| Myanmar | 24,910,000 |
| Philippines | 19,960,170 |
| Cambodia | 11,410,000 |
| Malaysia | 2,418,148 |
| Brunei | 2,675 |

FIGURE 1. Rice producing countries in Southeast Asia (2021)

The production of rice is expected to increase significantly in the near future to meet the demands of the growing population. This rising demand for rice has resulted in a noticeable upsurge in the production of rice straw (Rajamoorthy et al. 2015), considering the production ratio of rice grain to straw typically at 1:1.5 (Singh & Brar 2021). Rice straw, a byproduct of rice cultivation, holds significant value due to its versatile applications in agriculture, including soil improvement, animal bedding, fodder, and even mushroom cultivation. It also plays a role in energy production (heat, electricity, syngas, biofuel) and contributes to the production of industrial products like silica and bioplastics (Mofijur et al. 2019). However, due to time constraints and cost considerations, many farmers still resort to open burning for disposing of rice straw and preparing the land for the next cultivation (Shaha & Valaki 2022). Unfortunately, this practice has negative environmental consequences associated with the emission of greenhouse gases (GHGs) and fine particulate matter. Hence, developing a more sustainable rice straw management practice is essential for combating global environmental issues.

The positive potential of rice straw as a source of renewable energy has received increasing attention (Shaha & Valaki 2023), particularly in its conversion into biomethane gas, a promising substitute for natural gas. In accordance with the long-term plans established by governments across Southeast Asia, for more secure and sustainable energy production, including the attainment of net-zero emissions and carbon neutrality targets, there is an imperative need to shift towards renewable energy sources such as biomass. This transition not only addresses the rising energy demand while contributing to these targets but also serves as a means to reduce greenhouse gas emissions and enhance energy security (Abdul Razak et al. 2021).

Despite the great potential of rice straw for bioenergy production, the full cycle of its production and process poses several environmental pollutions, which is not entirely understood. Therefore, by employing a life cycle assessment (LCA) approach, it is possible to provide a comprehensive understanding of the environmental impacts of rice straw usage for bioenergy and to ensure the sustainability of the environment. This method is frequently used as a tool in environmental management for addressing all the possible impacts of a product or service over the course of its entire life cycle (Soam et al. 2017; Hanafiah et al. 2022; Rashid et al. 2023). Researchers involved in LCA studies have utilized a variety of software tools to aid in their assessments, including SimaPro, OpenLCA, Aspen Plus, and others. Performing this evaluation is extremely beneficial, since it allows for the improvement of each process involved (Abu et al. 2023; Kaita & Harun 2023). In general, LCA assessment involves four phases (refer figure 2). In the first phase, the goals and scope of the research are defined, along with the boundary of the system and the functional unit of the study. The second phase is a life-cycle inventory (LCI), which involves the detailed tracking of all flows in and out of the product system, including raw materials used, energy consumption, water consumption, and emissions to air, water, and land. Life Cycle Impact Assessment before the 'analysis' (LCIA), involves providing indicators for interpreting the inventory data in terms of contributions to different impact categories, such as global warming potential (GWP), human toxicity, eutrophication and so forth. Lastly, the interpretation phase involves discussing the results of the LCI and LCIA as well as drawing conclusions and making recommendations (Jolliet et al. 2015).

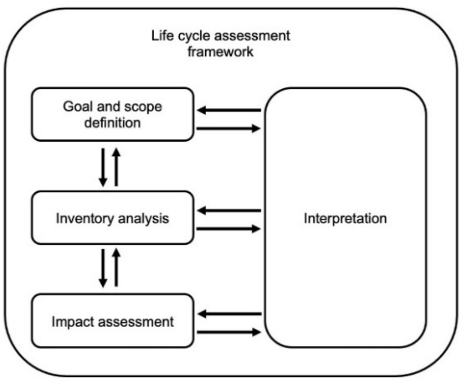



FIGURE 2. General phases of Life Cycle Assessment (based on ISO 14040)

Apparently, the utilisation of rice straw for bioenergy production is fully in line with the current attractiveness of research. Indeed, according to the years since the discovery of this “waste to wealth” materials, the number of publications related to rice straw for bioenergy resource has steadily increased (Figure 3). For instance, Sharma et al. conducted a study on biofuel from rice straw (Sharma et al. 2020). Cuong et al. conducted a study on renewable energy from biomass surplus resource: potential of power generation from rice straw in Vietnam (Cuong et al. 2021) while Liu et al. conducted a study on energy from combustion of rice straw: status and challenges to China (Liu et al. 2011).

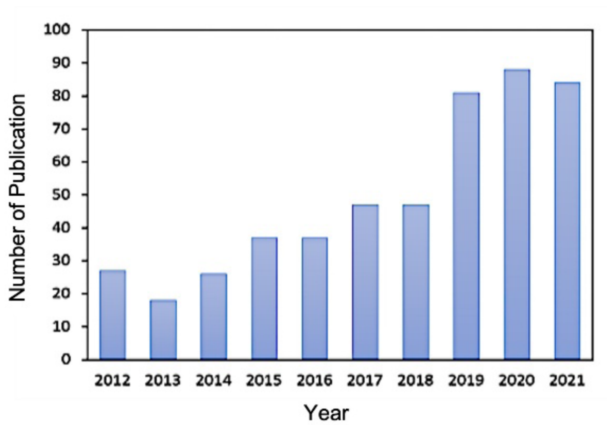



FIGURE 3. Number of publications from 2012 to 2021 on the topic of rice straw and bioenergy production from Web of Science

## METHODOLOGY

The purpose of this review is to provide a brief overview of the potential of rice straw for bioenergy production using the LCA approach based on research conducted in Southeast Asia. Several search engines and databases such as Springer, Web of Science, and Scopus were used in the search process, as they provide advanced searching functions, comprehensiveness, quality control of the articles, and a multidisciplinary focus. During the search, different branches and names of rice straw were considered, including paddy straw, biomass, organic waste, and agricultural waste. Additionally, keywords such as bioenergy, biofuel, energy potential, and life cycle assessment were also included. In the next step, all articles were screened by selecting the criteria for article selection, which is done automatically based on the database’s sorting function. Only articles published in English language included in the review to avoid misunderstanding. Furthermore, the period of publication that was chosen is between 2012 to 2022, as this timeline was deemed to be an adequate period to observe the trend of the research topic. Besides, this study considering only studies published in scientific indexed journals. This process excluded 252 articles because they did not meet the following criteria. Hence, a total of 112 articles were subjected to the eligibility process, which is conducted manually by reading the abstract of the articles. Out of these studies, only about 36% have been conducted in the Southeast Asia region. The primary focus of research on rice residue management has been on the southern and eastern Asian regions, primarily due to the significant volume of rice waste produced in these areas. Surprisingly, there has been limited research conducted in Southeast Asia, despite the region's crucial role in the rice industry. Therefore, this review aims to address the knowledge gap within Southeast Asia and provide a brief overview of rice straw's potential for use in bioenergy, using the LCA approach based on research conducted in the region. Articles that meet the criteria, such as study location in Southeast Asia, using the LCA approach, and using rice straw to produce bioenergy, are selected to be included in this study. Therefore, only 13 articles were included in this review, with 99 articles excluded primarily due to not meeting the specified criteria. The LCA of rice production is also included in this study. The inclusion of LCA for rice production in this study serves the purpose of assessing resource efficiency and emissions, facilitating the identification of strategies to reduce inputs and enhance resource management practices. This assessment is particularly important for promoting sustainable and responsible bioenergy practices, as rice straw utilization for bioenergy production is not solely about the straw itself but also the inputs required during cultivation.

## RESULTS AND DISCUSSION

The data presented in Table 1 provides an overview of studies conducted in Southeast Asia regarding the rice production and the utilization of rice straw for bioenergy production based on (LCA). Most of the studies were conducted in Thailand (7 studies) (Mungkung et al. 2020; Ramsden, Wilson & Phrommarat 2017; Rathnayake et al. 2018; Silalertruksa et al. 2013; Silalertruksa & Gheewala 2013; Thanawong, Perret & Basset-Mens 2014; Yodkhum, Gheewala & Sampattagul 2017), representing about half of the reviewed papers. The earliest article published on the LCA of rice straw utilization for bioenergy was also from Thailand in 2013, indicating early investigation of the environmental impacts of rice straw in this region (Silalertruksa et al. 2013; Silalertruksa & Gheewala 2013).

Typically, rice straw case studies involve a cradle-to-gate system boundaries approach, which considers the raw material acquisition, manufacturing, and processing stages. However, the disposal stage and the potential toxicity of the product associated with the emission of rice straw during its life cycle are often overlooked. This can be represented by the fact that among the 13 studies reviewed, 11 studies considered system boundaries from cradle to gate (Abdul Rahman et al. 2019; Harun, Hanafiah & Aziz 2021; Mungkung et al. 2020; Ramsden, Wilson & Phrommarat 2017; Rathnayake et al. 2018; Shafie, Masjuki & Mahlia 2014; Silalertruksa et al. 2013; Thanawong, Perret & Basset-Mens 2014; Yodkhum et al. 2017) whereas only two assessed the entire life cycle of rice straw from cradle-to-grave (Shafie et al. 2013; Silalertruksa & Gheewala 2013).

The majority of the reviewed studies assessed the environmental performance of rice straw up to the midpoint level, which includes eutrophication, acidification, toxicity, fossil fuel depletion potential, and water footprint (Harun, Hanafiah & Aziz 2021; Mungkung et al. 2020; Ramsden, Wilson & Phrommarat 2017; Rathnayake et al. 2018; Shafie et al. 2013; 2014; Thanawong et al. 2014). Only one reviewed study extended the assessment of environment impacts to the endpoint level (Yusoff et al. 2015). Among the various impact categories evaluated in these studies, global warming potential (GWP) emerges as the most extensively examined category. It is important to emphasize the specific significance of GWP in the context of rice cultivation, especially in flooded paddy fields, as they represent a significant source of methane emissions, a highly potent greenhouse gas (Shafie et al. 2014). This is further supported by research conducted by Rathnayake et al. Silalertruksa & Gheewala, Yodkhum et al. and Abdul Rahman et al., all of which reported similar findings (Abdul Rahman et al. 2019; Rathnayake et al. 2018; Silalertruksa & Gheewala 2013; Yodkhum, Gheewala & Sampattagul 2017). Notably, during rice straw cultivation, methane is produced under anaerobic conditions in flooded paddy rice fields (Rathnayake et al. 2018), contributes approximately 80% of global greenhouse gas emissions (Yodkhum, Gheewala & Sampattagul 2017). The management of water in rice fields is therefore important for not only reducing methane emissions but also for increasing rice yield and preventing weed growth. Additionally, a good agricultural practice (GAP) suggests maintaining the water level at 5-10 cm from the soil surface to prevent weed growth during the tillering stage of seeds (i.e., approximately 20-30 days after seed germination). Also, it is recommended that the water from the field be drained off 20 days after the flowering date or 10 days before harvesting (Silalertruksa & Gheewala 2013). Given methane's significantly higher heat-trapping capability per molecule compared to carbon dioxide, its role in flooded rice paddy fields during rice straw cultivation is of utmost importance in the broader context of climate change mitigation.

TABLE 1. Life cycle assessment studies conducted in Southeast Asia regarding the rice production and the use of rice straw for bioenergy production.

| Year | Location | Objectives | Functional Unit | System Boundaries | Method/ LCA Software | Impact categories | Impact assessment | | References |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Midpoint | Endpoint | |
| 2020 | Malaysia | This research aims to assess the environmental impacts of conventional and organic rice cultivation in Malaysia | 1 ton of rice grains harvested | Cradle-to-gate | ReCipe 2016 SimaPro 8.5 | Global warming potential Water Consumption Potential Fossil fuel depletion potential | O | X | (Harun, Hanafiah & Aziz 2021) |
| 2020 | Thailand | The research aims to assess the environmental impacts of organic rice farming in different regions of Thailand. | 1 kg of milled rice in polypropylene bag | Cradle-to-gate | IPCC | Greenhouse gas Water footprint | O | X | (Mungkung et al. 2020) |
| 2019 | Malaysia | This research aims to quantify the environmental emissions associated with conventional rice production in Malaysia | 1 ton of un-milled rice grains | Cradle-to-gate | IPCC-EFDB My-LCID | Greenhouse gas | O | X | (Abdul Rahman et al. 2019) |
| 2019 | Vietnam | This research aims to calculate the carbon footprint of rice production, identify major emission sources, and propose mitigation strategies. | 1 kg of rice grown | | IPCC | Greenhouse gas | O | X | (Trang et al.2019) |
| 2018 | Thailand | This research aims to identify cleaner designs with renewable process energy and sustainable waste recovery, using cassava, cane molasses, and rice straw-based bioethanol | 1000 L bioethanol at 99.7% purity | Cradle-to-gate | ReCipe SimaPro 8.2 | Climate change Acidification Eutrophication Human and eco- toxicity Fossil depletion Particulate matter formation | O | X | (Rathnayake et al. 2018) |
| 2017 | Thailand | The research aims to assess the environmental and economic aspects of rice-based crop production in northern Thailand. | 1 ha crop production | Cradle-to-gate | SimaPro 7.3 BML 2001 | Depletion of abiotic resource (energy, mineral) Global warming potential Human and eco- toxicity Eutrophication Acidification | O | X | (Ramsden, Wilson & Phrommarat 2017) |

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| 2017 | Thailand | This research aims to assess greenhouse gas emissions of organic rice production, specifically focusing on the Khao Dawk Mali 105 variety in Thailand. | 1 kg paddy at farm gate | Cradle-to-gate | IPCC | Greenhouse gas | O | X | (Yodkhum, Gheewala & Sampattagul 2017) |
| 2016 | Malaysia | This research aims to assess the environmental impacts of rice production in a Kedah paddy field. | 1 MT harvested grain | Cradle-to-gate | Eco-Indicator 95<br>LIME | Global warming potential<br>Eutrophication potential | O | O | Yusoff, S. & Panchakaran, P 2015) |
| 2014 | Malaysia | This research aims to assess the environment impacts of rice straw-based power generation in Malaysia and compare it with the coal and natural gas system. | 1 kWh of electricity generation | Cradle-to-gate | CML 2001 | Global warming potential<br>Eutrophication potential<br>Acidification potential | O | X | (Shafie, Masjuki & Mahlia 2014) |
| 2014 | Thailand | The research aims to assess the environmental and economic aspects of rice production under different conditions (rain-fed and irrigated) in Northeastern Thailand. | Primary:<br>1kg of rawpaddy rice (un-milled) at thefarm gate<br>Secondary:<br>1 ha of land used to produce raw paddy rice (un-milled) at farm gate | Cradle-to-gate | IPCC<br>CML<br>SimaPro 7.3.2 | Global warming potential potentialEutrophication<br>Acidification<br>Resource use | O | X | (Thanawong, Perret & Basset-Mens 2014) |
| 2013 | Thailand | This research aims to compare the environmental performances of four rice straw utilization systems (direct combustion for electricity, biochemical conversion to bio-ethanol and biogas, thermo-chemical conversion to bio-DME, and incorporation into the soil as fertilizer | 1 ton of dryrice straw | Cradle-to-grave | CML2 | Global warming potential | O | X | (Silalertruksa & Gheewala 2013) |

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|---|---|---|---|---|---|---|---|---|---|
| 2013 | Thailand | This research aims to assess the greenhouse gas (GHG) emissions of using rice straw for bio-DME production in Thailand and compare the two scenarios of its utilization as automotive fuel for diesel engines and as an LPG supplement for household application | Per MJ OF fuel | Cradle-to-gate | NA | Global warming potential | O | X | (Silalertruksa et al. 2013) |
| 2013 | Malaysia | This research aims to assess the economic feasibility and environmental impacts of co-firing rice straw at coal power plants in Malaysia | 6,132,000 MWh (Manjung Power Plant,MP) and 2,628,000 MWh (Kapar Power Plant,KP) | Cradle-to-grave | CML 2002 | Global warming potential<br>Eutrophication potential<br>Acidification potential<br>Human toxicity | O | X | (Shafie, Mahlia & Masjuki 2013) |

According to Silalertruksa & Gheewala, among the possible rice straw utilization systems for producing bioenergy, it is found that a biochemical conversion yields the highest environmental benefits, especially with regard to greenhouse gas emissions and resource depletion compared to thermochemical pathway (Silalertruksa & Gheewala 2013). The findings reveal that for every ton of dry rice straw, rice straw-derived bioethanol demonstrates the most significant net reduction in global warming potential, achieving a reduction of 283 kg $CO_2$ equivalent. This is followed by rice straw bio-Dimethyl ether (bio-DME) and electricity, which yield net GWP reductions of approximately 245 and 116 kg $CO_2$ equivalent, respectively. Similarly, in the context of abiotic resource depletion, mirroring the trends observed in global warming potential, rice straw-based bioethanol emerges as the most effective, resulting in the highest net reduction of abiotic resource depletion, specifically reducing around 3.1 kg Sb equivalent per ton of dry rice straw. This is followed by the rice straw-based bio-DME and electricity systems, which achieve net abiotic resource depletion reductions of approximately 2.7 and 1.3 kg Sb equivalent per ton of dry rice straw, respectively. A study conducted by Silalertruksa et al., (2013) reported that, by using rice straw bio-DME for diesel engines, GHG emissions could be reduced by 12-60 g $CO_2$ eq/MJ or 14-70% as compared to existing diesel fuel used for transportation. Meanwhile, the use of rice straw bio-DME as an LPG supplement for household applications would result in a GHG emission reduction of about 1-49 g $CO_2$-eq/MJ or 2-66% when compared with the use of Liquefied Petroleum Gas (LPG) at the same performance (Silalertruksa et al. 2013). Additionally, despite the direct combustion of rice straw for electricity resulting in several environmental benefits, the net benefits of this pathway were marginally lower than those of the bioethanol and bio-DME pathways (Silalertruksa & Gheewala 2013). Overall, bioenergy production from rice straw has been found to have fewer adverse environmental impacts than energy production from fossil fuels.

As aforementioned, LCA provides an understanding of potential environmental problems and ensures the environmental sustainability of rice straw as a bioenergy source throughout its entire life cycle (Soam et al. 2017). Thus, a comprehensive tool such as LCA can greatly benefit any scientific study intended to enhance the environmental performance of a system. However, based on the results of this study, several knowledge gaps currently exist in LCA studies on the utilization of rice straw for bioenergy.

Detailed recommendations are provided in Table 2 for future researchers to improve consistency, transparency, and completeness of the research. There is a need to conduct a more comprehensive LCA studies of rice straw for bioenergy production, from raw material collection to bioenergy application, with special focus on the transportation, storage, and processing of rice straw. The identification of the most appropriate technologies or waste-to-energy conversion can benefit both the environment and bioenergy production. The hazardous gases released during waste-to-bioenergy processes should be taken into consideration. Hence, a comparative study of the conversion technology waste-to-energy is crucial to determine the most effective and environmentally friendly technology. Besides, further research is suggested to combine both material flow analysis (MFA) and LCA approaches to address the inadequacy of data on LCI. In this regard, the MFA approach will outline all the possible inputs and outputs of each process involved in which the outcomes may be used in the LCI.

## CONCLUSION

After thoroughly reviewing the literature, rice straw offers promising opportunities for bioenergy production to replace fossil fuels due to its vast availability and life cycle GHG emission benefits. In addition to its attractive lignocellulosic material, rice straw is ideal for producing both liquid and gaseous fuel oils, particularly bioethanol, due to the high amount of cellulose and hemicellulose content that can be readily hydrolyzed into fermentable sugars. Furthermore, the biochemical conversion pathway for producing biogas and bioethanol yields the highest environmental benefits, particularly pertaining to GHG emissions and resource depletion. Besides, rice straw also has high potential for producing bio- DME to substitute fossil fuels such as LPG and diesel. Compared to diesel fuel used for transportation, rice straw bio-DME could reduce greenhouse gas emissions by approximately 14–70% meanwhile, when used as an LPG supplement for household applications, it can result in a reduction of approximately 2–66% in GHG emissions compared to LPG at the same performance.

Therefore, removing the straw from rice fields can significantly tackle global environmental issues such as climate change and scarcity of resources. The information presented can also serve as a guideline to improve rice straw management practices in order to achieve environmental sustainability in the agriculture sector. Even so, further LCA discussions on rice straw utilization for bioenergy are still required to gather more information, so that more initiatives and mitigations can be developed and proposed. These discussions should delve into specific aspects such as the optimization of conversion processes, logistical challenges, and comparative study of the conversion technology waste-to-energy. Given the limited

TABLE 2 Limitations and recommendations for LCA practitioners in the rice straw field

| No | Limitation | Uncertainties | Recommendation |
|---|---|---|---|
| 1. | Inadequate data on LCI | Uncertainties in the process of inputs and outputs | Combining MFA and LCA approach |
| 2. | Potential emission from various waste management processes | Uncertainties in the outputs and final emissions | Incorporate cradle-to-grave approach |
| 3. | Insufficient primary research on the difference conversion technologies used for waste-to-energy | Uncertainty regarding the use of sustainable conversion technologies | Conduct a comparative study of the technologies used to convert rice straw into bioenergy |

number of studies conducted on rice straw's utilization in bioenergy production in Southeast Asia, obtaining more detailed information through additional LCAs is required to confirm those results. This will ultimately ensure a more robust and sustainable transition to bioenergy derived from rice straw.

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DECLARATION OF COMPETING INTEREST

None

REFERENCES

Abdul Rahman, M.H., Chen, S.S., Abdul Razak, P.R., Abu Bakar, N.A., Shahrun, M.S., Zin Zawawi, N., Muhamad Mujab, A.A., Abdullah, F., Jumat, F., Kamaruzaman, R., Saidon, S.A. & Abdul Talib, S.A. 2019. Life cycle assessment in conventional rice farming system: Estimation of greenhouse gas emissions using cradle-to-gate approach. *Journal of Cleaner Production* 212: 1526–1535.

Abdul Razak, A.M., Raja Othman, R.N., Abdullah, M.F. & Ku Ahmad, K.Z. 2021. An Overview of Banana Biomass as a Potential Renewable Energy Source in Malaysia. *Jurnal Kejuruteraan* si4(1): 181–191.

Abu, R., Ab Aziz, M.A., Che Hassan, C.H., Zainon Noor, Z. & Abd Jalil, R. 2023. A Comparative Life Cycle Assessment of Dry and Wet Anaerobic Digestion Technologies for Food Waste Management. *Jurnal Kejuruteraan* 35(2): 317–349.

Cuong, T.T., Le, H.A., Khai, N.M., Hung, P.A., Linh, L.T., Thanh, N.V., Tri, N.D. & Huan, N.X. 2021. OPEN Renewable energy from biomass surplus resource: potential of power generation from rice straw in Vietnam. *Scientific Reports*.

FAO. World Food Situation. Available online:https://www.fao.org/worldfoodsituation/csdb/en/ (accessed on 2 November 2022).

Hanafiah, M. M., Hasan, M., K. Razman, K., Harun, S. N., & Sakawi, Z. 2022. Life Cycle Assessment of Laser-Induced Maize Production: Adoption of Sustainable Agriculture Practices. *Applied Sciences*, *12*(22): 11779.

Harun, S.N., Hanafiah, M.M. & Aziz, N.I.H.A. 2021. An LCA-Based Environmental Performance of Rice Production for Developing a Sustainable Agri-Food System in Malaysia. *Environmental Management* 67(1): 146–161.

Kaita, M. S., & Harun, S. N. (2023, May). Application of integrated LCA-GIS model in the agricultural sector: A brief overview. In *IOP Conference Series: Earth and Environmental Science* (Vol. 1167, No. 1, p. 012015). IOP Publishing.

Liu, Z., Xu, A. & Long, B. 2011. Energy from Combustion of Rice Straw: Status and Challenges to China. *Energy and Power Engineering* 03(03): 325–331.

Mofijur, Mahlia, Logeswaran, Anwar, Silitonga, Rahman, & Shamsuddin. 2019. Potential of Rice Industry Biomass as a Renewable Energy Source. *Energies* 12(21): 4116.

Mungkung, R., Sitthikitpanya, S., Dangsiri, S. & Gheewala, S.H. 2020. Life cycle assessment of Thai Hom Mali rice to support the policy decision on organic farming area expansion. *Sustainability (Switzerland)* 12(15): 1–14.

Rajamoorthy, Y., Rahim, K. b A. & Munusamy, S. 2015. Rice Industry in Malaysia: Challenges, Policies and Implications. *Procedia Economics and Finance* 31(15): 861–867.

Ramsden, S.J., Wilson, P. & Phrommarat, B. 2017. Integrating economic and environmental impact analysis: The case of rice-based farming in northern Thailand. *Agricultural Systems* 157(October 2016): 1–10.

Rashid, S. S., Harun, S. N., Hanafiah, M. M., Razman, K. K., Liu, Y. Q., & Tholibon, D. A. (2023). Life cycle assessment and its application in wastewater treatment: a brief overview. *Processes*, *11*(1) 208.

Rathnayake, M., Chaireongsirikul, T., Svangariyaskul, A., Lawtrakul, L. & Toochinda, P. 2018. Process simulation-based life cycle assessment for bioethanol production from cassava, cane molasses, and rice straw. *Journal of Cleaner Production* 190: 24–35.

Shafie, S.M., Mahlia, T.M.I. & Masjuki, H.H. 2013. Life cycle assessment of rice straw co-firing with coal power generation in Malaysia. *Energy* 57: 284–294.

Shafie, S.M., Masjuki, H.H. & Mahlia, T.M.I. 2014. Life cycle assessment of rice straw-based power generation in Malaysia. *Energy* 70: 401–410.

Shaha, J. B., & Valakic, J. B. 2022. Techno Economic Analysis of Cotton Stalk Biomass Based Bio-Oil Production Using Slow Pyrolysis Process. *Jurnal Kejuruteraan*, *34*(3), 495-504.

Shaha, J. B., & Valakic, J. B. 2023. A Comprehensive Review on Feasibility of Different Agro Residues for Production of Bio-Oil, Bio-Char and Pyro-Gas. *Jurnal Kejuruteraan* 35(1): 77–93.

Sharma, A., Singh, G. & Arya, S.K. 2020. Biofuel from rice straw. *Journal of Cleaner Production* 277: 124101.

Silalertruksa, T. & Gheewala, S.H. 2013. A comparative LCA of rice straw utilization for fuels and fertilizer in Thailand. *Bioresource Technology* 150: 412–419.

Silalertruksa, T., Gheewala, S.H., Sagisaka, M. & Yamaguchi, K. 2013. Life cycle GHG analysis of rice straw bio-DME production and application in Thailand. *Applied Energy* 112: 560–567.

Singh, L. & Brar, B.S. 2021. A Review on Rice Straw Management Strategies. *Nature Environment and Pollution Technology* 20(4).

Soam, S., Borjesson, P., Sharma, P.K., Gupta, R.P., Tuli, D.K. & Kumar, R. 2017. Life cycle assessment of rice straw utilization practices in India. *Bioresource Technology* 228: 89–98.

Thanawong, K., Perret, S.R. & Basset-Mens, C. 2014. Eco-efficiency of paddy rice production in Northeastern Thailand: A comparison of rain-fed and irrigated cropping systems. *Journal of Cleaner Production* 73(December 2021): 204–217.

Yodkhum, S., Gheewala, S.H. & Sampattagul, S. 2017. Life cycle GHG evaluation of organic rice production in northern Thailand. *Journal of Environmental Management* 196: 217–223.

Yuan, S., Stuart, A.M., Laborte, A.G., Rattalino Edreira, J.I., Dobermann, A., Kien, L.V.N., Thúy, L.T., Paothong, K., Traesang, P., Tint, K.M., San, S.S., Villafuerte, M.Q., Quicho, E.D., Pame, A.R.P., Then, R., Flor, R.J., Thon, N., Agus, F., Agustiani, N., Deng, N., Li, T. & Grassini, P. 2022. Southeast Asia must narrow down the yield gap to continue to be a major rice bowl. *Nature Food* 3(3): 217–226.

Yusoff, S. & Panchakaran, P. 2015 Life cycle assessment on paddy cultivation in Malaysia: A case study in Kedah. LCA Rice. 1-10