Environmental Management
https://doi.org/10.1007/s00267-020-01365-7

An LCA-Based Environmental Performance of Rice Production for Developing a Sustainable Agri-Food System in Malaysia

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Received: 10 April 2020 / Accepted: 15 September 2020

Abstract
This study aims to assess the environmental impacts of conventional and organic rice cultivations and proposes a sustainable conceptual framework of rice farming based on the life cycle assessment (LCA) approach. A cradle-to-gate LCA was performed by using the ReCiPe 2016 method and SimaPro 8.5 software. The functional unit was one ton of rice grains harvested. Primary data were obtained from the farmer, while secondary data were collected from Ecoinvent 3.0, the Agri Footprint 3.0 database and the literature. The total characterization factors for global warming potential (GWP), water consumption potential (WCP) and fossil fuel depletion potential (FFP) were 457.89 kg CO_2-eq, 98.18 m^3 and 84.56 kg oil-eq, respectively, at the midpoint level for conventional rice, while the impacts for organic rice were 140.55 kg CO_2-eq, 29.45 m^3 and 22.25 kg oil-eq, respectively. At the endpoint level, the total characterization factors for human health damage (HH), ecosystem damage (ED) and resource availability (RA) for conventional rice were 9.63×10^{-4} DALY, 5.54×10^{-6} species.year and 30.98 Dollar, respectively, while for organic rice, the impacts were 2.60×10^{-4} DALY, 2.28×10^{-6} species.year and 8.44 Dollar, respectively. Rice cultivation impacted the environment, particularly in relation to three impact categories: GWP, WCP and FFP. The cultivation phase of rice production was the main contributor to environmental impacts due to the production and application of fertilizer and pesticides. It can be concluded that the application of LCA in agricultural sector is able to provide information and responses for policy makers in understanding the potential environmental impacts at various spatial levels.

Keywords Life cycle assessment · Rice production · Organic farming · Conventional farming · Sustainability

Introduction

Rice is the most widely consumed staple food for more than 3 billion people in Asia (FAO 2016; Khoshnevisan et al. 2014; Pishgar-Komleh et al. 2011). Rice production in Malaysia provides the primary food source, as the average Malaysian citizen consumes 82.3 kg of rice per year, and an average of 3.7 metric tons (MT) of rice is produced per hectare of paddy field (Yusoff and Panchakaran). According to the Department of Statistics Malaysia (DOSM) (2018), the rice cultivation area in Malaysia increased from 2014 to 2017, with the rice cultivation area recorded in 2016 being 688,770 ha. However, the production of rice has decreased due to factors such as bad weather, pests, and diseases (USDA 2018). According to Dasar Agromakanan Negara (DAN) (MOA 2018), rice consumption is expected to increase by 2.30 million tons by 2020, which represents a 1.6% growth per annum, and paddy production is expected to increase from 2.55 million tons in 2010 to 2.91 million tons in 2020, representing a growth of 1.3% per annum due to population growth.

To increase rice production, more research and development should be expended to advance technology. Advanced materials and techniques such as machinery, fertilizers, and pesticides that have been applied to increase the production of rice can cause adverse environmental impacts that some believe to be unacceptably high (Blengini and Busto 2009; Habibi et al. 2019; Khoramdel et al. 2017; Ramsden et al. 2017; Yodkhum et al. 2017). Apart from soil and water pollution as well as energy and raw material consumption,

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greenhouse gas emissions, eutrophication, and acidification are major environmental concerns related to rice fields (Blengini and Busto 2009; Brodt et al. 2014; Qin et al. 2010). According to Blengini and Busto (2009), Jeong et al. (2018), and Jimmy et al. (2017), the methane emissions from paddy fields contribute to 10–13% of the worldwide anthropogenic methane emissions, thus contributing greatly to the global warming phenomenon. The greenhouse gas emissions from the agricultural sector in Malaysia have increased from 9886.82 Gg CO_2 eq in 1994 to 15,775.30 Gg CO_2 eq in 2011 (NRE 2015). Malaysia aims to reduce its greenhouse gas (GHG) emissions intensity by 45% per unit of GDP by 2030 relative to the emissions intensity of 2005. In response to these issues and challenges, there are many initiatives that have been conducted by the Malaysian government to reduce the environmental burdens of rice production in this country. For instance, the National Policy on Environment (2002), National Green Technology Policy (2009), and National Policy on Climate Change (2009) have been developed by the government to reduce the short- and long-term effects and improve the sustainability of the rice sector. Furthermore, the Ministry of Agriculture and Agro-Based Industry has launched a comprehensive scheme for agriculture named Malaysia Good Agriculture Practices (MyGAP).

Several mitigation strategies have been applied to reduce the environmental burdens produced from rice fields, such as organic farming techniques, biological control, crop rotation, and intercropping (Kumar et al. 2019). Organic farming has become one of the alternatives in sustainable rice production due to the avoidance of synthetic fertilizer and chemical pesticides (Batáry et al. 2012; Meng et al. 2017). However, a comprehensive evaluation of the whole production system must be carried out to conclude that organic cultivation is better than conventional cultivation techniques. Hence, it is necessary to evaluate and manage the environmental burden posed by the rice production process. Thus, life cycle assessment (LCA) can be used to measure the environmental performance of rice production throughout the entire life cycle, which is known as 'cradle-to-grave' analysis (Dijkman et al. 2018; Masuda 2018). LCA is commonly used in environmental management, as this method can address all the possible impacts of a product or service through its entire life cycle (Aziz et al. 2019b; Khoshnevisan et al. 2014). Recently, many studies have used LCA in research on rice production around the world (Dijkman et al. 2018; Habibi et al. 2019; Jimmy et al. 2017; Soam et al. 2017; Yodkhum et al. 2017). LCA study has also becoming popular in rice-producing countries. For instance, in Thailand, Mungkung et al. (2019) have conducted an LCA study to evaluate the impacts of climate change, water use, and biodiversity on Thai organic Hom Mali rice. Kim et al. (2018) evaluated the environmental implications of eco-labeling for rice farming systems in South Korea, including organic farming, non-pesticide farming, and low-pesticide farming. Masuda (2019) carried out an eco-efficiency assessment of an intensive rice production in Japan. He et al. (2018) have performed an environmental LCA of long-term organic rice production and compared it with conventional rice in Subtropical China. However, LCA is still in its infancy stage in Malaysia. Thus, this study aims to identify and quantify the environmental impacts of conventional and organic rice production in the chosen paddy fields in Selangor, Malaysia, focusing on the paddy cultivation stages.

The History and Development of the Rice Sector in Malaysia

In Malaysia, the rice sector is governed by the Ministry of Agriculture and Agro-based Industry (MOA) mandate. There are many agencies under the MOA responsible for supporting the mandates of paddy and rice sector development in Malaysia, such as the Department of Agriculture (DOA), the Malaysian Agricultural Research and Development Institute (MARDI), and the Farmers Organization Authority (LPP). The paddy and rice sector has been supported by 12 designated authorities, namely, the Muda Agricultural Development Authority (MADA), KEMUBU Agricultural Development Authority (KADA), North West Integrated Agricultural Development Project (PBLS), Integrated Agricultural Development Project (IADA) Seberang Perak, IADA Penang, IADA KETARA, IADA KERIAN, IADA Kemasin Semerak, IADA Rompin, IADA Pekan, IADA Batang Lupar, and IADA Kota Belud. The designated authorities are responsible for managing the granary areas in Malaysia.

Malaysia's agricultural policies have been divided into pre-independence and post-independence phases. During the pre-independence phase, rice was cultivated on a small scale, intended only for domestic consumption. However, after independence, the rice sector received special attention from the government. The Green Book Plan (1979) was launched during the first Malaysia Plan (1966–1970) by the late Prime Minister Tun Abdul Razak. The formation of key granary areas was one of the initiatives implemented through The Green Book Plan (1979).

During the 1960s–1970s, many initiatives for the rice industry in Malaysia were made by the government, e.g., the establishment of agricultural research institutions and the formation of key granary areas. The Malaysian Agricultural Research and Development Institute (MARDI) was established in 1969 to lead research on agriculture, especially for the rice sector. The growing concern regarding the development of the rice sector by the government encouraged the establishment of Lembaga Padi dan Beras Negara (LPN) in 1971, followed by MADA and the National Farmer's

Organization (NAFAS) in 1972. MADA was recorded as the largest granary area in Malaysia. The establishment of these organizations and authorities resulted in improvements in rice production and cultivation practices.

The First National Agriculture Policy (NAP1) was launched in 1984 to ensure that the development rate of the agricultural sector in Malaysia remained stable. The main aim of this policy was to contribute to the agricultural sector during the country's development, with the main interest being to reduce the poverty rate in Malaysia. NAP1 presented the guidelines for agricultural development until 2000. Moreover, the key role of the sector, the obstacles faced and the strategies were presented in the policy. In addition, NAP1 was developed as a guideline to assist the government and private sector in activating the agricultural sector and hence the country's economy (4th Malaysian Plan 1981). The Second National Agriculture (NAP2) policy was legislated after the revision of NAP1 to ensure that any changes could be implemented in the agricultural sector. NAP2 was developed in the period of 1992–1997, and it placed more emphasis on overcoming issues regarding productivity enhancement, efficiency, involvement of the private sector, and competitiveness with other sectors. In addition, the sustainability of resources was highlighted, including agricultural land availability, water, and climate change. The Third National Agricultural Policy (NAP3) aimed to address environmental sustainability in line with the enhancement of food security. The environmental issues that were addressed include climate change and the sustainability of resources such as agricultural land availability and water.

The rice sector was included in one of the seven specialized industries listed by the National Agri-Food Policy (DAN) 2011–2020 to drive the modernization of Malaysia's agri-food sector. DAN 2011–2020 targets increasing productivity and yield to ensure a sufficient food supply, high-value agricultural development, and sustainable agricultural development. The government of Malaysia also aims to achieve 80% self-sufficiency in rice by 2020 (MOA 2018). Hence, the government has provided several input incentives for farmers, such as subsidized seeds and fertilizer, to increase rice production.

In the past 50 years, the government has spent billions of Ringgit Malaysia (MYR) to increase rice production and strengthen the rice sector in the country. The government has given continuous attention to the Malaysian rice sector from the First Malaysia Plan (1966–1970) to the recent Tenth Malaysia Plan. The support from the government includes research and development (R&D), credit facilities, subsidized retail prices, guaranteed minimum prices, extension support, fertilizer subsidies, and irrigation investment. This support was provided by the government through several intervention program, such as Skim Baja Padi Kerajaan Persekutuan, Skim Insentif Pengeluaran Padi (SBPKP), Skim Insentif Pengeluaran Padi (SIPP), Insentif Peningkatan Pengeluaran Beras Negara (IPPB), Insentif Benih Padi Sah (IBPS), Skim Baja dan Racun Padi Bukit/Hama, Skim Subsidi Harga Padi (SSHP) Guaranteed Minimum Price (GMP), Rice Check, Farmer Sustainability Index, National Key Economic Area (NKEA) and Malaysian Good Agricultural Practice (MyGAP).

An LCA-Based Sustainable Framework for Rice Cultivation

The rice sector is an important sector in Malaysia that provides food and jobs for the community and generates income for the country. The rice consumption in this country has increased due to factors such as population growth and the increase in immigrants from neighboring countries. In 2014, the rice production in Malaysia was 1.83 million MT, while the total rice consumption was ~2.72 million MT. Hence, the government has imported ~0.9 million MT of rice from other countries, such as Indonesia, Myanmar, Vietnam, India, and Bangladesh.

Farmers have preferred to implement conventional farming techniques without considering long-term impacts such as environmental degradation, resource depletion, water deterioration, and biodiversity loss (Bayard and Jolly; Musyoka et al. 2019; Shiferaw et al. 2009). In addition, the use of synthetic fertilizer, chemical pesticides, and non-renewable sources has caused environmental pollution. Therefore, sustainable agricultural practices have been widely promoted at the international level due to growing concerns about environmental protection and human health. The increasing world population has resulted in a higher demand for rice yield and quality. Hence, it is necessary to develop rice production practices through user- and environmentally friendly modern technologies that could produce higher yields with lower production costs, limit natural resource use, and minimize the environmental burden.

Together with the other world countries, Malaysia has adopted the 2030 Agenda for Sustainable Development, with the aim of moving toward more sustainable, resilient, and inclusive development. The 2030 Agenda includes 17 Sustainable Development Goals (SDGs), with 169 targets and 244 indicators used to measure social, economic, and environmental aspects. The Malaysian government commitment to the 2030 Agenda has been aligned with the strategies and initiatives of the 11th Malaysia Plan. There are many strategies that have been proposed and implemented in Malaysia to commit to Goal 2 (end hunger, achieve food security and improve nutrition, and promote sustainable agriculture). For instance, Malaysia is increasing efforts to strengthen its food security by improving the self-sufficiency levels (SSLs) in food production and preparing for impact-related disasters (Economic Planning Unit 2016). Sustainable agricultural

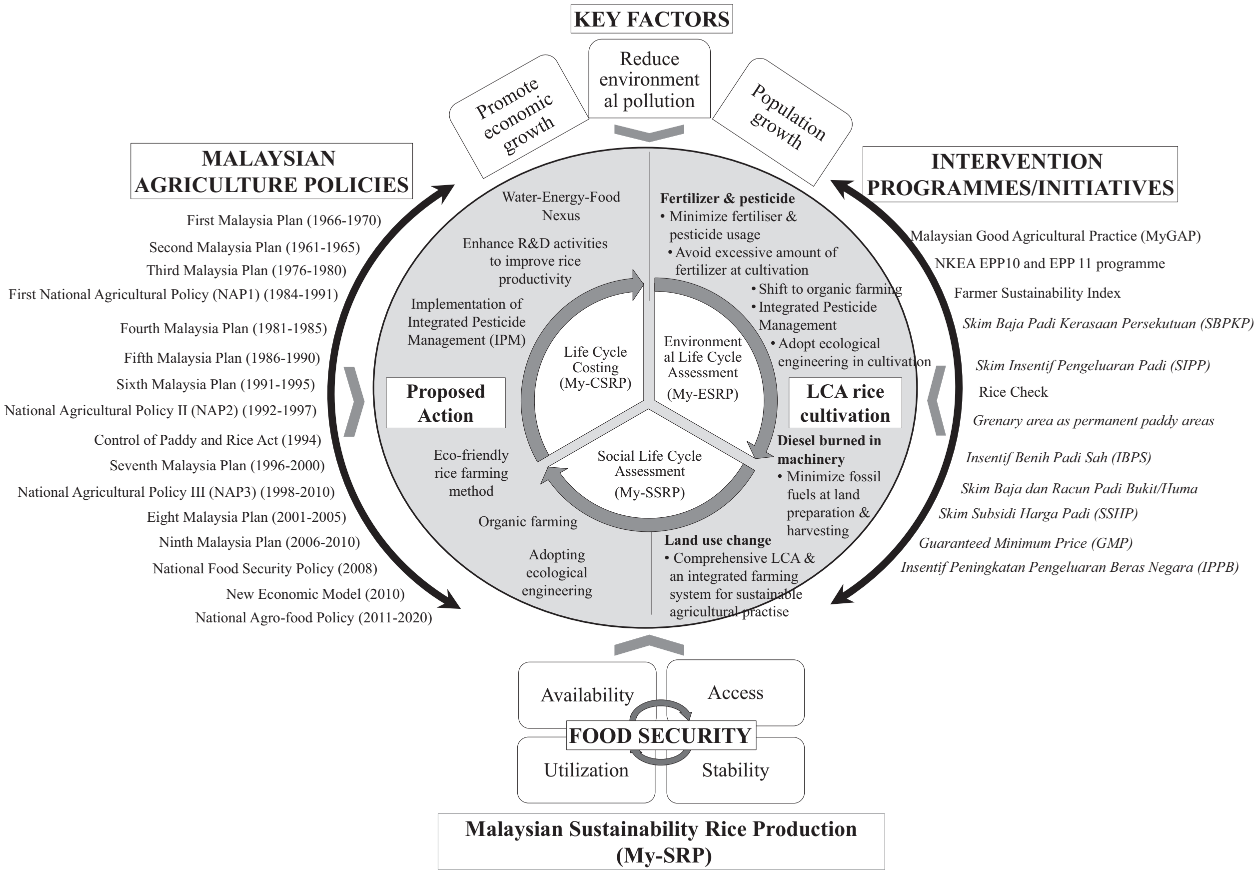

Fig. 1 An LCA-based sustainable environmental rice production conceptual framework

development in Malaysia is guided by the National Agrofood Policy 2011–2020 and National Commodity Policy 2011–2020. According to the Department of Statistics Malaysia (2017), the production of major agro-food commodities has increased at an average rate of 3.9% annually between 2011 and 2016, and the SSL target for paddies was achieved in 2015. This achievement was made possible by various factors, such as the use of quality seeds, the wider adoption of effective technologies among farmers, and the establishment of new large-scale rice production areas.

Generally, the overall performance of the rice sector in the country was measured by its ability to increase rice production and SSL. However, the primary goal for agro-food policy is food security, which includes environmental sustainability, food safety, and affordability. While food security is multidimensional and beyond the measure of production and self-sufficiency level (SSL), it is important to incorporate other aspects that are equally important into the production of rice. Accordingly, the measurement of the nation's food security by SSL addresses only the 'availability' factor, and thus, it does not sufficiently reflect the true status of the nation's food security.

There are many strategies that have been proposed and implemented in Malaysia to increase rice production, e.g., support programs and initiatives from the government, research and development (R&D), and farmer training. Furthermore, the country adopted a series of certification schemes of good agricultural practices, such as Malaysia Good Agricultural Practices (MyGAP) and Malaysia Organic (MyOrganic), to ensure sustainable rice production. Thus, the growing concern about sustainable food production has led to an increasing number of studies on the LCA of agricultural production systems (Blengini and Busto 2009; Meisterling et al. 2009; Wang et al. 2010).

Therefore, a conceptual framework for LCA-based environmental sustainable evaluation of rice production, namely, Malaysian Sustainability Rice Production (My-SRP), was developed in this study based on the results of interviews and a life cycle impact assessment (LCIA). My-SRP consisted of three parts: Malaysian Environmental Sustainability Rice Production (My-ESRP), Malaysian Costing Sustainability Rice Production (My-CSRP), and Malaysian Social Sustainability Rice Production (My-SSRP). The conceptual framework is illustrated in Fig. 1. The conceptual framework was developed to propose strategies and initiatives that have the potential to improve the sustainability of rice production in Malaysia. The proposed strategies and initiatives from cradle-to-gate were presented in the framework, together with existing policies, intervention programs, and initiatives that have affected the sustainability of rice production.

In general, sustainable development is defined as development that meets the needs of the present without compromising the ability of future generations to meet their own needs (Aziz et al. 2020; Ismail and Hanafiah 2019a, 2019b). According to the FAO (2016), agricultural sustainability is defined as agriculture that meets the needs of present and future generations with its products and services while ensuring profitability, environmental health, and social and economic equity. According to Aziz et al. (2020), several rice sustainability challenges must be emphasized: resource use efficiency, global greenhouse gas emissions, impacts on ecosystem services, soil impacts, pest and disease impacts, and climate change impacts. The Sustainable Rice Platform (SRP) (2015) highlighted 12 principles for sustainable rice production, including profitability, labor productivity, rice grain yield, water productivity, nitrogen-use efficiency, phosphorus-use efficiency, pesticide usage, greenhouse gas emission, food safety, women empowerment, child labor and worker health and safety.

Malaysian Sustainable Rice Production (My-SRP) was developed by integrating the LCA approach. There are other tools that can be applied to support decision making and to evaluate the environmental performance of rice production, such as the carbon footprint, water footprint and GHG life cycle analysis. However, LCA has been chosen because it is capable of holistically assessing the environmental sustainability of rice production systems. A LCA consists of a combination of three different dimensions of environmental, social, and economic evaluation in the same system (Aziz et al. 2019a; Aziz and Hanafiah 2020). A LCA consists of three evaluation elements, namely, environmental LCA, life cycle costing (LCC), and social life cycle assessment (S-LCA) (Ismail and Hanafiah 2020). Environmental LCA produces numerical data and indicators to evaluate the resource used and the environmental impacts. LCC is the process of cost eva luation in a whole life cycle of a product or system, while the SLCA is the evaluation of social indicators.

In this study, the focus was on the Malaysian Environmental Sustainable Rice Production (My-ESRP) section. The proposed initiatives mainly focused on fertilizer and pesticide production and application, water consumption, diesel usage and land-use change. The environmental performance of rice cultivation could be enhanced by minimizing chemical and pesticide applications. Based on this study, organic farming is one of the best ways to reduce the environmental impacts of rice cultivation. As mentioned earlier, Malaysian Good Agricultural Practices (MyGAP) was one of the efforts implemented by the government to encourage farmers to practice environmentally friendly cultivation techniques. My-ESRP could provide guidelines for the environmental sustainability of rice production in Malaysia. Therefore, to achieve a thorough understanding of sustainable rice production, it is suggested that My-ESRP be carried out by extending this study into My-CSRP and My-SSRP using the LCC and S-LCA approaches. Hence, My-SRP could be a guideline for measuring food security in Malaysia as a whole.

Environmental Impact Assessment of Conventional and Organic Rice Cultivation Methods

Life cycle assessment is a well-framed methodology standardized under the ISO 14040-ISO 14044. It is a cradle-to-grave approach that spans from the process of raw material extraction to the disposal of a product. LCA is based on four methodological stages: goal definition and scope, life cycle inventory analysis (LCI), life cycle inventory assessment (LCIA), and interpretation.

Goal and Scope, Unit Process, Functional Unit, and System Boundaries

The goal of this study was to investigate the environmental impacts of conventional and organic farming systems on the cradle-to-gate of un-milled rice grains from any seed variety. The study area was located in Sabak Bernam, Selangor, Malaysia. Further rice processing stages, such as storage, transport, packaging, delivery to consumers, and consumption were not considered in this study. This choice was justified by the fact that approximately 60–90% of the global warming impact of rice has been related to production processes at the field level (Fawibe et al. 2019; Hokazono et al. 2009; Yodkhum et al. 2017). Furthermore, Blengini and Busto (2009) found that most other environmental impacts were predominantly generated at the farm level. In this study, the rice milling stage and the indirect environmental burdens of capital goods and rice straw were excluded due to time constraints as well as a lack of data. As most of the straw was burned on the paddy field, its emission was considered neutral, and no allocation criteria were applied (Gathorne-Hardy 2016; Hokazono and Hayashi 2012; Jimmy et al. 2017; Jumadi et al. 2019; Wang et al. 2010).

The system boundary has been divided into two systems: foreground and background systems. The foreground system was based on primary and secondary data, including all the agricultural practices and inputs that are performed from the land preparation process, starting after the previous crop was harvested. The inputs include all machine operations, such as rotary tillage, seeding machines, pesticide and fertilizer machines, harvesters, corresponding infrastructures, and fuel used. The inputs of irrigation water, pesticides, fertilizers, and rice seed were also considered. Together

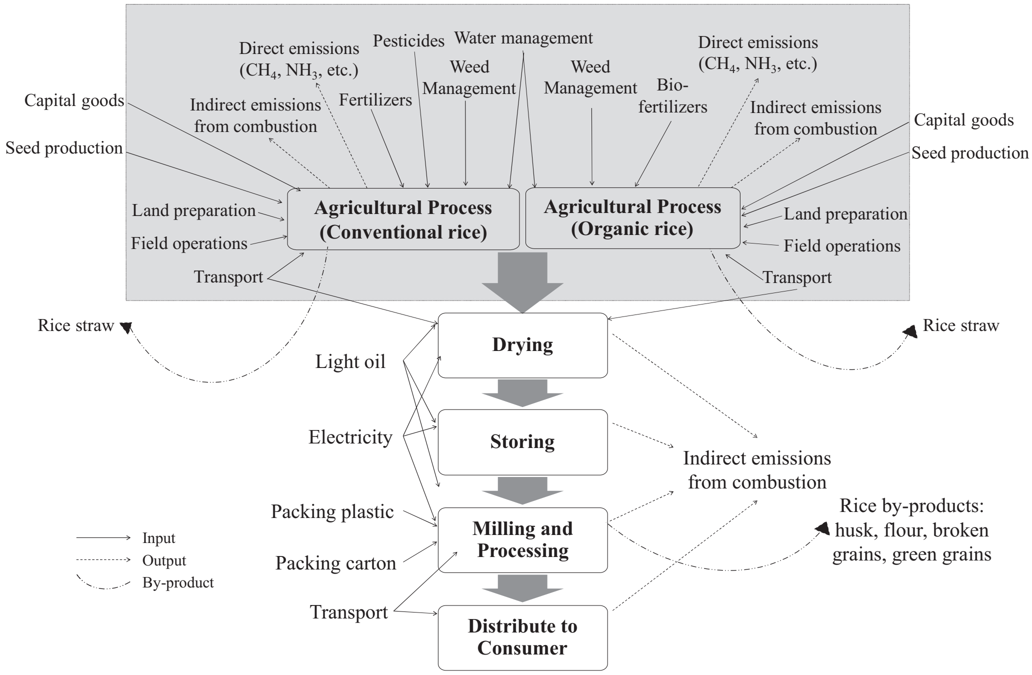

Fig. 2 System boundary of cradle-to-gate rice production

with the foreground system, the background system includes all the production and manufacturing of plant management applications, machines, diesel consumption, and transportation to the paddy field.

As the main function of the system under study was to evaluate the environmental impact of rice cultivation, the functional unit selected was one ton of harvested paddy grains. Figure 2 provides a graphic display of the system boundary, as well as the input and emission categories of this study.

The input data were obtained from interviews with farmers, on-site records, agronomists, and literature. The crop management practices were investigated by interviewing the farmers and by using information from standard operating procedures of rice farming supplied by agronomists from MARDI and MADA, Malaysia. The key data relevant to fertilizers and pesticides were supplied by rice farms and retrieved from the literature. The data relevant to greenhouse gas emissions from paddy fields were estimated according to the Intergovernmental Panel on Climate Change (IPCC) models (IPCC 2006). The water used was estimated from interview sessions with the farmer and information from agronomists as well as from the available literature. The direct energy use and ancillary materials used for farming were obtained from field measurements or estimations.

Data Sources and Analysis

SimaPro 8.5 software was used as a tool to perform the life cycle impact assessment analysis. This software can be used to monitor the performance of sustainability as well as to systematically analyze a complex life cycle and evaluate the environmental impact at every stage of the life cycle of a product or service. The background data sources used in this study were Ecoinvent 3.4 (Weidema et al. 2013), Agri-footprint 4.0 (Durlinger et al. 2014), and USLCI (Norris 2004). The Ecoinvent 3.4 database contains LCI data for energy production, transportation, chemical production, fruits, and vegetables. The agri-footprint database is a comprehensive LCI database with information about agricultural products, focusing on the agricultural and food sectors and covering the potential impacts at the end-point level on the three areas of protection: human health, ecosystem quality, and resource availability. On the other hand, the USLCI database contains data modules that quantify the material and energy flows into and out of the environment.

A life cycle impact category indicator was evaluated for 17 different impact categories at the midpoint, and then the indicators were divided into three damage assessment categories at the endpoint level using the ReCiPe 2016 method developed by (Huijbregts et al. 2017). The impact categories at the midpoint level included global warming (GWP), stratospheric ozone depletion (ODP), ionizing 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 noncarcinogenic toxicity (HTPnc), land use (LOP), mineral resource scarcity (SOP), fossil resource scarcity (FFP), and water consumption (WCP). At the endpoint level, the damage assessment categories included damage to human health (HH), damage to ecosystem quality (ED), and damage to resource availability (RA). The unit DALY was used for HH and referred to disability-adjusted life years. The unit represents the years that are lost or that a person is disabled due to a disease or accident. In addition, the unit used for ED is species × year, representing the local species loss integrated over time, while USD2013 was used for RA, which represents the extra costs involved for future mineral and fossil resource extractions.

Life Cycle Inventory (LCI)

The LCI was a stage where data were collected and analyzed, including inventory data from the input and output processes of rice production. The inventory data consisted of the amount of energy and material consumed and the quantities of emissions released to the environment. The data sources for this study included primary data, questionnaires from onsite records and interviews with farmers, literature reviews, and databases in SimaPro 8.5. The questionnaires consisted of the generic information, process descriptions, and input and output flows of the product system. The questionnaire was developed based on the guideline in ISO 14040 (2006). The interview with the farmers at the representative organic and conventional rice fields was conducted to obtain and validate information concerning agricultural practices. Figure 3 shows the LCI data for this study. The input inventory of rice production included land preparation, planting, water management, weed management, soil fertility, disease control, and harvesting processes.

In this study, the cultivation period was 105 days for both conventional and organic rice. The rice farming process includes land preparation, cultivation, and harvesting. Machinery and tractors were highly used in the land preparation and harvesting phase. Land preparation is important and provides soft soil mass for transplanting, effective weed control, and recycling of plant nutrients. The process of land preparation includes slashing, plowing and harrowing, levelling and flooding. The slashing process was performed immediately after harvesting using a rotor slasher to distribute crop residues and weeds over the field and incorporate them into the soil. Plowing and harrowing processes were performed two times in dry and wet conditions, with depths of 10 and 5 cm, respectively. Plowing and harrowing were performed 30 and 10 days before seed sowing using a tractor (60–80 hp) with a rotary tiller size of 1.2–1.75 m. The field levelling process was performed using a tractor (40 hp) with an attached niplo to a depth of ~5 cm. Seeds (150 kg/ha) were sown in the field using a knapsack-powered row seeder. During the harvesting process, a combine harvester was used, with a rate of ~3 h/ha. In this study, the yield of conventional rice was 6 ton/ha/cultivation season, while the yield of organic rice was 8 ton/ha/cultivation season.

The source of water used in rice cultivation in this study was from the irrigation scheme. The water was supplied through irrigation channels that flow naturally and hence do not consume any energy. During the land preparation phase, water was flooded to a depth of ~10 cm in the rice field after

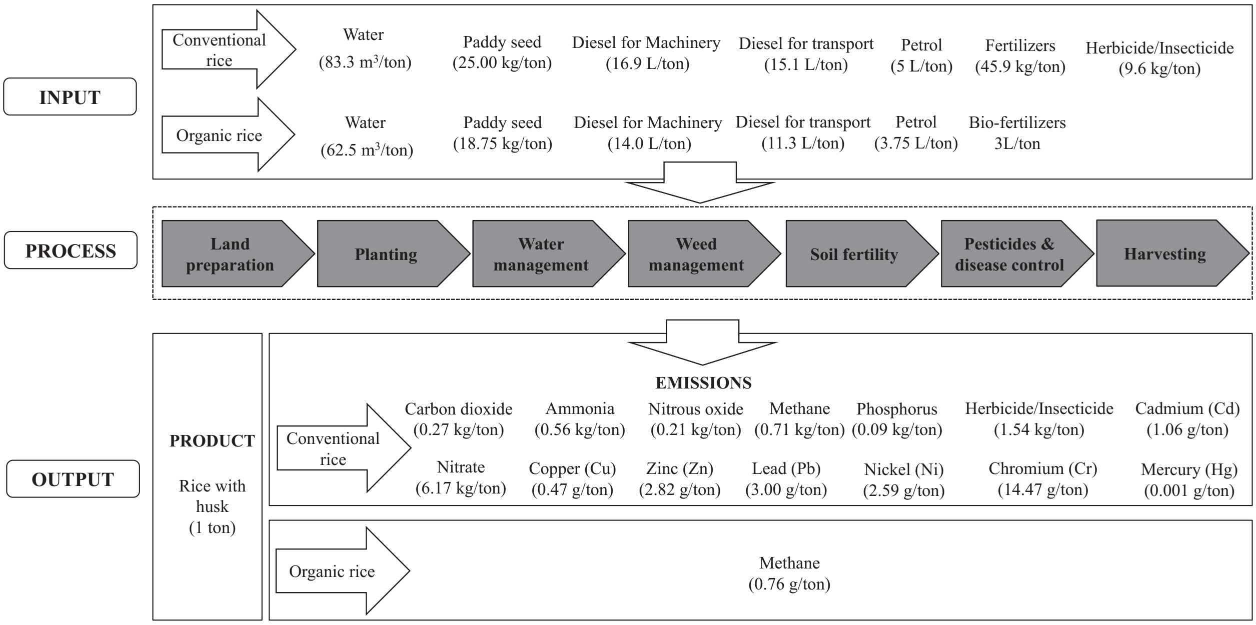

Fig. 3 LCI for rice production (per ton of rice)

the first plowing and harrowing process. The flooded water in the field was released before the seed sowing process. However, the field was flooded again at a depth of ~5 cm during the cultivation phase.

Pesticides were applied multiple times during the rice cultivation process. During the land preparation phase, the first application of pesticides was performed after the second plowing and harrowing process. Pesticides (chlorophacinone or warfarin) were applied to reduce the rat population and to prevent the presence of golden apple snails in the rice field. Herbicide application was performed twice in the land preparation phase. The herbicides used were paraquat, glyphosate, and glufosinate. In the cultivation phase, pesticides and herbicides were applied approximately eight times using a rotor sprayer. The pesticides and herbicides used in conventional rice fields included propanil, quinclorac, sulfonylurea, fipronil, cartap, niclosamide, and formaldehyde. The chemical fertilizers were applied four times in conventional rice cultivation. The fertilizer used included nitrogen (N) from ammonium sulfate, phosphorus (P) from rock phosphate, potassium (K) from potassium chloride, and urea from animal manure. The amount of fertilizer applied was ~350 kg/ha for NPK and 150 kg/ha for urea.

The emissions produced from fertilizer and pesticide applications were estimated according to Eggleston (2006), Struijs et al. (2011), and Van Zelm et al. (2014). The pesticide emissions were calculated by referring to the approach in the product environmental footprint (FEP), in which the emission routes of pesticides were 90% to the soil, 1% to the fresh water, and 9% to the air. The following equations show the calculation of the emissions of methane (CH_4), nitrous oxide (N_2O), nitrate (NO_3-), ammonia (NH_3), carbon dioxide (CO_2) and phosphorus (P) caused by fertilizer application. CH_4 emissions from rice fields were estimated according to IPCC (2006) guidelines as below.

$$CH_{4_{Rice}} = EF_i \times t \times A \times 10^{-6}$$

$$EF_i = EF_c x SF_w x SF_p x SF_0 x SF_{s,r}$$

where,

$CH_{4_{Rice}}$ = annual methane emissions from rice cultivation (Gg CH_4/year),

t = is the cultivation period of rice (day)

A = is annual harvested area of rice (ha/year)

EF_i = adjusted daily emission factor for a particular harvested area (kg CH_4/ha/day)

EF_c = baseline emission factor for continuously flooded fields without organic amendments

SF_w = scaling factor to account for the difference in water regime during the cultivation period

SF_p = scaling factor to account for the difference in water regime in the pre-season before the cultivation period

SF_0 = scaling factor used for application of organic amendment

$SF_{s,r}$ = scaling factor for soil type, rice cultivar, etc. if available

Nitrous oxide (N_2O) emissions:

$$N_2O = (F_{SN} + F_{ON} + F_{CR} + F_{SOM}) \times EF_1 \times \frac{44}{28}$$

Nitrate (NO_3^-) emissions:

$$NO_3^- = \left((F_{SN} + F_{ON} + F_{CR} + F_{SOM}) \times F_{LEACH-(H)}\right) \times \frac{62}{14}$$

Ammonia (NH_3) emissions:

$$NH_3 = (F_{SN} \times Frac_{GASF}) \times \frac{17}{14}$$

where,

F_{SN} = the amount of synthetic fertilizer N applied to soils (kg N)

F_{ON} = the amount of N in manure applied to soils (kg N)

F_{CR} = the amount of N in crop residues (above-ground and below-ground) (kg N)

F_{SOM} = the amount of N in mineral soils that is mineralized (kg N)

EF_1 = emission factor for N_2O emissions from N inputs $\left(\frac{kgN_2O{-}N}{kgN_{input}}\right)$

$F_{LEACH\text{-}(H)}$ = fraction of all N added that is lost through leaching $\left(\frac{\text{kg N}}{\text{kg of N addition}}\right)$

$Frac_{GASF}$ = fraction of fertilizer N that volatilizes as NH_3 and NO_x $\left(\frac{\text{kg N volatilized}}{\text{kg N applied}}\right)$

Carbon dioxide (CO_2) emissions:

$$CO_2{-}C = (M_{limestone} \times EF_{limestone}) + (M_{dolomite} \times EF_{dolomite}) + (M_{urea} \times EF_{urea}) \tag{28}$$

Where,

CO_2-C = C emissions from lime, dolomite, and urea application (kg C)

$M_{limestone}$ = amount of calcic limestone ($CaCO_3$)

$M_{dolomite}$ = amount of dolomite ($CaMg(CO_3)_2$)

M_{urea} = amount of urea (kg)

$EF_{limestone}$, $EF_{dolomite}$, EF_{urea} = emission factor $\left(\frac{\text{kg C}}{\text{kg of limestone/dolomite/urea}}\right)$

Phosphorus (P) emissions were calculated using the following equation:

$$= \text{amount of P fertilizer (kg)} \times 0.053(\text{emission factor})$$

The default emission factors that have been used were based on IPCC (2006) guidelines, as shown in Table 1.

Table 1 Emission factors and constants

IPCC Tier 1 Emission factors and constants	Value
EF_1	0.01
$EF_{dolomite}$	0.13
$EF_{limestone}$	0.12
EF_{urea}	0.2
$F_{LEACH\text{-}(H)}$	0.3
$Frac_{GASF}$	0.1
Conversion from kg CO_2-C to kg CO_2	44/12
Conversion from kg N_2O-N to kg N_2O	44/28
Conversion from kg NH_3-N to kg NH_3	17/14
Conversion from kg NO_3^--N to kg NO_3^-	62/14

Source: IPCC (2006)

Heavy metal contamination in the soil was due to fertilizer application and was calculated based on the approach by Mels et al. (2008) and Nemecek and Schnetzer (2011), as shown in Table 2.

Results and Discussion

The life cycle impact assessment (LCIA) was conducted using the results from inventory analysis (LCI) to translate them into environmental impacts. Hence, the consequences of these inputs and emissions can be understood as well as provide enough information to guide decision making (Golsteijn et al. 2015). The LCIA phase consists of four consecutive steps: classification, characterization, normalization, and weighting. According to ISO 14044 (2006), classification and characterization are compulsory steps. Normalization and weighting are optional steps in the LCIA phase. In this study, the classification and characterization steps were chosen based on the goal and scope of the study. The LCI results were organized and combined into the impact categories to which they contributed at the classification step. Characterization factors were used to convert and combine the LCI results into representative indicators of impacts. Hence, the LCI results could be compared within each impact category at the characterization step. The equation of the characterization factor is shown below:

$$\text{Inventory data} \times \text{Characterization factor} = \text{Impact indicator}$$

At the midpoint level, a reference substance was introduced so that there was a difference in the unit of the indicator for each category. For emission-based impact categories and resource depletion, a mass (in kg) reference substance to a specific environmental compartment was used. On the other hand, for land use, the unit represented the area and time integrated for one type of land use. At the endpoint level, better information on the environmental relevance of the environmental flows was provided (Hauschild and Huijbregts 2015). The endpoint characterization factors (CFe) were directly derived from the midpoint characterization factor (CFm). The midpoint to endpoint factors were constant per impact category (F). The midpoint to endpoint conversion was as follows:

$$\text{CFe} = \text{CFm} \times \text{F}$$

Table 2 Heavy metal content of fertilizers

Mineral fertilizers	Unit	Cd	Cu	Zn	Pb	Ni	Cr
N fertilizer	mg/kg N	6	26	203	54.9	20.9	77.9
P fertilizer	mg/kg P	90.5	207	1923	154	202	1245
K fertilizer	mg/kg K	0.2	8.7	11.3	1.5	4.5	10.5

Source: Mels et al. (2008) and Nemecek and Schnetzer (2011)

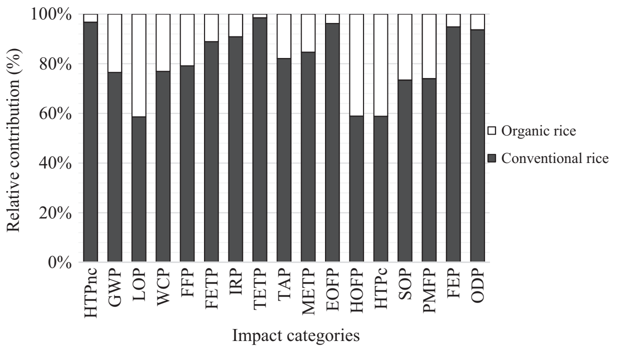

Fig. 4 Relative contribution of 17 impact categories at the midpoint level from conventional and organic rice cultivation

Impact Categories at the Midpoint Level

Figure 4 illustrates the relative contributions of the 17 impact categories from conventional and organic rice cultivation at the midpoint level. This study emphasized global warming potential (GWP), water consumption (WC), and fossil fuel depletion (FFP), as they were the three most significant environmental impacts and are a major concern in rice production activity.

Figure 5 shows the contribution of conventional and organic rice to GWP. The GWP uses characterization factors from the International Panel of Climate Change for a time frame of 100 years. Based on the results obtained, the value of the GWP_{100} indicator represents the aggregation of indirect and direct greenhouse gas emissions leading up to the production of paddy rice at each step of its life cycle, and this method not limited to only the greenhouse gas emission that is emitted directly from the rice fields. The contributions from various substances that contributed to climate change were calculated with respect to an equivalent substance, CO_2. The total characterization factors of GWP for conventional and

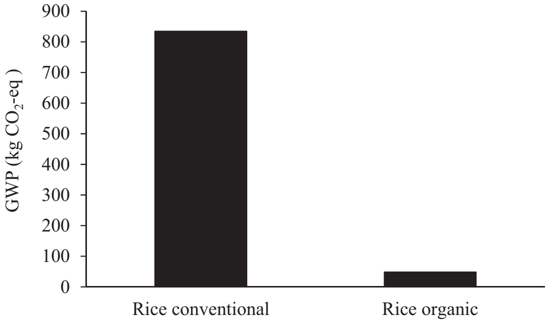

Fig. 5 Relative contribution towards GWP

Table 3 GWP of previous studies

Author	GWP_{100} (per 1 ton of rice)
Jimmy et al. (2017)	3150 kg CO_2 eq
Thanawong et al. (2014)	Ranges between 2970 and 5550 kg CO_2 eq
Kasmaprapruet et al. (2009)	2900 kg CO_2 eq
Blengini and Busto (2009)	2374 kg CO_2 eq
Hokazono and Hayashi (2012)	1460 kg CO_2 eq

organic rice were 457.89 kg CO_2-eq and 140.55 kg CO_2-eq, respectively. The results show that the characterization factor of GWP for conventional rice was ~53% higher than that for organic rice. The GHG emissions for conventional rice were higher than those for organic rice because of the chemical fertilizers that were used. For organic rice, biofertilizer was used in the cultivation process, and the assumption was made that there was no environmental impact.

The GWP per ton of rice in this study was lower than that in previous studies, as shown in Table 3. The difference can be explained by the yield of rice produced in this study. The yield was considered high, 6 ton/ha for conventional rice and 8 ton/ha for organic rice, compared to the average yield from Bangladesh, which corresponded to 4 ton/ha, and contributed to the high GWP impact (3150 kg CO_2 eq/ton of rice), as reported by Jimmy et al. (2017). Moreover, these results were in line with the findings reported by Thanawong et al. (2014), who compared the impacts of GWP in two study areas, the Central Plains of Thailand (4–6 ton/ha) and Isaan (2.5 ton/ha), which showed that the lower impact of GWP was coming from the one with the higher yield. Thanawong et al. (2014) also reported the difference in GWP impacts between two cropping systems: irrigated and rain-fed systems, and indicated that rain-fed systems contributed the lowest impact in comparison to irrigated rice farm systems. Accordingly, the rice fields in this present study had a non-mechanized irrigation system, and no powered pump was used, which was similar to the rice field in Italy as reported by Hokazono and Hayashi (2012), which had an almost similar GWP emission of 1460 kg CO_2eq per 1 ton of rice. This irrigation system practice contributed a contribution of zero to GWP, as there was no diesel combustion and no energy was consumed (Jimmy et al. 2017).

Table 4 GHG emissions for conventional rice and organic rice

Substance	Conventional rice	Organic rice
CO_2	296.61	113.54
N_2O	95.77	6.42
CH_4	65.32	20.56

The main contributors to GWP were nitrous oxide (N_2O), carbon dioxide (CO_2) and methane (CH_4). The total GHG emissions for conventional rice and organic rice are shown in Table 4.

Many previous studies have reported that rice field emissions make the highest contribution to GHG emissions in the rice production process (He et al. 2018; Koga and Tajima 2011; Soni et al. 2013; Wang et al. 2010). Based on this study, it was found that the main processes that contributed to GHG emissions from rice cultivation were the emissions from conventional rice fields (86.52 kg CO_2-eq), followed by diesel usage (42.03 kg CO_2-eq from conventional rice and 31.33 kg CO_2-eq from organic rice), fertilizer application (36.29 kg CO_2-eq from conventional rice and 0.23 kg CO_2-eq from organic rice) and transportation (12.35 kg CO_2-eq from conventional rice and 8.37 kg CO_2-eq from organic rice). The GHG emissions from diesel and transportation were primarily from the burning of fossil fuel for all transport, tractors and combine harvest activity; hence, the main emission type from this activity was CO_2 (Lee et al. 2017; Othman 2017; Shahid et al. 2014).

From the results, it was clear that most of the GHG emissions from conventional rice were higher, by 87.44% for N_2O, 44.76% for CH_4, and 44.63% for CO_2, than that of organic rice. The GHG emissions were mainly produced from the consumption of diesel for tractors used in land preparation and rice harvesting, as well as the transportation of rice seeds from the nursery to the rice field and the transportation of rice grain from the field to factory. N_2O was produced from field emissions (denitrification) and from the application of N fertilizer. The N_2O emissions from rice fields are affected by many factors, including the type of fertilizer, climate, and soil type (Yodkhum et al. 2017; Zhao et al. 2019).

Furthermore, the amount of CH_4 that is emitted from a rice field is primarily determined by three processes: CH_4 production, oxidation, and transport from the soil to atmosphere. CH_4 is generated under anaerobic conditions from organic matter in flooded fields (Brodt et al. 2014). GHG emissions can be reduced by adjusting rice production

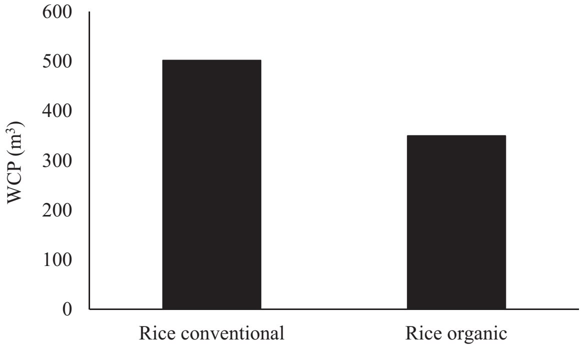

Fig. 6 Relative contribution towards WCP

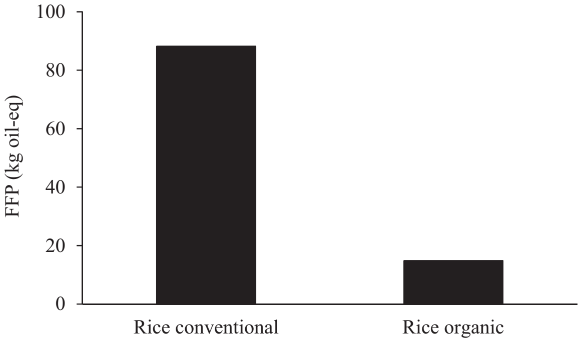

Fig. 7 Relative contribution towards FFP

practices, such as by reducing the flooding period, applying the system of rice intensification (SRI) method and using environmentally friendly machines, fertilizer, and pesticides (Gathorne-Hardy 2016; Yodkhum et al. 2017). As the organic rice in this study applied the system of rice intensification (SRI) method, it had lower methane emissions than those of conventional rice. This difference is because of the SRI management method, which applies shallow and intermittent irrigation, hence creating aerobic soil conditions. Previous studies have shown that SRI management practices could reduce methane emissions by between 22% and 64% (Gathorne-Hardy 2016; Yodkhum et al. 2017). Therefore, this study proved that GHG emissions from organic rice were lower than those from conventional rice due to field emissions and the use of fertilizers. Furthermore, SRI can be used as an alternative method to meet the objectives of the clean development mechanism (CDM), introduced by the Kyoto Protocol for climate change mitigation.

In this study, approximately 500 m^3 of water for conventional rice and 350 m^3 of water for organic rice were required to produce 1 ton of rice. Figure 6 shows the contributions of conventional and organic rice to WCP. The results showed that the water used in conventional rice was approximately 18% higher than that used in organic rice because organic rice was flooded intermittently compared to conventional rice to achieve better soil aeration. As claimed in previous studies, water is the main factor for rice yield gaps and yield variability (Harun and Hanafiah 2018a, 2018b). However, it was reported that Asian countries face water scarcity issues due to the expansion of the urban and industrial sectors, which affected agricultural yield as well as food production (Akinbile et al. 2011; Hanafiah et al. 2019).

Malaysia is rich in water resources compared to other regions because the country receives an annual rainfall of approximately 2500 mm (Harun and Hanafiah 2017). In addition, Peninsular Malaysia's catchment area of 29,000 km^2 is drained by a dense network of rivers and streams (Akinbile et al. 2011). Hence, it is assumed that the water sources in Malaysia are sufficient to meet the water requirement for rice cultivation. Nevertheless, in the matter of sufficient water used, exploring ways to produce a high rice yield with less water consumption and appropriate irrigation management is essential to overcome food insecurity and several environmental problems, such as water depletion and reductions in water quality (Gathorne-Hardy 2013).

Figure 7 illustrates the contribution of conventional and organic rice to FFP. The impact on FFP was related to fuel application for machinery and the transportation of raw materials to the field. In this study, 5 L petrol and 32 L diesel were applied to run the machinery for the production of 1 ton of conventional rice. This amount contributed ~84.6 kg oil-eq to the FFP impact, which was 58% higher than that of organic rice. The types of machinery used were tractor and rotary harrow for land preparation in dry and wet conditions, knapsack sprayer pump for fertilizer and pesticide application, automatic seed applicator, and combine harvester for rice harvesting. The transportation used in this study was a 7-ton truck, and the average distance from the retailer to the rice field was more than 400 km. The high application of fossil fuels would cause an increase in fossil depletion (Jimmy et al. 2017; Yusoff and Panchakaran 2015).

Damage Assessment at Endpoint Level

Damage assessment was performed at the endpoint level to observe how the impacts could cause total damage to the environment in three categories: human health (HH), ecosystem quality (ED), and resource availability (RA) (Fig. 8). The unit for HH is presented in DALY (disability adjusted life years), ED is presented in species.year (the local species loss integrated over time), and RA is presented in USD2013 (dollar). Conventional rice impacted HH, ED and RA at 9.63×10^{-4} DALY, 5.54×10^{-6} species.year, and 30.98 Dollar, respectively, while the organic rice contributed ~2.60×10^{-4} DALY, 2.28×10^{-6} species.year and 8.44 Dollar, respectively (Table 5).

The impacts on HH and ED were mainly related to WCP and GWP, while RA was related to FFP. The presented results showed that the total impacts of WCP on HH damage from conventional and organic rice cultivation were

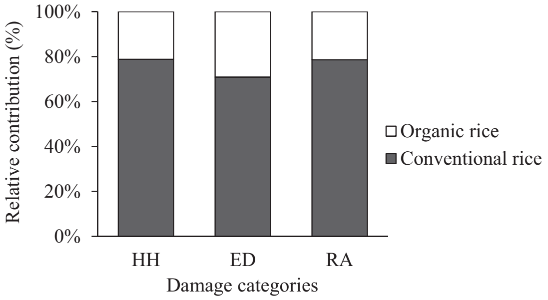

Fig. 8 Damage assessment at the endpoint level

2.18×10^{-4} DALY per m^3 of water consumption and 6.54×10^{-5} DALY per m^3 of water consumption, respectively. The total impacts for HH damage by GWP from conventional and organic rice were 4.25×10^{-4} DALY per kg of emission and 1.30×10^{-4} DALY per kg of emission, respectively. However, the total impact damage of ED by WCP was 1.33×10^{-6} species.year/m^3 from conventional rice and 3.98×10^{-7} species.year/m^3 from organic rice. The total damage impact of ED by GWP was 1.28×10^{-6} species.year/m^3 from conventional rice and 3.94×10^{-7} species.year/m^3 for organic rice. For RA, the total impact damage by FFP from conventional and organic rice was 3.07×10^1 Dollar and 8.43 Dollar, respectively.

Damage to HH was mainly contributed by CO_2, N_2O, and fipronil substances. CO_2 was emitted from the transportation and fertilizer production processes, and N_2O was emitted from the diesel-burning process from machinery during the cultivation process. In addition to HH, fipronil affected ED due to pesticide usage during the cultivation process. Pesticides are degraded by biotic and abiotic processes when released to the environment (Bagheri et al. 2019; Gaona et al. 2019; Sande et al. 2011). Meanwhile, damage to the ecosystem is caused by the use of fertilizers that generate ammonia and nitric acid. Excessive concentrations of nitrogen and phosphor in fertilizers will lead to water eutrophication and soil acidification. Damage to resources was mainly caused by fossil depletion due to the natural gas used in fertilizer production and diesel used to generate energy for land preparation (Hartono and Johannes 2017).

There are increasing studies regarding the LCA of agriculture in Malaysia since it was recognized under the 9th Malaysia Plan (2006–2010) (Ng et al. 2012). Several studies have been conducted on the LCA of rice production. (Rahman et al. 2019) and (Yusoff and Panchakaran 2015) conducted a cradle-to-gate analysis of the LCA of rice cultivation and found that the major environmental hotspot in rice production was paddy cultivation. Rahman et al. (2019) also reported that the application of fertilizer contributed to high GHG emissions.

In this study, the environmental hotspot in rice production was assessed using the cradle-to-gate approach. Based on the LCA characterization, the results showed that the environmental hotspot for rice production was the paddy cultivation process. Hence, some improvements should be made to rice cultivation practices. Based on the results obtained from this study, improvements can be made in relation to fertilizer and pesticide application, water consumption and diesel burned in machinery to reduce emissions from rice fields. The application of fertilizer and pesticides should be reduced, and the application should not exceed the recommended quantity that has been suggested by the Ministry of Agriculture and rice authorities. The high amount of fertilizer usage has been reported as the leading contributor to the global warming potential (Huang et al. 2010). Pesticide application should be replaced with a more environmentally friendly technique, such as integrated pest management (IPM). For example, the population of pests could be controlled by adopting a biological control technique.

Flood condition practices in rice fields have led to high water consumption and contribute to high emissions. For instance, applying new technologies such as alternate wetting and drying (AWD) could reduce the water consumption in rice cultivation (Rahman et al. 2019). Concerning diesel usage, improvements in environmental performance could be made in

Table 5 The results of impact categories at the endpoint level

Area of protection	Unit	Conventional rice	Organic rice
Human Health			
WCP	DALY	2.18E−04	6.54E−05
GWP	DALY	4.25E−04	1.30E−04
PMFP	DALY	1.64E−04	5.78E−05
HTPnc	DALY	1.52E−04	5.15E−06
HOFP	DALY	5.35E−07	3.74E−07
HTPc	DALY	1.12E−06	4.08E−07
ODP	DALY	1.88E−06	1.27E−07
IRP	DALY	9.43E−08	9.48E−09
Total	DALY	9.63E−04	2.60E−04
Ecosystem damage			
WCP, Terrestrial ecosystem	species.year	1.33E−06	3.98E−07
GWP, Terrestrial ecosystems	species.year	1.28E−06	3.94E−07
EOFP	species.year	7.73E−08	5.39E−08
TAP	species.year	5.51E−07	1.20E−07
TETP	species.year	3.90E−07	5.91E−09
LOP	species.year	1.84E−06	1.30E−06
WCP, aquatic ecosystem	species.year	5.93E−11	1.78E−11
FEP	species.year	5.95E−08	3.24E−09
FETP	species.year	1.03E−08	1.29E−09
METP	species.year	1.53E−10	2.77E−11
GWP, Freshwater ecosystems	species.year	3.50E−11	1.08E−11
Total	species.year	5.54E−06	2.28E−06
Resource availability			
FFP	USD2013	3.07E+01	8.43E+00
SOP	USD2013	2.49E−01	9.76E−03
Total	USD2013	3.10E+01	8.44E+00

relation to transportation, tractors, and machinery used in the field. The diesel used could be changed to other forms of environmentally friendly fuel, such as biofuels. To enhance the environmental performance of rice production in Malaysia, the government should also provide more incentives for organic farming.

Sensitivity Analysis

As organic rice contributed less of an effect in rice production, the improvement was focused on conventional rice practices. Sensitivity analysis was performed to assess the influence of the selected parameter in the rice cultivation phases, and an alternative scenario was created to quantify the impacts of possible improvements. As mentioned in the previous section, the improvement options were focused on fertilizer application, water use, transportation, and diesel consumption due to the significant impacts identified in the impact assessment. Therefore, the change in the LCI was made by reducing fertilizer application, water use, transportation, and diesel by 30%. For sensitivity analysis, there are no standard methods provided under the ISO standards (Aziz and Hanafiah 2020; Yusoff and Panchakaran 2015). Therefore, the alternative scenario was created as an assumption to demonstrate a possible example of an enhancement. Table 6 shows the results of the base and alternative scenarios in conventional rice production.

Based on the results obtained, the reduction made in the input of fertilizer, transportation, and diesel affected the characterized results compared to the base scenario. It was shown that the impact contributions of the alternative scenario were lower than those of the base scenario. The impacts of GWP, WCP, and FFP were reduced by 1%, 17%, and 5%, respectively, when the reduction of the significant input was performed. Therefore, it should be noted that the results were based on European characterization factors, and this assumption could influence the accuracy and representativeness of the results. However, it could be concluded that the results from this study still stand.

Table 6 Characterized results of the base and alternative scenarios

Impact category	Unit	Base scenario	Alternative scenario
HTPnc	kg 1,4-DBC e	2.29E+04	2.27E+04
GWP	kg CO_2 eq	4.58E+02	3.84E+02
LOP	m^2a crop eq	2.08E+02	2.05E+02
WCP	m^3	9.82E+01	7.30E+01
FFP	kg oil eq	8.46E+01	6.22E+01
FETP	kg 1,4-DCB e	1.49E+01	1.48E+01
IRP	kBq Co-60 eq	1.11E+01	8.08E+00
TETP	kg 1,4-DCB e	7.24E+00	7.22E+00
TAP	kg SO_2 eq	2.60E+00	2.30E+00
METP	kg 1,4-DBC e	1.46E+00	1.38E+00
EOFP	kg Cu eq	1.08E+00	7.62E−01
HOFP	kg NOx eq	5.99E−01	4.42E−01
HTPc	kg NOx eq	5.88E−01	4.34E−01
SOP	kg 1,4-DBC e	3.39E−01	2.75E−01
PMFP	kg $PM_{2.5}$ eq	2.62E−01	2.09E−01
FEP	kg P eq	9.75E−02	9.64E−02
ODP	kg CFC11 eq	3.55E−03	3.26E−03

Many studies from other countries have been conducted on the LCA of rice production. Blengini and Busto (2009), Jimmy et al. (2017), Nabavi-Pelesaraei et al. (2017), and Yusoff and Panchakaran (2015) found that the cultivation stage was a hotspot in rice production, with field emissions, fertilizer application, and fossil fuel usage being the main factors contributing to GHG emissions. Mungkung et al. (2019) reported that the impact of Hom Mali organic rice production on climate change and water use were 2.88 kg CO_2 eq/kg of paddy rice and 1.34 m^3 H_2O eq, respectively. The main contributor to climate change impact was related to the direct CH_4 and N_2O emissions from rice field. Water use impact was linked to the requirement of flooded system. Kim et al. (2018) found that the ranks of environmental impacts of rice farming in Korea were 48.6, 35.8, 28.9, and 16.7 for conventional, low-pesticide, non-pesticide, and organic farming practices, respectively. Masuda (2019) indicated that the eco-efficiency of intensive rice production in Japan can be improved by expanding the size of rice farms with consideration of implementing the economies of scale, reducing outsource of farm work and savings in chemical fertilizers and pesticides. The results from the study conducted by He et al. (2018) in China showed that the environmental impact indices for conventional rice was 10 times higher than organic rice. The highest environmental index for conventional and organic rice was aquatic toxicity potential and water depletion, respectively. He et al. (2018) and Nunes et al. (2016) suggested that the organic rice system has the potential to be a sustainable agricultural practice in comparison with conventional practices, as organic cultivation uses less water and biogenic fertilizer. It can be concluded that the environmental sustainability of rice production can be enhanced by reducing water usage, chemical fertilizer application, and fossil fuel usage.

Limitations of the Study

Based on this study, the highest emissions generated from rice cultivation could be identified. As discussed earlier, rice cultivation is one of the major contributors to greenhouse gases. To improve the environmental performance of rice production, some mitigation measures could be applied. We suggest focusing on improving cultivation practices, such as the implementation of new technologies in rice cultivation.

Moreover, an environmentally friendly cultivation technique could be one of the best solutions to enhance environmental emissions from rice fields. Hence, transformation from old conventional rice cultivation techniques to organic cultivation techniques could be one of the best approaches to enhance emissions from rice fields. Organic farming methods attempt to reduce the environmental impact of rice cultivation by promoting the use of organic fertilizers and avoiding the use of chemical fertilizers and pesticides (Aguilera et al. 2015). The Malaysian government aimed to reduce the intensity of carbon emissions to gross domestic product (GDP) by 45% in 2030. Moreover, the government should attempt to reduce GHG emissions in major key factors, including agriculture. Hence, this study could support government initiatives and could be a guideline for sustainability in rice production.

The LCA method is very useful because it can determine the integrated impacts on humans, ecosystems, and resources. This method can be used by many parties, including policy makers, producers, and consumers, as a guide for selecting sustainable products and production. In addition, the LCA method can be used as guidelines in choosing the type of fertilizers, pesticides, or other inputs, as this method clearly shows the difference in emissions produced with the applications of different inputs so that environmental impacts can be reduced. There were several limitations in this study, including a lack of data for chemical inputs and emissions as well as poor access to data that forced estimations to be made; additionally, there were time constraints and a lack of local references as well as a lack of national databases. Notably, the database for this study was derived from European datasets. Thus, the accuracy representativeness of the results obtained could have been affected. Hence, the results obtained may not represent the accurate potential impacts of Malaysia due to the lack of national database access. In addition, this study was limited to environmental performance at the farm gate only, and it is recommended that further research on LCA be conducted for other phases of rice production.

Conclusions and Policy Recommendations

The performance of rice production is pertinent as Malaysia relies primarily on key granary areas. In conclusion, this study provides useful information for the agricultural sector in Malaysia. The results from this study could serve as a guideline for achieving sustainability in food production. It could also be used to assist policy makers and farmers to introduce a more environmentally sustainable rice production techniques in Malaysia. Nevertheless, further LCA studies on rice production are still needed to gather more information on rice field management; hence, further initiatives and efforts could be taken to improve the sustainability of the rice sector. In addition, more primary research on the LCA of rice cultivation in Malaysia must be conducted, so that the assessment of environmental impact will be more comprehensive. The results of this study support the National Agro-Food Policy 2011–2020 goal to address food security and safety as well as to ensure the sustainability of the agro-food industry in Malaysia. A broad application of LCA makes this approach well suited to analyse the environmental performance of rice production for other rice-producing countries in the world, especially in the southeast Asia region.

Acknowledgements MMH was financed by the research grants (DIP-2019-001; MI-2020-005).

Compliance with Ethical Standards

Conflicts of Interest The authors declare that they have no conflict of interest.

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