

Article

Life Cycle Assessment of Conventional and Organic Rice Production Under Alternative Irrigation Management in Thailand

Dussadee Rattanaphra ¹, Sittinun Tawkaew ², Wilasinee Kingkam ¹ , Sasikarn Nuchdang ¹ , Parinya Khongprom ³, Kittiwat Kitpakornsanti ⁴ and Unchalee Suwanmanee ^{2,*} 

¹ Nuclear Technology Research and Development Center, Thailand Institute of Nuclear Technology, Nakorn Nayok 26120, Thailand; dussadeer@tint.or.th (D.R.); wilasinee@tint.or.th (W.K.); sasikarn@tint.or.th (S.N.)

² Department of Chemical Engineering, Faculty of Engineering, Srinakharinwirot University, Nakorn Nayok 26120, Thailand; sittinun@g.swu.ac.th

³ Department of Chemical Engineering, Faculty of Engineering, Prince of Songkla University, Songkhla 90110, Thailand; kparinya@eng.psu.ac.th

⁴ Climate Change and Environment Research Center, Department of Climate Change and Environment, Technopolis, Pathumthani 12120, Thailand; kittiwankit@gmail.com

* Correspondence: unchalee@g.swu.ac.th; Tel.: +66-02-6495000 (ext. 27105)

Abstract

This study evaluates the environmental sustainability of conventional and organic rice production systems in Nakorn Nayok province, Thailand, focusing on the Khao Dawk Mali 105 variety. Limited studies have evaluated comparative production systems, alternative water management scenarios, and uncertainty in rice life cycle assessment (LCA) under tropical smallholder conditions. A cradle-to-farm gate LCA was conducted under water-sowing continuous flooding (WSF), with 1 kg paddy rice as the functional unit and the ReCiPe 2016 midpoint (H) method. The results showed that organic systems under flooding exhibit higher global warming potential (GWP) than conventional systems, primarily due to methane emissions, which contributed over 83% of the total GWP. The relatively high GWP values compared with previous studies are associated with continuous flooding conditions, methodological assumptions based on IPCC default emission factors, and lower yield in the studied systems. Uncertainty analysis suggests that organic WSF had higher environmental impacts in 8 out of 18 midpoint categories, while sensitivity analysis highlights the importance of water management. Alternative practices, including dry-sowing delayed flooding (DSF) and saturated soil (ST), can reduce the GWP by 39–57% and water consumption by 8–18%, highlighting the importance of water management as an effective strategy for improving environmental sustainability in rice production systems. Sensitivity and multivariate analyses suggest that resource use and water management are key drivers of environmental impacts. Overall, the findings demonstrate that water management and yield are key factors influencing environmental performance in rice production systems and provide insight for improving sustainability under tropical agricultural conditions.

Keywords: Nakorn Nayok Thailand; organic rice systems; water management regimes; life cycle sustainability; multivariate analysis



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1. Introduction

Global greenhouse gas (GHG) emissions increased by 1.3% or 665 Mt CO₂ equivalent (CO₂ eq.) in 2024, reaching a new record high of 53.2 Gt CO₂ eq. [1]. The agricultural sector accounts for 12.3% of total global anthropogenic GHG emissions [2]. Agricultural activities contributed moderately to carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) emissions, accounting for 14%, 41% and 61% of total anthropogenic emissions, respectively [3]. Rice cultivation is one of the largest anthropogenic sources of methane, contributing about 12% of global methane emissions due to anaerobic decomposition of organic matter under flooded paddy conditions [4,5].

In 2025, the global rice cultivation area reached 168.59 million hectares, while the average yield increased to 4720 kg ha⁻¹, corresponding to growth rates of harvested area and yield of 1.5% and 0.4% compared with 2024, respectively [6]. Rice cultivation occupies the largest share of cultivated land, accounting for 43.4% of the total agricultural area, and approximately 5.17 million households engage in rice farming, representing 67.2% of all agricultural households in Thailand [7]. Therefore, given its economic importance and large cultivation area, rice production significantly contributes to national GHG emissions. In 2024, Thailand's greenhouse gas emissions increased by 5.23% or 21 Mt CO₂ eq., reaching a total of 422.38 Mt CO₂ eq. [1]. The agricultural sector ranked third, contributing 15.69% of total GHG emissions, and rice cultivation contributed about 51.28% of agriculture-related emissions [7]. Organic rice production has expanded in response to growing consumer awareness of health concerns and environmental sustainability. Organic agriculture in Thailand has been practiced since the 1980s and has been promoted under national policies on sustainable agriculture and the Thailand 4.0 strategy. The National Organic Agriculture Development Plan aims to expand organic production areas from 48,000 to 160,000 hectares within three years [8]. According to Thailand's Organic Agriculture Action Plan (2023–2027), the total certified organic agricultural area reached approximately 168,000 ha in 2025.

Beyond climate mitigation, rice production plays a role in food security and poverty alleviation in Thailand [9,10]. As the majority of agricultural households depend on rice farming, sustainability transitions within this sector have direct implications for rural livelihoods and socio-economic resilience [7]. Therefore, improving environmental performance in rice systems must be aligned with development objectives, including income stability, productivity, and resource efficiency, in line with sustainable development pathways [11]. Sustainable rice production is aligned with several Sustainable Development Goals (SDGs), particularly with SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action) [12]. As rice remains a primary staple and a critical livelihood source in many developing countries, improving its environmental performance strengthens both food security and sustainable agrifood systems [10]. Integrating environmental mitigation strategies into rice production therefore supports national climate commitments and sustainable development pathways [11,13]. Previous LCA studies have highlighted the importance of integrating water management, fertilizer use, and residue management to improve the environmental performance of rice systems. For the example, Bacenetti et al. (2016) [14] assessed the environmental profile of organic cultivation in Lomallina, Northern Italy. Their results indicated that the main environmental hotspots, particularly in terms of global warming potential, are dominated by methane emissions from flood fields (44%), as well as electricity and energy required for compost production, and fertilizer application. Giuliana et al. (2024) [15] studied and evaluated conventional rice production systems in Europe, in Northern Italy, and found that irrigation water use, methane emissions, and energy consumption were dominant contributors to global warming and freshwater ecotoxicity. The study indicated that using intermittent

flooding of paddy fields (DSI) could reduce environmental impacts by 40% compared with continuous flooding. Similarly, Minamikawa et al. (2025) [16] highlighted the influence of water management and rice yield on global warming potential, and reported that methane emission reduction from continuous flooding can be achieved through the implementation of alternate wetting and drying (AWD). The relative reduction in methane emissions under AWD were observed to be 39% in Japan, 57–62% in China, 31–52% in Asia, and 52–59% globally, compared with continuous flooding. Previous LCA studies in Thailand have primarily focused on rice production under continuous flooding. For the example, Yodkhum et al. (2017) [17] evaluated the global warming potential of organic rice production in Chaing Mai Province, Northern Thailand, and their results indicated that field emissions were the major source of GHG emissions (83%), followed by energy consumption for land preparation and harvesting. Mungkung et al. (2020) [18] evaluated environmental impacts of organic rice production in Northern and Northeastern Thailand, covering a cultivation area of 846 ha, involving 392 farmers. Their results showed that the global warming potential ranged from 3.46 to 3.86 kg CO₂ eq. kg⁻¹ paddy rice, based on average rice yields of 2946 kg ha⁻¹ and 3267 kg ha⁻¹. Methane from rice fields was the main contributor, accounting for 91–93% of total GHG emissions. Arunrat et al. (2021) [19] evaluated and compared the global warming potential of small- and large-scale conventional rice farming across Northern, Northeastern, Central and Southern Thailand. They found that large-scale farming emitted 2.19 kg CO₂ eq. kg⁻¹ paddy rice, while smallholder farming emitted 2.31 kg CO₂ eq. kg⁻¹ paddy rice. Field methane emissions account for the largest share of GHG emissions (71–76%), followed by post-harvesting burning (10–14%) and fertilizer application (7.1–7.6%). More recently, Khamfong et al. (2025) [20] evaluated the environmental and economic performance of organic rice production in Uttaradit Province, Northern Thailand. Their results showed that the global warming potential was 2.19 kg CO₂ eq. kg⁻¹ paddy rice, with field methane emission, land preparation and field flooding being dominant contributors. Integrating AWD with solar pumping reduced GHG emission by 31% and improved economic output by 61% compared with the baseline scenarios.

As summarized in Table 1, previous rice LCA studies have mainly focused on greenhouse gas emissions or selected environmental impacts. Studies integrating uncertainty analysis, irrigation sensitivity assessment, and multivariate interpretation remain limited [17–20]. The present study addresses these gaps by combining these approaches within a single analytical framework to evaluate conventional and organic rice production systems under alternative irrigation regimes, covering cultivation through post-harvest processes.

This approach enables comprehensive evaluation of water management practices on environmental implications, providing opportunities for sustainability improvement in rice cultivation under tropical conditions. Therefore, the aims of this study are to: (i) assess the environmental sustainability of conventional and organic paddy rice production under water-sowing continuous flooding (WSF) in Nakorn Nayok central province, central Thailand, using an LCA approach with the ReCiPe 2016 midpoint method to identify environmental hotspots across 18 impact categories; (ii) evaluate uncertainty using Monte Carlo simulation to identify the robustness of the results; (iii) perform a sensitivity analysis to investigate the influence of irrigation water management regimes, including the baseline water-sowing continuous flooding (WSF) and two alternative practices, dry-sowing delayed flooding (DSF) and saturated soil (ST); and (iv) support the interpretation of environmental impact patterns in cultivation practices using multivariate analysis (MVA). The findings contribute to improving the sustainability of smallholder rice production systems in Thailand. Although the inventory data were derived from a previous published field

study, the present work considerably extends its application through multi-impact assessment, uncertainty analysis, irrigation scenario evaluation, and multivariate interpretation.

Table 1. LCA studies and their main characteristics in terms of modeling choice for rice production.

Country	Systems	System Boundary	Functional Unit	Irrigation	LCA Method	Sensitivity Analysis	Uncertainty Analysis	Multivariate Analysis	References
Italy	Organic farm	Cradle-to-farm gate (included harvesting)	1 kg paddy rice	Non-flooded	ILCD Midpoint	Yes	No	No	[14]
Italy	Conventional farm	Cradle-to-farm gate (included harvesting)	1 hectare	WSF, DSF, ¹ DSI	ReCiPe 2016 Midpoint (H)	Yes	Yes	Yes	[15]
Thailand	Organic farm	Cradle-to-farm gate (included harvesting)	1 kg paddy rice	Non-Flooded	GWP	No	No	No	[17]
China	Conventional and organic farms	Cradle-to-farm gate (included harvesting)	1 hectare	Flooded	ReCiPe 2016 Midpoint (H)	No	No	No	[21]
This study	Conventional and organic farms	Cradle-to-farm gate (included harvesting)	1 kg paddy rice	WSF, DSF, ST	ReCiPe 2016 Midpoint (H)	Yes	Yes	Yes	–

¹ DSI is Dry-sowing-intermittent irrigation.

2. Materials and Methods

2.1. Description of Rice Production Systems

This study compares conventional and organic rice production systems cultivated under water-sowing continuous flooding (WSF) conditions. Both systems used Khao Dawk Mali 105 rice and followed similar cultivation stages, including land preparation, planting, crop management, harvesting, and post-harvest residue management.

The conventional production system relied on synthetic fertilizers (21-0-0, 15-15-15, and 8-24-24), whereas the organic system applied cow manure as the sole nutrient source and avoided synthetic agrochemicals. Conventional farms used broadcast sowing, while organic farms adopted transplanting. Land preparation was conducted using gasoline- or diesel-powered tractors, and irrigation water was supplied to maintain a water depth of approximately 5–10 cm under WSF conditions. Both systems involved manual harvesting. Post-harvest residue management differed between systems, with rice straw being disposed of through open burning in the conventional system and composting in the organic system. No pesticides were applied during the cultivation period.

2.2. Goal and Scope Definition

The primary goal of this LCA study was to evaluate and compare the environmental performance of conventional and organic rice production systems under WSF conditions in Thailand. This study was conducted in Mueang District, Nakhon Nayok Province, Central Thailand, which is an important area for both domestic and international rice markets. This area has a tropical climate with the temperature ranging from 21 to 36 °C, average rainfall of 1426 mm, and an irrigation water availability of 241 million m³, providing suitable conditions for paddy rice cultivation [22–24].

Functional Unit and System Boundary

The environmental performance of conventional and organic paddy rice production followed the LCA framework based on ISO 14040 (ISO 2019) and ISO 14044 (ISO 2019) standards [25,26]. The functional unit was 1 kg of paddy rice. The use of a mass-based functional unit may influence comparative results due to yield differences; however, it is

commonly applied in rice LCA studies [14,15,17] and allows for comparison with the existing literature. The system boundary followed a cradle-to-farm gate approach consisting of land preparation, seeding, planting, fertilizing, paddy rice harvesting and post-harvesting, and transportation of materials to the farm. For post-harvesting, rice straw was composted in organic farms, whereas open burning was practiced in conventional farms. The system boundary of the study is shown in Figure 1. Within the study area, the rice productions involved the main inputs, including seed, fertilizers, energy (fuels and electricity), and irrigation water. Only cow manure or organic fertilizer was applied in organic paddy rice fields in accordance with the organic agricultural standard based on the non-use of agricultural chemicals, whereas chemical fertilizer (N, P, and K) was used in conventional farms.

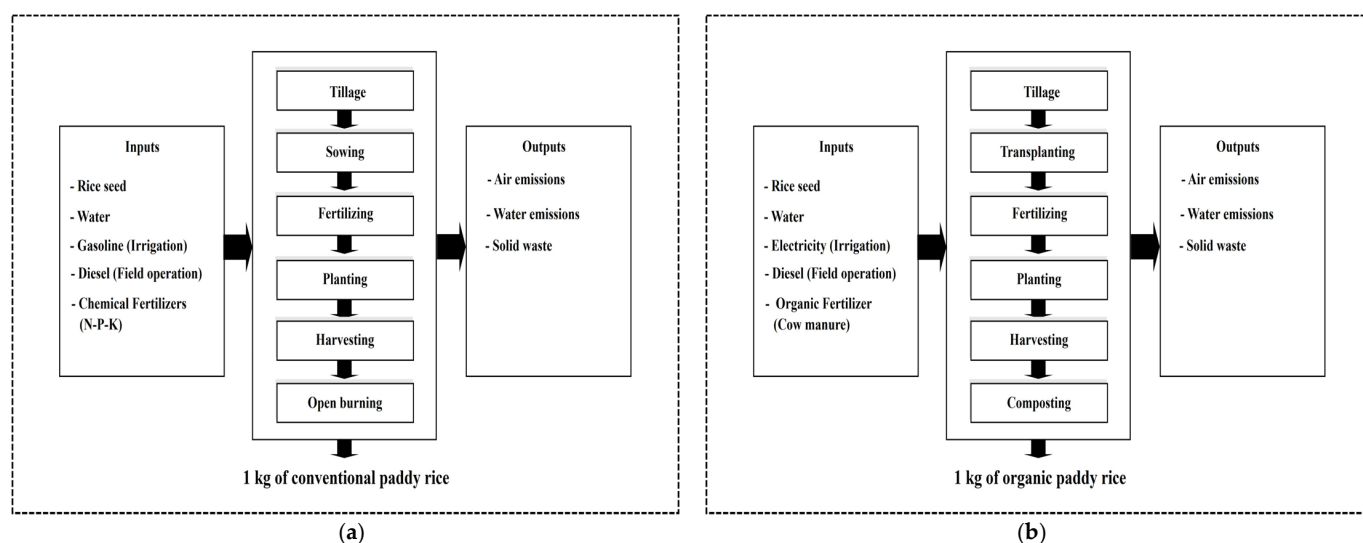


Figure 1. System boundaries of the study: (a) conventional and (b) organic paddy rice.

2.3. Life Cycle Inventory (LCI)

LCI data were obtained from the field-based dataset reported by Mitphumwiboon et al. (2020) [27], in which organic and conventional rice farming results were collected at Mueang District, Nakhon Nayok Province, Central Thailand (14° N, 101° E), at 400–1200 m above mean sea level, during the 2019–2020 cultivation period. This study adopted an attributional LCA approach. The data included resource inputs and farm operations. The annual inputs of rice cultivation covered six main stages, including tillage, sowing or transplanting, planting, fertilizing, harvesting and post-harvesting. Khao Dawk Mali 105 and water-sowing continuous flooding (WSF) were used in both organic and conventional systems. No allocation procedure was required because no co-products were included within the system boundary. Rice straw remained within the system boundary and was treated as a post-harvest residue, being managed through open burning in the conventional system and composting in the organic system. Detailed inventory data for conventional and organic rice production systems are presented in Table 2.

Table 2. LCI 1 kg of conventional and organic paddy rice under WSF.

Input	Unit	Conventional-WSF	Organic-WSF	References
Rice seed	kg	0.077	0.200	[27]
Water	m ³	3.44	6.99	[27]
Electricity	kWh	–	2.10	[27]

Table 2. Cont.

Input	Unit	Conventional-WSF	Organic-WSF	References
Gasoline	L	0.118	–	[27]
Diesel use	L	0.040	0.200	[27]
Organic manure	kg	–	0.200	[27]
Fertilizer N	kg	0.0034	–	[27]
Fertilizer P	kg	0.0030	–	[27]
Fertilizer K	kg	0.0030	–	[27]
Output				
Paddy rice	kg	1.00	1.00	[27]
Emission to air				
CH ₄ (Anaerobic decomposition)	kg	1.21	1.46	[27–29]
Direct N₂O-N				
N ₂ O _{Direct} (Organic manure)	kg	–	4.84×10^{-5}	[27–29]
N ₂ O _{Direct} (Fertilizer N)	kg	7.45×10^{-5}	–	[27–29]
Indirect N₂O-N				
N ₂ O _{Indirect} (Organic manure)	kg	–	7.26×10^{-6}	[27–29]
N ₂ O _{Indirect} (Fertilizer N)	kg	5.85×10^{-6}	–	
CO ₂	kg	3.65×10^{-1}	5.40×10^{-2}	[27,30,31]
CH ₄	kg	3.04×10^{-4}	2.18×10^{-6}	[27,30,31]
N ₂ O	kg	4.90×10^{-5}	4.38×10^{-7}	[27,30,31]
Compost				
CO ₂	kg	–	0.11	[27–29]
CH ₄	kg	–	1.81	[27–29]
Rice straw open burning				
CO ₂	kg	3.39×10^{-1}	–	[27,32]
CH ₄	kg	2.78×10^{-4}	–	[27,32]
N ₂ O	kg	1.62×10^{-5}	–	[27,32]
CO	kg	8.05×10^{-3}	–	[27,32]
NO _x	kg	9.28×10^{-4}	–	[27,32]
SO ₂	kg	7.19×10^{-4}	–	[27,32]
PM _{2.5}	kg	4.64×10^{-4}	–	[27,32]
PM ₁₀	kg	3.02×10^{-3}	–	[27,32]
NMHC	kg	3.00×10^{-3}	–	[27,32]
TPM	kg	8.58×10^{-4}	–	[27,32]
PAHs	kg	4.32×10^{-3}	–	[27,32]
PCDD/F	kg	1.16×10^{-13}	–	[27,32]
Emission to water				
N ₂ O _{Leaching/runoff}	kg	1.40×10^{-5}	9.13×10^{-6}	[27–29]

Data quality was assessed in terms of representativeness, completeness, temporal coverage, and geographical coverage in accordance with ISO 14044 [26]. The foreground inventory data were obtained from field-based observations of conventional and organic rice production systems, providing high geographical and temporal representativeness for the study area. The inventory dataset included the major material, energy, and agricultural inputs associated with rice cultivation and post-harvest management. Background datasets were obtained from the ecoinvent database and the Thai National Life Cycle Inventory Database [33] was selected to provide the best available representation of technologies and conditions relevant to the study.

The data for the conventional farms were collected over a period of 5 months (February to June 2019) covering an agricultural area of 62.5 ha [27]. Rice cultivation begins with about one day of seedling cultivation, then land preparation with a gasoline-powered tractor. During transplanting, after primary tillage, a water depth of 5–10 cm was maintained using a diesel pump. In the crop management stage, the synthetic chemical fertilizers (21-0-0, 15-15-15, and 8-24-24) were mainly applied twice (about days 10 and day 50) until the ripening stage (150 days). Finally, the crop was harvested manually and disposed of by open burning. No crop-protection chemicals were included in the inventory dataset because no inputs were reported in the field survey data [27].

The data for the organic farms were collected for a period of 4 months (August to November 2019) covering an agricultural area of 12.5 ha [27]. The rice cultivation started with seed and land preparation, including seedling cultivation about 7 days before land preparation using a diesel-powered tractor. During planting, organic rice farms use transplanting, while conventional farms use broadcast sowing. For the transplanting stage, after secondary tillage, a water depth of 5–10 cm was maintained by electrically pumping water into the fields, and the young plants were transplanted into the wetland field with 20–25 cm spacing between them. In the crop management stage, there were four main operations: only cow manure was applied as the organic fertilizer at seedling emergence (1–20 days), tillering (21–55 days), and booting (56–90 days), and the field was drained after ripening (91–120 days). The final stage was manual harvesting, followed by disposal via composting.

Irrigation Water Requirement

The amount of daily irrigation was estimated from the water balance, including crop water requirement (CWR), water loss including percolation and seepage, and effective rainfall following the irrigation practices by Bouman et al. (2007) and Steduto et al. (2012) [34,35]. The formula used in this study is expressed below in Equation (1).

$$I_d = \begin{cases} \text{CWR} + \text{WPL} - \text{ER}, & \text{if } \text{ER} < \text{CWR} + \text{WPL} \\ 0, & \text{if } \text{ER} \geq \text{CWR} + \text{WPL} \end{cases} \quad (1)$$

where I_d is daily irrigation requirement (mm d^{-1}), CWR is crop water requirement (mm d^{-1}), WPL is water loss due to percolation and seepage (mm d^{-1}), and ER is effective rainfall (mm d^{-1}). The CWR was estimated by multiplying the crop coefficient (K_c) by the reference crop evaporation (ET_o). The K_c for rice was obtained from the Royal Irrigation Department (2012) [36] and ET_o was estimated using the CROPWAT model [37]. The reference crop ET_o represented the Penman–Monteith evaporation and was represented on the basis of daily climatic data in the year 2019, August to November, for organic farms and February to June for conventional farms. In this study, WPL was assumed to be 6 mm d^{-1} , consistent with typical values reported for continuously flooded rice fields [34,38,39].

The calculated total irrigation water withdrawal (I_{total}) for rice cultivation in the LCI is as shown in Equation (2). Irrigation water pumping energy was subsequently derived from the total irrigation volume required for each water management regime.

$$I_{\text{total}} = \sum_{d=1}^t I_d \quad (2)$$

where I_{total} is total irrigation water withdrawal (mm), t is cultivation period (day): 150 days for the conventional farm and 120 days for the organic farm.

2.4. Life Cycle Impact Assessment (LCIA)

The life cycle impact assessment (LCIA) was conducted in SimaPro Craft 10.2.0.2, using Ecoinvent v3.11 as the primary background database. The ReCiPe 2016 midpoint (H) was applied for characterization impact assessment. The midpoint approach of ReCiPe 2016 was the selected methodology in the LCIA due to its robustness and widespread application in agricultural and rice production LCA studies [40,41] and the hierarchical perspective was considered as recommended. The method is particularly suitable for assessing greenhouse gas emissions from rice production systems and has been widely adopted in rice LCA studies [17,20]. This study included on-farm greenhouse gas (GHG) emissions and post-harvesting processes, as follows.

2.4.1. Greenhouse Gas Emission

The estimate of rice field emissions included CH_4 , direct N_2O , and indirect N_2O from volatilization, leaching and runoff nitrogen (N).

Methane Emission

CH_4 emissions from flooded rice fields were evaluated according to the IPCC (2006; 2019) [27,28] Tier 1 approach and calculated using Equations (3) and (5).

$$\text{CH}_4_{\text{rice field}} = \text{EF}_i \times t \times A \quad (3)$$

$$\text{EF}_i = \text{EF}_c \times \text{SF}_w \times \text{SF}_p \times \text{SF}_o \quad (4)$$

$$\text{SF}_0 = \left(1 + \sum \text{ROA}_i \times \text{CFOA}_i\right)^{0.59} \quad (5)$$

where $\text{CH}_4_{\text{rice field}}$ is annual methane emission ($\text{kg CH}_4 \text{ year}^{-1}$); EF_i is a daily emission factor for condition i ($\text{kg CH}_4 \text{ ha}^{-1} \text{ day}^{-1}$); t is the cultivation period (150 days for the conventional farm and 120 days for organic farm); A is annual harvested area (62.50 ha for conventional farm and 12.50 ha for the organic farm); EF_c is the baseline emission factor for continuously flooded fields ($1.22 \text{ kg CH}_4 \text{ ha}^{-1} \text{ day}^{-1}$ for irrigated Southeast Asia); SF_w is the scaling factor for the water regime during the cultivation period (1.00 for continuously flooded conditions); SF_p is the scaling factor for the water regime in the pre-season before the cultivation period (flooded 120–150 days, with a value of 2.41); SF_o is the type and amount of organic amendment applied; ROA_i is the application rate of organic amendment i (0.29 for the conversion straw-to-grain ratio [41]); and CFOA_i is the conversion factor for organic amendment i (0.05 for compost). The Tier 1 approach was selected because site-specific emission factors and detailed activity data required for Tier 2 calculations were not available. Therefore, default IPCC scaling factors were applied in accordance with the IPCC guidelines.

Nitrous Oxide (N_2O)

Direct N_2O emission from nitrogen (N) input ($\text{N}_2\text{O}_{\text{Direct}} - \text{N}$), indirect N_2O emission from the atmospheric deposition of N volatilized from managed soil ($\text{N}_2\text{O}_{\text{ATD}} - \text{N}$),

and indirect N_2O emission from leaching and runoff in the region ($\text{N}_2\text{O}_{\text{ATD}} - \text{N}$) were calculated using Equations (6)–(8).

$$\text{N}_2\text{O}_{\text{Direct}} - \text{N} = (\text{F}_{\text{SN}} + \text{F}_{\text{ON}}) \times \text{EF}_1 + (\text{F}_{\text{SN}} + \text{F}_{\text{ON}}) \times \text{EF}_{1\text{FR}} \quad (6)$$

$$\text{N}_2\text{O}_{\text{ATD}} - \text{N} = [(\text{F}_{\text{SN}} \times \text{Frac}_{\text{GASF}}) + (\text{F}_{\text{ON}} \times \text{Frac}_{\text{GASM}})] \times \text{EF}_2 \quad (7)$$

$$\text{N}_2\text{O}_{\text{L}} - \text{N} = (\text{F}_{\text{SN}} + \text{F}_{\text{ON}}) \times \text{Frac}_{\text{LEACH}} \times \text{EF}_3 \quad (8)$$

where F_{SN} is the annual amount of synthetic fertilizer N (kg N year^{-1}); F_{ON} is the annual amount of organic fertilizer N (kg N year^{-1}); EF_1 is the emission factor for direct N_2O emission from N inputs ($0.01 \text{ kg N}_2\text{O} (\text{kg N input})^{-1}$); $\text{EF}_{1\text{FR}}$ is the emission factor developed for N_2O emission ($0.003 \text{ kg N}_2\text{O} (\text{kg N input})^{-1}$); $\text{Frac}_{\text{GASF}}$ is the fraction of synthetic fertilizer N that volatilizes as NH_3 and NO_x ($0.11 \text{ kg NH}_3 + \text{NO}_x (\text{kg N input})^{-1}$); $\text{Frac}_{\text{GASM}}$ is the fraction of organic fertilizer N that volatilizes as NH_3 and NO_x ($0.21 \text{ kg NH}_3 + \text{NO}_x (\text{kg N input})^{-1}$); EF_2 is the emission factor for N_2O emissions from the atmospheric deposition of volatilized N ($0.01 \text{ kg N}_2\text{O} (\text{kg NH}_3 + \text{NO}_x)^{-1}$); $\text{Frac}_{\text{LEACH}}$ is the fraction of N inputs lost from leaching/runoff ($0.24 \text{ kg N} (\text{kg N input})^{-1}$); and EF_3 is the emission factor for N_2O emissions from leaching/runoff ($0.011 \text{ kg N}_2\text{O} (\text{kg N leaching/runoff})^{-1}$). This assumption simplifies the analysis and may not fully reflect field variations under different water regimes.

2.4.2. Emission from Post-Harvesting

For the conventional farm, emissions from rice straw open burning were calculated based on Gadde et al. (2009) [32], while emissions from rice straw composting of the organic farm were estimated using the IPCC Tier 1 approach [28,29] as calculated and reported in Table 2.

2.5. Modeling Assumptions and System Boundaries

For both conventional and organic systems, CH_4 emissions from anaerobic decomposition and N_2O emission from rice fields (direct, indirect, and leaching/runoff $\text{N}_2\text{O}-\text{N}$) were calculated based on the IPCC guidelines [28,29].

For the conventional system, rice straw open burning was calculated based on Gadde et al. (2009) [32] and Delivand et al. (2011) [42].

For the organic system, CH_4 and N_2O emissions from rice straw composting were estimated using the IPCC Tier 1 approach for the biological treatment of solid waste (composting) [28,29].

The transportation distance for raw materials and fuels in both the conventional and organic systems was assumed to be 30 km.

Environmental impacts associated with irrigation water supply were included from the assessment and irrigation water was considered a natural resource.

The GHG emissions from land use change (LUC) were not considered because the rice cultivation area has been established for more than 20 years [28,29].

The electricity used was investigated using the Thai National Life Cycle Inventory Database in 2025 [33].

2.6. Uncertainty Analysis

Uncertainty analysis is one of the main applications of LCA, which is used to identify hotspots and support a comparative assertion regarding the relative environmental performance within the life cycle of products, especially in comparisons between two product systems [25,43,44]. The Monte Carlo simulation was performed to analyze the uncertainty associated with both the LCI and LCIA results [45]. This approach propagates uncertainty

by estimating the probability distribution of a variety of outcomes through repeated random sampling, which provides probabilistic results instead of a single point estimate [46]. In this study, the Monte Carlo analysis was performed in SimaPro Craft 10.2.0.2 using the ReCiPe 2016 midpoint (H) method with 1000 iterations [47]. The uncertainty of the results was evaluated using the 95% confidence intervals derived from the simulation output (significance level 0.05). Descriptive statistics including the mean, median, sample standard deviation (SD), coefficient of variable (CV), and standard error of the mean (SEM) were reported for each midpoint indicator.

2.7. Sensitivity Analysis

Sensitivity analysis was performed to evaluate variations in key input parameters on the LCA results, including fertilizer consumption, electricity use, and fuel use (gasoline and diesel) in machinery. As water management practices are important factors in rice cultivation, a sensitivity analysis was considered, particularly in terms of change in flooding patterns, field emissions, and energy use for irrigation water pumping. Moreover, several previous LCA studies, including that by Giuliana et al. (2024) [15], from Italy, and Khamfong et al. (2025) [20], from Thailand, have examined the environmental impacts associated with different water management practices in rice cultivation.

Three water management regimes were considered. Dry-sowing delayed flood (DSF) and saturated soil (ST) scenarios were evaluated as hypothetical management scenarios and were not based on field experiments conducted in this study. First, WSF was used as the baseline practice in Section 2.2 under continuous flooding with gasoline and electricity for the conventional farm organic system, representing typical central Thailand practices [48,49]. Second, DSF involves flooding the paddy field at the time of seedling emergence of the 3rd–4th rice leaf and maintaining the floodwater depth range of 5–10 cm at 7.5 cm. Third, ST represents the condition under which all soil pores are filled with water. At saturation, air-filled porosity approaches zero, and additional water contributes to free drainage or ponding. The alternative water management systems (DSF and ST) were defined to analyze changes in CH₄ emissions from rice fields. In this analysis, rice yield and N₂O emissions, including direct, indirect, and leaching, were assumed to remain constant in different water management scenarios [28,29]. This assumption was consistent with the use of IPCC Tier 1 default emission factors, which do not explicitly account for variations in water management practices. Therefore, the analysis focuses on changes in CH₄ emissions, while acknowledging that CH₄–N₂O trade-offs, as well as yield variations, may occur under field conditions. Percolation and seepage losses were assumed to be 6 mm d^{−1} for WSF and DSF systems, consistent with values reported for continuously flooded rice fields [34,38]. For the ST system, lower daily water losses of 3.5 mm d^{−1} were assumed due to reduced ponding duration and intermittent drainage [34,50]. Irrigation was applied from the first day under WSF and ST regimes, whereas under DSF irrigation it was delayed until the 3rd–4th leaf stage (about 15 days after sowing), following dry-sowing delayed flooding practices [28,51]. For the conventional sowing system, an initial ponding depth of 75 mm was assumed to account for weed control, wind, and wave effects, and to maintain a water depth of 5–10 cm during early cultivation stages [52,53].

2.8. Multivariate Analysis

Principal component analysis (PCA) was performed using Minitab[®] software version 21.4 (Minitab LLC, State College, PA, USA) to explore relationships among environmental impact categories and identify patterns between conventional and organic rice production systems. The analysis was conducted using the environmental impact results obtained from the ReCiPe 2016 midpoint (H) method. A correlation matrix was used to standardize

variables and minimize the influence of different measurement units and scales. Principal components with eigenvalues greater than 1 were considered for interpretation.

3. Results and Discussion

3.1. GHG Emissions from Conventional and Organic Paddy Rice Systems

The comparative analysis revealed that the GWP of the organic WSF system was 1.62 times higher than that of the conventional WSF system. The major sources contributing to this difference are discussed below.

In the conventional system, the total GWP was 6.68 kg CO₂ eq. kg⁻¹ paddy rice, as reported in Figure 2a, and was dominated by methane emissions from flooded rice fields (85.04%), followed by fuel combustion (5.86%) and rice straw open burning (5.30%). Other contributors, including inputs such as seed, fertilizers, and transportation, accounted for 0.05–1.72% of the total impact. Compared with previous studies, Xu et al. (2020) [54] reported GHG emissions of 0.47–0.98 kg CO₂ eq. kg⁻¹ of paddy rice in China, while Amirahmadi et al. (2022) [55] reported 0.38 kg CO₂ eq. kg⁻¹ of paddy rice in Iran. These lower GHG emissions were associated with higher rice yields per unit of fuel consumption (34.91–116.79 kg paddy rice kg⁻¹ fuel [54] and 19.41–27.23 kg paddy rice kg⁻¹ fuel [55]) compared with the present study (22.04 kg paddy rice kg⁻¹ fuel), indicating greater fuel-use efficiency. However, methane emissions were the main contributor to GWP (over 85% of total emissions). Lower rice yield and fuel-use efficiency were considered additional contributing factors.

Figure 2b presents GHG emissions from the entire life cycle of organic paddy rice. The total global warming impact for the organic WSF was 10.78 kg CO₂ eq. kg⁻¹ of paddy rice. Methane emissions from flooded fields accounted for the largest share of total GHG emissions of 9.05 kg CO₂ eq., accounting for 83.93%, followed by electricity use (11.78%) and seed production (2.77%), while other inputs contributed less than 1.52% of the total impact. The high methane emissions observed in this study were primarily attributed to continuous flooding conditions (Nakorn Nayok), leading to higher SF_w and SF_p values of 1.00 and 2.41, respectively, according to the IPCC Tier 1 methodology. In contrast, Yodkhum et al. (2017) [17] considered non-flooded conditions in Chiang Mai, leading to lower SF_w and SF_p values of 0.27 and 0.68, respectively. Therefore, the methane emissions in the present study (392.74 kg CH₄ ha⁻¹) were higher than those reported for Chiang Mai (5.21 kg CH₄ ha⁻¹) [17] and TGO (30.41 kg CH₄ ha⁻¹) [56]. Overall, the GHG emissions of organic paddy rice for Chiang Mai was 0.58 kg CO₂ eq. kg⁻¹ of paddy rice [17] and the national average in Thailand was 7.03 kg CO₂ eq. kg⁻¹ of paddy rice [56], which were 1.53–18.57 times lower than the values obtained in this study.

The GWP values obtained in this study are higher than those reported in most previous LCA studies, which may be attributed to continuous flooding conditions leading to higher methane emission factors under the IPCC Tier 1 approach, as well as lower yield in the organic system. The use of IPCC Tier 1 emission factors may introduce uncertainty because site-specific management conditions were not obviously represented in the methane estimation process. In a similar field, GHG emissions from organic paddy rice in Utharadit province, Thailand, when studied by Khamfong et al. (2025) [20], showed that the highest GHG emissions from land preparation reached 48% and methane emissions from flooded rice fields totaled 12%. In Chiang Mai province, Thailand, when studied by Yodkhum et al. (2017) [17], the main contribution was from rice fields, with emissions of 83%. Bacenetti et al. (2016) [14] reported that GHG emissions were dominated by field emissions (41%) and compost production (49%). These results highlight the sensitivity of GWP to water management and methodological assumptions, which should therefore be studied and evaluated.

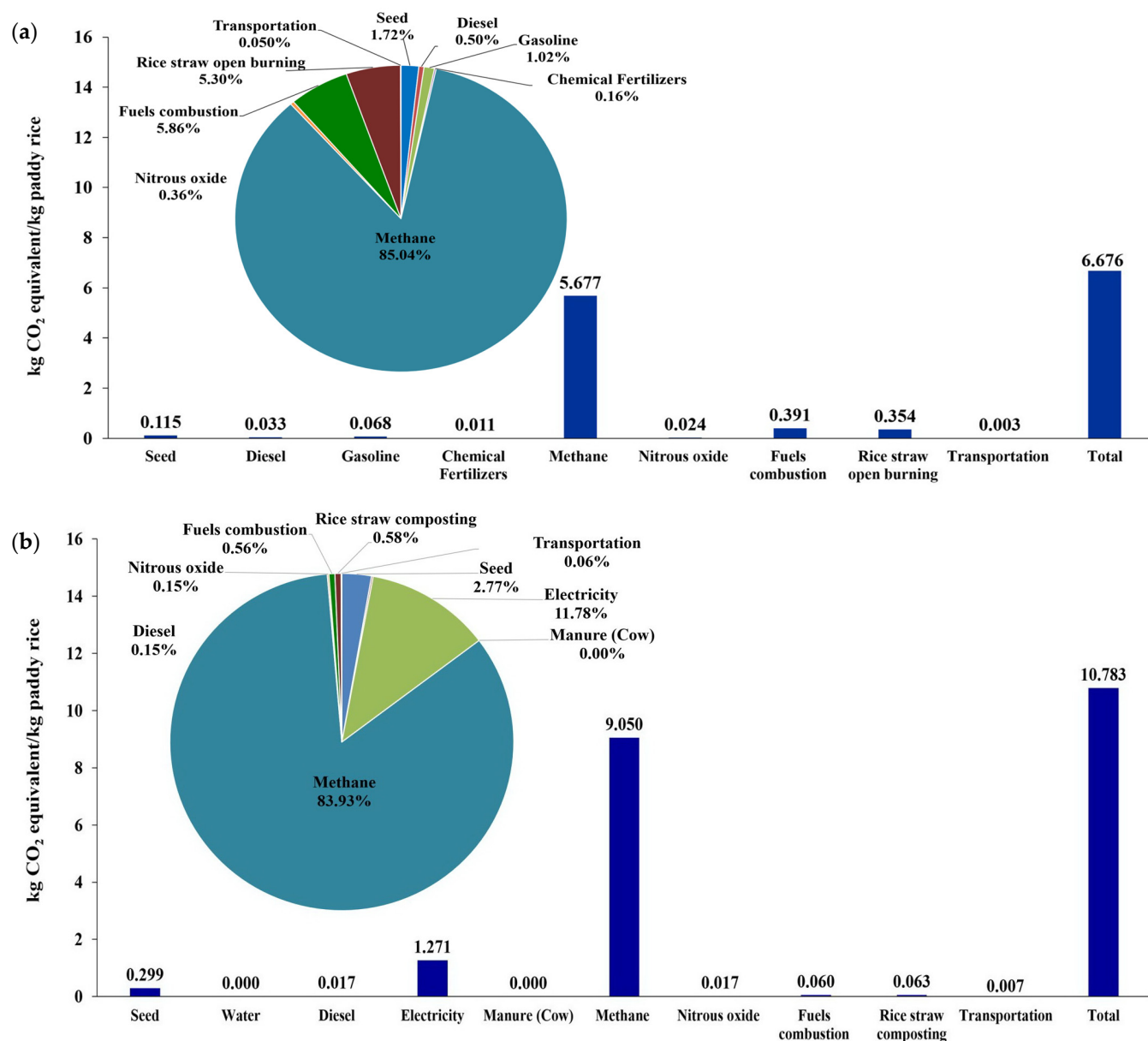


Figure 2. Global warming impact from material inputs and outputs and contribution analysis: (a) conventional WSF (b) and organic WSF.

3.2. ReCiPe 2016 Midpoint (H)

The LCIA was conducted using a ReCiPe 2016 midpoint impact assessment, which considered 18 impact categories with different units of measurement, as shown in Table 3 and Supplementary Tables S1 and S2. The characterized results were expressed as a relative contributions profile for midpoint environmental impacts, as shown in Figure 3a,b. The comparative analysis of the environmental profile of each system is illustrated in Figure 4. Detailed contribution analyses for each impact category are presented in S2–S4 of the Supplementary Materials.

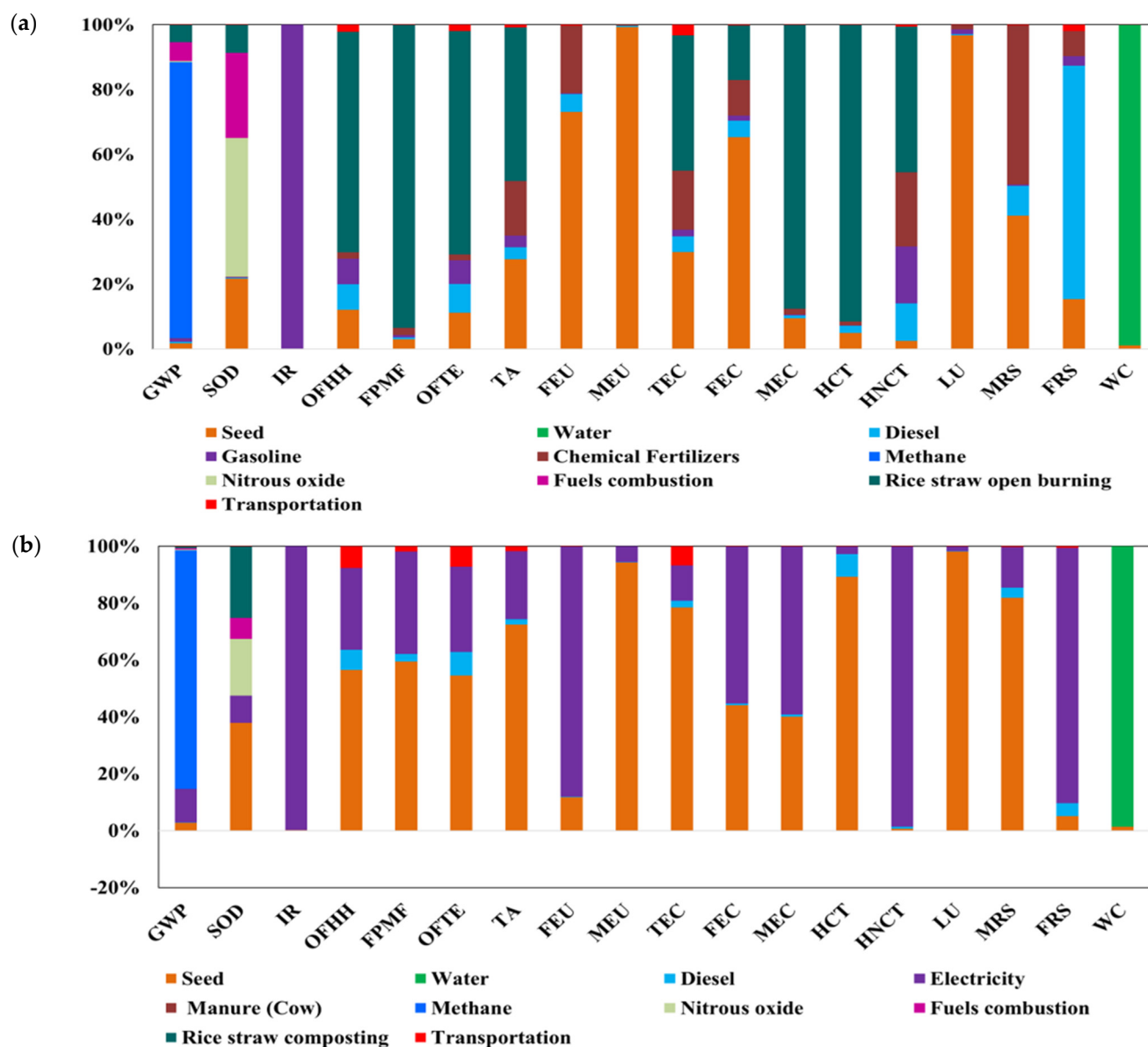


Figure 3. The contribution analysis of midpoint environmental impact assessment: (a) conventional WSF (b) and organic WSF.

Table 3. ReCiPe 2016 midpoint (H) impact categories, abbreviations, and units used in this study.

Impact Category	Abbreviation	Unit
Global warming potential	GWP	kg CO ₂ eq.
Stratospheric ozone depletion	SOD	kg CFC11 eq.
Ionizing radiation	IR	kBq Co-60 eq.
Ozone formation, human health	OFHH	kg NO _x eq.
Fine particulate matter formation	FPMF	kg PM _{2.5} eq.
Ozone formation, terrestrial ecosystems	OFTE	kg NO _x eq.
Terrestrial acidification	TA	kg SO ₂ eq.
Freshwater eutrophication	FEU	kg P eq.
Marine eutrophication	MEU	kg N eq.

Table 3. Cont.

Impact Category	Abbreviation	Unit
Terrestrial ecotoxicity	TEC	kg 1,4-DCB eq.
Freshwater ecotoxicity	FEC	kg 1,4-DCB eq.
Marine ecotoxicity	MEC	kg 1,4-DCB eq.
Human carcinogenic toxicity	HCT	kg 1,4-DCB eq.
Human non-carcinogenic toxicity	HNCT	kg 1,4-DCB eq.
Land use	LU	m ² a crop eq.
Mineral resource scarcity	MRS	kg Cu eq.
Fossil resource scarcity	FRS	kg oil eq.
Water consumption	WC	m ³

eq. denotes equivalent.

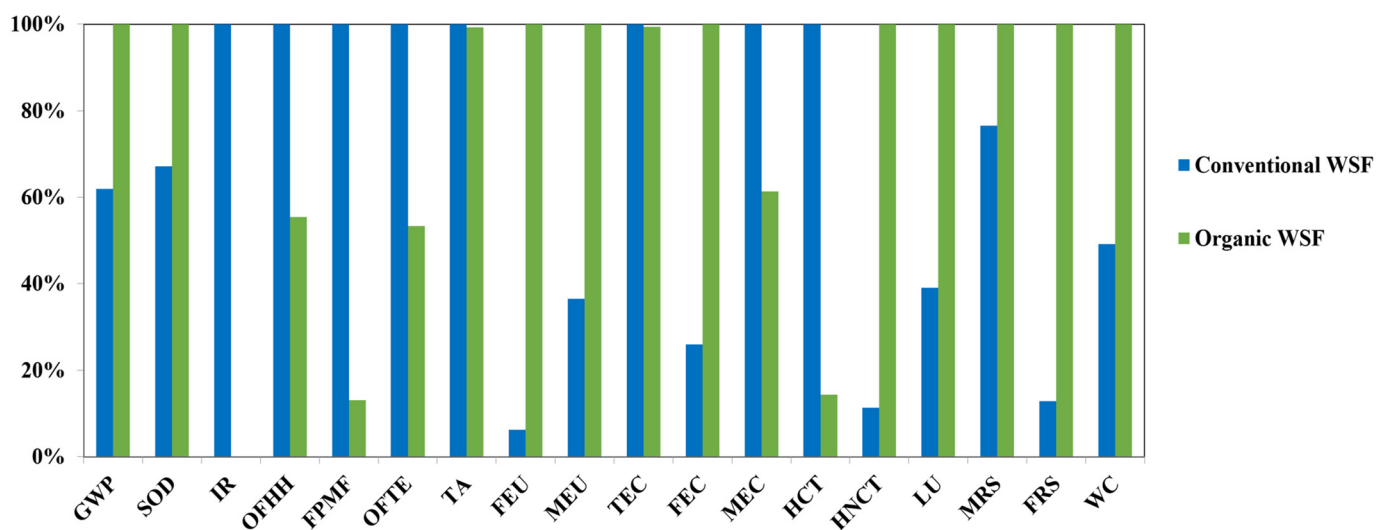


Figure 4. Comparison of characterized ReCiPe midpoint results for conventional WSF and organic WSF systems.

3.2.1. Air Emissions-Related Impacts (SOD, IR, OFHH, PFTE, FPMF, and TA)

The results show that SOD impact for conventional WSF was lower than organic WSF by 32.7%. The higher impact in organic WSF was mainly from seed consumption (37.8%) and composting (25.1%), whereas fertilizer use, fuel combustion, and seed production were important contributors in both systems.

For the IR impact, the conventional WSF had a much higher IR than that of organic WSF at 99%. The higher IR emissions in conventional WSF originated from upstream processes, particularly coal extraction and electricity generation, as reported by the USEEIO v2.0.1–411 data in SimaPro Craft v10.2.0.2. In contrast, IR emissions in organic WSF were mainly from electricity consumption (2.09 kWh kg^{−1} paddy rice), which reflects the characteristics of the Thailand electricity grid mix [30]. These findings highlight the importance of upstream energy supply chains in influencing IR emissions in rice production systems.

For OFHH, OFTE, FPMF, and TA, the conventional WSF exhibited higher impacts than the organic WSF system by 45–87%, primarily due to post-harvest rice straw open burning (47–93% of the total impact). A small difference was observed for TA (0.6%). In contrast, organic WSF originated from upstream processes related to seed and electricity consumptions. The organic system required a higher seed input (0.2 kg seed/kg paddy rice), compared with the conventional system (0.0769 kg seed kg^{−1} paddy rice).

3.2.2. Eutrophication-Related Impacts (FEU and MEU)

Regarding eutrophication-related impacts, FEU impact in the organic WSF was moderately higher than in the conventional WSF, by 63.45%, whereas a small difference (0.60%) was observed for MEU. These impacts originated from the upstream processes related to the production of electricity, seed and fuels, which involve N- and P-containing emissions [15,57].

3.2.3. Toxicity-Related Impacts (TEC, FEC, MEC, HCT, and HNCT)

The conventional WSF exhibited higher MEC (39%) and HCT (86%) impacts than the organic WSF, whereas FEC and HNCT impacts showed moderately lower impacts than those of the organic system by 74.05% and 88.68%, respectively. Comparable TEC levels were observed for both systems, with only a 0.60% difference. The rice straw open burning was a major source of higher toxicity impacts in the conventional system, mainly due to the release of PAHs and polychlorinated compounds. In contrast, toxicity impacts in the organic system originated from upstream processes related to seed production and electricity generation. Similar observations were reported in previous studies, where fertilizer use and irrigation activities for seed production were identified as important contributors to toxicity-related impacts [15,57].

3.2.4. Resources and Water Consumption Impacts (MRS, LU, FRS, and WC)

Regarding resources and water consumption impacts, the organic WSF exhibited higher MRS, LU, FRS, and WC values than conventional WSF by 23–87%. For conventional WSF, the major contributions to MRS were chemical fertilizers (49%) and seed (41%). These results are in line with those of Giuliana et al. (2024) [15] and Yu et al. (2022) [57], who reported that the use of fertilizer accounted for 56–59% of the total impact.

The high LU impact for both systems was from seed production (96.7–98.1% of the total impact). This finding is consistent with that of Giuliana et al. (2024) [15], who identified that seed production affected LU by 52%. For FRS impact, diesel contributed approximately 72% for conventional WSF and electricity contributed about 90% for organic WSF. These results align with Giuliana et al. (2024) [15] and Xu et al. (2022) [21], who found that the energy consumption had the largest impact, contributing 35–74%. Finally, the organic WSF consumed more water ($6.98 \text{ m}^3 \text{ kg}^{-1}$ paddy rice) than the conventional WSF system ($3.44 \text{ m}^3 \text{ kg}^{-1}$ paddy rice), resulting in a 50.8% higher WC impact. This difference was due to lower yield organic rice production, which was 2.6 times lower than that of the conventional system.

3.3. Monte Carlo Uncertainty Analysis Results

Monte Carlo uncertainty analysis showed generally low variability for most ReCiPe 2016 midpoint categories. The level of uncertainty followed common practice in LCA [15,58,59], coefficients of variation (CV) below 10% indicated low uncertainty, values between 10 and 30% indicated moderate uncertainty, and CV values above 30% are considered high and require cautious interpretation. For the conventional WSF system (Supplementary Table S3), low uncertainty (CV < 10%) was observed for 13 midpoint categories. FE, ME, FEU, and LU showed moderate uncertainty (CV ~20–30%), while only HNCT exhibited strong high uncertainty (CV > 30%). Similarly, most impact categories under the Monte Carlo uncertainty analysis for organic rice with WSF management (Supplementary Table S4) exhibited CV values below 30%, except for HCT (42%), whereas only HNCT presented very high uncertainty (326%). Overall, most impact categories in both conventional and organic WSF systems exhibited CV values below 30%, indicating low uncertainty and the reliability of these impact categories on Monte Carlo LCA results, and providing a better

basis for comparing the environmental performance of rice production systems [15,60]. A comparison of CV for ReCiPe 2016 midpoint impact categories between conventional and organic rice systems under WSF is shown in Figure 5.

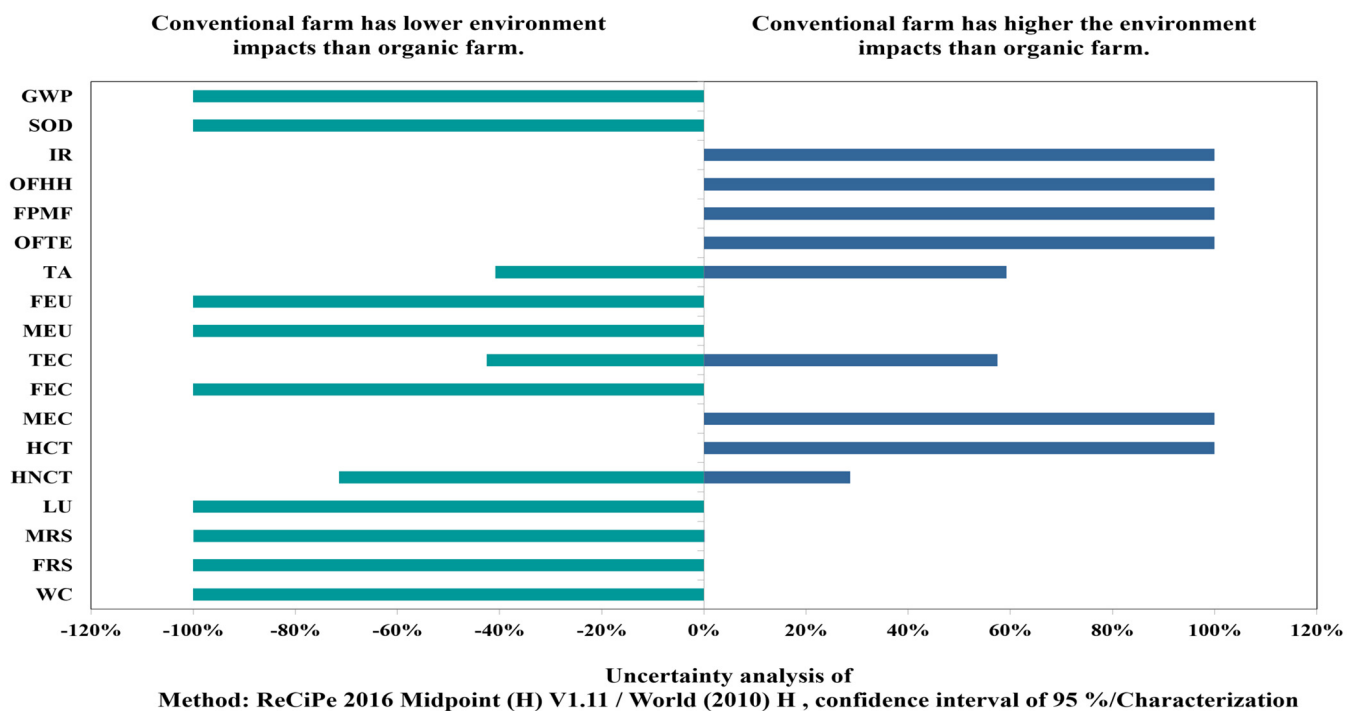


Figure 5. Relative deviations obtained for each impact category and characterization.

Uncertainty analysis of the LCIA showed that organic WSF showed a 100% probability of lower environmental impacts than the conventional WSF for HCT, MEC, OFTE, FPMF, OFHH, and IR. Meanwhile, HNCT, TEC, and TA showed a moderate 40.8–71.4% probability of lower impacts. These results indicated that the overall environmental impacts are similar to those observed in Sections 3.1 and 3.2 and primarily related to organic rice cultivation practices, seed and energy inputs (Figure 3b), and particularly high GWP impacts from methane emissions in flooded fields. In contrast, conventional WSF showed 100% probability of lower environmental impact values than the organic WSF for GWP, SOD, FEU, MEU, FEC, LU, MRS, FRS and WC. This is mainly due to the inputs of seed, chemical fertilizers, energy, and harvesting operations (Figure 3a) on conventional WSF in rice cultivation. For GWP, uncertainty was strongly influenced by methane-related processes because methane emissions were the dominant contributor to climate change impact. The observed variability originated from uncertainty in fertilizers, fuels, electricity, and seed production databases, which was propagated through the Monte Carlo simulation. These different patterns highlight the major emission pathways distinguishing organic and conventional rice systems.

Impact categories exhibiting higher CV were associated with inventory flows characterized by greater variability, particularly agricultural inputs and emission estimates. In contrast, impact categories dominated by more stable inventory flows tended to exhibit lower uncertainty. However, SimaPro Monte Carlo analysis does not separate uncertainty contributions from foreground data, background databases, and characterization models, and these sources may contribute to the variability observed among impact categories.

3.4. Sensitivity Analysis of Alternative Irrigation Scenarios

Sensitivity analysis was applied to evaluate the influence of key parameters on environmental performance, which is a common practice in LCA to assess the relative significance of parameters and support the interpretation of uncertainty results [15,61,62]. Several previous LCA studies, including Giuliana et al. (2024) [15] and Khamfong et al. (2025) [20], have examined the environmental impacts associated with different water management practices in rice cultivation. The changes in scaling factors (SF_w) for methane emissions under different water management regimes are shown in Table 4. The changes in LCI parameters and the corresponding results characterized from the sensitivity analysis are shown in Table 5 and Figure 6, respectively.

Table 4. Sensitivity analysis of difference parameters for CH_4 emissions from water system management.

Parameters	Unit	Conventional Systems			Organic Systems		
		WSF	DSF	ST	WSF	DSF	ST
EF_c from Equation (4)	$kg\ CH_4\ ha^{-1}\ day^{-1}$	1.22	1.22	1.22	1.22	1.22	1.22
SF_w from Equation (4)	$kg\ CH_4\ ha^{-1}\ day^{-1}$	1.00	0.55	0.36	1.00	0.55	0.36
SF_p from Equation (4)	$kg\ CH_4\ ha^{-1}\ day^{-1}$	2.41	2.41	2.41	2.41	2.41	2.41
SF_o from Equations (4) and (5)	$kg\ CH_4\ ha^{-1}\ day^{-1}$	11.19	11.19	11.19	6.47	6.47	6.47
ROA_i from Equation (5)	$kg\ CH_4\ ha^{-1}$	1178.13	1178.13	1178.13	453.13	453.13	453.13
$CFOA_i$ from Equation (5)	–	0.05	0.05	0.05	0.05	0.05	0.05
Cultivation period	day	150	150	150	120	120	120
Area	ha	62.50	62.50	62.50	12.50	12.50	12.50
Yield	$kg\ ha^{-1}$	4062.50	4062.50	4062.50	1562.50	1562.50	1562.50

Table 5. Sensitivity analysis of difference parameters for water system management.

Parameters	Unit	Conventional Systems			Organic Systems		
		WSF	DSF	ST	WSF	DSF	ST
Irrigation							
Water	m ³	3.44	3.02	2.90	6.99	6.36	5.69
Electricity	kWh	–	–	–	2.09	1.91	1.45
Gasoline	L	0.12	0.10	0.09	–	–	–
Fuel combustion							
CO ₂	kg	3.65×10^{-1}	3.34×10^{-1}	3.25×10^{-1}	–	–	–
CH ₄	kg	3.04×10^{-4}	2.67×10^{-4}	2.55×10^{-4}	–	–	–
N ₂ O	kg	4.90×10^{-5}	4.81×10^{-5}	7.15×10^{-6}	–	–	–
Anaerobic decomposition							
CH ₄	kg	1.21	0.67	0.44	1.46	0.80	0.53

For conventional systems under three water management, DSF and ST systems showed the largest reduction in GWP (38.86–55.39%) relative to WSF, while DSF and ST showed moderately lower values of SOD, IR and WC, with reductions of 12–22% compared to WSF. Most other impact categories (14 categories) showed similar levels across water management systems, with small differences ranging from 0.01% to 2.80%. Meanwhile, water management resulted in substantial results for the organic system from WSF to DSF and ST, and particularly for GWP (38.84–57.34%). DSF and ST systems showed moderate

reductions in IR, FEC, FEU, MEC, HNCT, FRS, and WC of 5–9% and 18–32%, respectively, compared to the WSF system. For the remaining impact categories (10 categories), DSF showed similar impact levels relative to WSF (0.16–3.23% reduction), while ST showed changes (0.54–11.10%).

Impact category	Conventional			Organic		
	WSF	DSF	ST	WSF	DSF	ST
GWP	62%	38%	28%	100%	61%	43%
SOD	67%	67%	52%	100%	99%	97%
IR	100%	88%	84%	0%	0%	0%
OFHH	100%	99%	99%	55%	54%	51%
FPMF	100%	100%	100%	13%	13%	12%
OFTE	100%	99%	99%	53%	52%	48%
TA	100%	100%	99%	99%	97%	92%
FEU	6%	6%	6%	100%	92%	73%
MEU	37%	37%	37%	100%	100%	98%
TEC	100%	100%	99%	99%	98%	96%
FEC	26%	26%	26%	100%	95%	83%
MEC	100%	100%	100%	61%	58%	50%
HCT	100%	100%	100%	14%	14%	14%
HNCT	11%	11%	11%	100%	91%	70%
LU	39%	39%	39%	100%	100%	99%
MRS	77%	77%	77%	100%	99%	96%
FRS	13%	13%	13%	100%	92%	72%
WC	49%	43%	42%	100%	91%	82%

Figure 6. Sensitivity analysis at midpoint level for different water system management methods (%), minimum = 0%, maximum = 100%).

It should be highlighted that the largest change was observed for GWP (38.87–57.37%) on organic systems, while conventional systems were lower, ranging from 38.86% to 55.39%. This is because organic systems are more strongly influenced by water management practices, particularly flooding factor, which affects methane emission from rice fields.

Overall, organic systems showed higher impacts for eight impact categories, including GWP (35–38%), SOD (33–46%), FEU (91–94%), MEU (64–64%), FEC (69–74%), HNCT (84–89%), LU (60–61%), MRS (19–23%), FRS (82–87%), and WC (49–53%), compared with conventional systems. These higher impacts can be explained by the association with raw material inputs, seed production, electricity, diesel, and irrigation water (Figure 3b), as well as the lower yield of the organic system, which was 2.60 times lower than that of the conventional system, leading to higher impacts. In contrast, the conventional system exhibited substantially higher impacts covering eight categories, including IR (100%), OFHH (45–48%), FPMF (87–88%), OFTE (47–51%), MEC (39–50%), and HCT (85–86%). Additionally, smaller higher impacts were observed for TA (0.75–7.46%) and TEC (0.60–3.89%), compared with organic systems.

Sensitivity analysis highlights noticeable differences in impact drivers and LCIA pathways for conventional and organic rice systems. Conventional systems are primarily controlled by energy inputs and fuel-related emissions, reducing the influence of water management on LCIA results. In contrast, organic systems are more sensitive to change in water management practices, with particularly strong implications for impact categories related to global warming and water use, emphasizing the importance for field-level management decisions.

3.5. Multivariate Statistical Analysis

The PCA was conducted to support the interpretation of relationships among rice cultivation, water management, and environmental impacts. However, the PCA results were evaluated with caution because only six production scenarios were included. The loading, eigenvalues, and percentage of explained variance for each component are summarized in Supplementary Table S5. The biplot of PCA was shown in Figure 7. The PC1 accounted for 87.50% of the total variance, the PC2 accounted for 11.10%, and PC2 and PC3 accounted for only 1.10% and 0.5%, respectively.

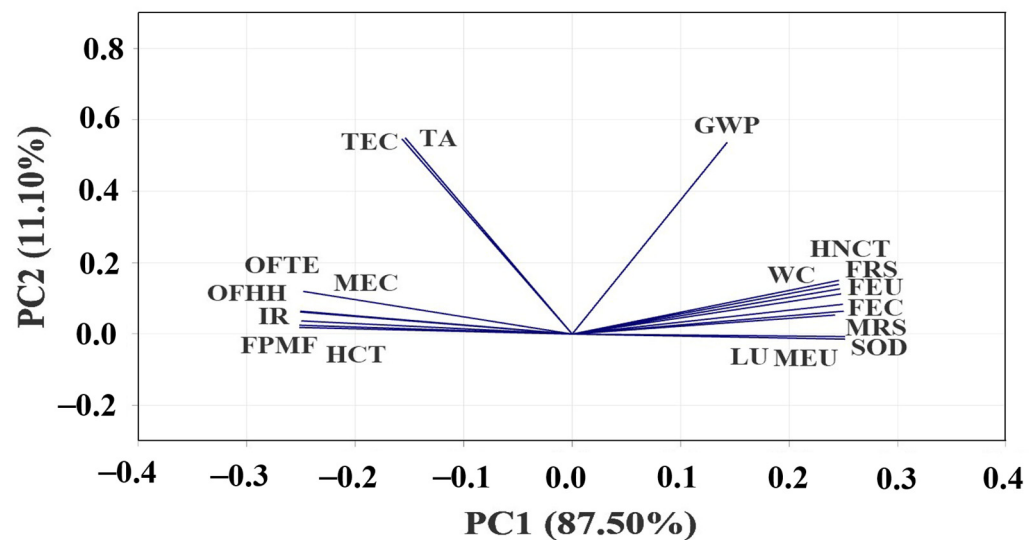


Figure 7. Biplot of PC1 and PC2 for rice cultivation and impact categories of six sensitivity results of conventional and organic systems.

The strongest PC1 explained 87.50% of the total variance and represents the overall environmental burden with consistently high positive correlations of 0.143–0.252 for ten impact categories, including GWP, SOD, FEU, MEU, FEC, HNCT, LU, MRS, FRS, and WC, whereas the negative correlations (−0.154 to −0.252) were observed for eight impact categories, including IR, OFHH, FPMF, OFTE, TA, TEC, MEC, and HCT. PC1 explained more than 85% of the total variance and clearly separated conventional and organic rice systems, indicating that seed, fertilizers and energy inputs (see Figures 2 and 3) are the primary influence of environmental impacts. The second PC2 accounted for 11.10% of the total variance and showed positive correlations (0.019 to 0.550) for 18 impact categories, particularly in GWP (0.538), TA (0.550), and TEC (0.547). These impacts are associated with emission-related processes and reflect differences among production scenarios, including the influence of water management practices. The PCA results support the interpretation of the LCA results by highlighting differences in environmental impact patterns between conventional and organic rice production systems.

3.6. Limitations and Future Research Needs

This study has several limitations that should be acknowledged. First, a mass-based functional unit (1 kg paddy rice) was adopted, which may influence comparative results due to yield differences between production systems. Alternative functional units, such as area-based (per hectare) or economic-based approaches, should be considered in future research. Second, the LCI data came from smallholder production systems in Nakhon Nayok Province and may not represent all rice farming in Thailand.

Third, methane and nitrous oxide emissions of WSF, DSF and ST systems were estimated using IPCC Tier 1 emission factors, which provide generalized estimates. Therefore, future research should incorporate parameters for site-specific conditions, such as soil properties, organic matter content, temperature, flooding duration, and local management practices, to improve the robustness of environmental impact estimates.

Fourth, the sensitivity analysis assumed constant crop yield, N_2O emissions, nitrogen-use efficiency, and nutrient cycling under alternative water-management scenarios.

In practice, crop yields and N_2O emissions change under different water management, which affects the environmental impacts per kilogram of paddy rice. Previous studies have reported N_2O emissions can rise slightly in non-flooded conditions. However, total GWP still decreases because CH_4 reductions are larger than N_2O increases [51,63]. Therefore, the environmental impact results should be interpreted as indicative estimates of irrigation management effects instead of predictions of field outcomes.

Fifth, the present study focused on the influence of irrigation management on environmental impacts, particularly methane emissions and water consumption. Water-security dimensions, including regional water scarcity, seasonal water stress, and basin-scale ecological effects, were excluded from the scope of this assessment. Therefore, the environmental benefits of saving irrigation water may not reflect broader water management.

Finally, the PCA results should be interpreted with caution because the analysis was based on six production-management scenarios. Therefore, PCA was used as an exploratory tool to support the interpretation of environmental impact patterns.

4. Conclusions

This study assessed and compared the environmental performance of conventional and organic rice production based on water-sowing continuous flooding (WSF) in Nakhon Nayok Province, Thailand, by applying the ReCiPe 2016 midpoint method across 16 impact categories. The results revealed that the GWP of the organic WSF system was $10.78 \text{ kg CO}_2 \text{ eq. kg}^{-1}$ of paddy rice, or 38% higher than that of conventional WSF because of methane emissions from flooded rice fields. Uncertainty analysis indicated that organic WSF had higher environmental impacts in 8 out of 18 categories, particularly related to toxicity and air emissions. Sensitivity analysis showed alternative irrigation regimes, including dry-sowing delayed flooding (DSF) and saturated soil (ST), and reduced environmental impacts compared with WSF, particularly in GWP (up to 57%). Principal component analysis indicated that seed inputs, fertilizer use, fuel consumption, and harvesting operations were the primary drivers of environmental impacts in conventional systems, whereas emission processes influenced environmental performance in organic rice systems.

These results confirmed that water management represents an effective strategy for reducing GWP impact, particularly methane emissions in rice cultivation systems. Overall, this study contributes to integrating environmental assessment into sustainability agricultural production by combining comparative LCA, uncertainty analysis, irrigation sensitivity assessment, and multivariate interpretation. These approaches provide a robust framework for supporting environmental decision-making and the development of sustainable rice production practices.

Nevertheless, the findings should be interpreted with caution because methane emissions were estimated using IPCC Tier 1 emission factors, which may not reflect site-specific conditions. Future studies should include more conventional and organic rice farms to improve the representative data in Nakhon Nayok Province. Measuring local GHG, irrigation system management, and regional water planning will reduce uncertainty in environmental impact estimates and better support sustainable rice farming. This will provide a stronger basis for regional planning and farming policies.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/agriculture16151644/s1>: Supplementary Table S1 Midpoint environmental impact assessment of conventional WSF; Supplementary Table S2 Midpoint environmental impact assessment of organic WSF; Supplementary Table S3 Uncertainty analysis using Monte Carlo simulation at the midpoint level of conventional WSF; Supplementary Table S4 Uncertainty analysis using Monte Carlo simulation at the midpoint level of organic WSF; Supplementary Table S5 Principal component loading for the impact categories of six sensitivity results of conventional and organic systems; and Supplementary S2–S4 Detailed contribution analysis.

Author Contributions: Conceptualization, D.R. and U.S.; methodology, U.S.; software, U.S.; validation, D.R. and U.S.; formal analysis, U.S.; investigation, U.S.; resources, D.R. and U.S.; data curation, S.T., W.K., S.N., P.K. and K.K.; writing—original draft preparation, D.R. and U.S.; writing—review and editing, D.R. and U.S.; visualization, D.R. and U.S.; supervision, D.R. and U.S.; project administration, D.R., S.T., W.K., S.N., P.K., K.K. and U.S.; funding acquisition, D.R. and U.S. All authors have read and agreed to the published version of the manuscript.

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

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