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Life Cycle Assessment of the Solok Rice Production System in the Gunung Talang District, Solok Regency, West Sumatra

Shabrina Nashya Aswin[1], Alfi Asben[1] and Novizar Nazir[2.]

[1] *Agricultural Industrial Technology Departement, Faculty of Agricultural Technology, Andalas University, Padang, West Sumatera, 25613 Indonesia*
[2] *Food and Agricultural Product Processing Departement, Faculty of Agricultural Technology, Andalas University, Padang, West Sumatera, 25613 Indonesia*

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CORRESPONDING AUTHOR

*E-mail: *nashyashabrina24@gmail.com*

A B S T R A C T

Solok rice is an important agricultural commodity that contributes significantly to the economic prosperity of the West Sumatra region. As indigenous knowledge from West Sumatra, the development and preservation of Solok rice can stimulate a nationwide increase in rice production. The cumulative effects of the entire sequence of activities comprising Solok rice production will impact environmental quality due to increased output. Therefore, a Life Cycle Assessment (LCA)-based environmental impact assessment of Solok rice production is necessary. The analysis results indicate that the total greenhouse gas emissions from Solok rice production equal 1.94 kg CO2eq per kilogram of rice. The subsequent potential effects include acidification at a rate of 0.06 kilograms of SO2-equivalent per kilogram of rice and eutrophication at kilograms of PO43-equivalent per kilogram of rice. The calculation of net energy yielded a Net Energy Value (NEV) of 18.36 GJ and a Net Energy Ratio (NER) greater than 1. To mitigate emission values in the land and environment, the current system improvement emphasizes fertilizer consumption, increasing the use of organic materials, and instituting production waste recycling.

1. INTRODUCTION

1.1. Research Background

Rice is of great importance as a commodity due to its central role as the major staple food widely consumed by the population of Indonesia. The annual increase in national rice consumption is expected to align with population growth constantly. Given the strategic importance of rice as a vital agricultural commodity, it becomes important to continually provide sufficient domestic rice availability. This requires dedicated efforts aimed at enhancing rice production.

The Solok Regency is situated among the top three contributors to rice production in West Sumatra. Rice production in the Solok Regency experienced an increase from the year 2018 to 2019, rising from 94,047.09 tons to 97,035.07 tons [1]. The Gunung Talang District is one of the largest rice production centres in Solok Regency, with a harvested area covering 10,076.6 hectares. The district yielded 66,391.6 tons of paddy with a productivity rate of 6.59 tons per hectare, resulting in a total rice production of 33,003 tons [2]. Gunung Talang District is a central area for producing Solok rice. Solok rice is one of the agricultural products that serve as the mainstay of the local community's economy and has been marketed beyond the region to places such as Riau, Jambi, and Bengkulu. The development and preservation of Solok rice as a local wisdom of West Sumatra can contribute to increasing national rice production. This increase in production may also have implications for the environmental quality due to the overall series of activities involved in Solok rice production. In the agricultural sector, rice production is considered a primary cause of emissions and environmental pollution in developing countries [3].

Greenhouse Gas (GHG) emissions from the agricultural sector arise from (1) methane (CH_4) emissions from rice cultivation in flooded paddies, carbon dioxide (CO_2) due to the addition of lime and urea fertilizer, nitrous oxide (N_2O) emissions from the soil, including indirect N_2O emissions from N additions to the soil due to volatilization/deposition and leaching, and non-CO_2 emissions from biomass burning during agricultural activities [4]. The sources of pollutants causing acidification originate from using fuels such as diesel and electricity, as well as from using chemicalfertiliserss. One of the sources of pollutants in eutrophication within the agricultural sector comes from using chemical fertilizers and treating liquid waste when discharged into the environment. The resulting emissions consist of phosphates present in water bodies. In this study, the rice cultivation phase is the stage in the rice production system that contributes the most significant impact on eutrophication. As known, applying chemical fertilizers to paddy fields has negative environmental implications, resulting in emissions affecting both the soil and the surrounding water bodies [5].

Hence, it is imperative to undertake a life cycle assessment (LCA) of rice and its production to ascertain the energy consumption and emissions associated with rice production to mitigate environmental damage. The utilization of the Life Cycle Assessment (LCA) technique is necessary for the examination of the extent of emissions generated during the rice-producing process.

The rice milling process typically involves several stages, from cultivation, which includes inputs such as seeds, fertilizers, technology, and irrigation, to post-harvest processing, which includes threshing, transportation, drying, milling, storage, and packaging. Each stage of the rice milling process requires energy, which can be quantified and analyzed for its environmental impact using the LCA method. Therefore, conducting an environmental impact analysis on the Solok rice production system using the LCA method is essential to gain insights into the Solok rice production system. It helps calculate and analyze the emissions generated and explore alternative improvements to reduce the impact at each Solok rice life cycle stage.

1.2. Research Objective

This research aimed: (1) to understand the process stages, raw material flow, and energy consumption in the Solok rice production system; (2) To ascertain the environmental impacts, such as greenhouse gas emissions, acidification, and eutrophication, that may arise from the Solok rice production system; (3) to obtain alternative improvements in efforts to reduce the environmental impact in the Solok rice production system.

2. MATERIALS AND METHODS

2.1. Location and time of research

The research location was *purposively* selected, so the sampling was intentionally chosen based on specific considerations and objectives. This study will be conducted in the Gunung Talang District, Solok Regency, West Sumatra. This research location is chosen because Gunung Talang District has the highest rice productivity and production in Solok Regency and has the most rice processing/milling facilities in the regency.

2.2. Population and sampling technique

In this study, the sampling (respondents) from a population was conducted among farmers and owners of *rice milling* units. The selection criteria for the sample in this research included farmers who cultivate the Sokan variety in the Gunung Talang District, farmers who follow standard operational procedures as recommended by the local government, farmers with a minimum land area of 1 hectare, and rice production exceeding 5 tons per hectare. For *rice milling* units, the selection criteria included units that process paddy from the farmers who were chosen as the sample for this study. The number of respondents in the data collection process for the field research is as follows:

1. 9 farmers are cultivating the Sokan rice variety, comprising 3 farmers from Jawi-jawi Village, 3 from Talang Village, and 3 from Cupak Village.
2. There are 3 farmers and individual businesses owning *rice milling* units.

2.3. The types of data

The research data used in the analysis were obtained through the inventory process of the entire Solok rice production and input processes

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Tab1e 1. Data Collection Process

Stages of Process	Data Type	Unit
Cultivation	Land area	Hectare
	Equipment & Operational Machine	
	Electricity	Kwh
	Raw Material:	
	Seeds	Kg
	Fertilizer	Kg
	Pesticides	Liter
	Irrigation	m^3
Transportation	Fuel Consumption	liter
Rice Production	Equipment & Production Machine	
	Electricity	Kwh
	Additional Material	Kg

2.4. The stages of research

This research was conducted based on the methods outlined in ISO 14040-2006 *Principles and Framework* LCA and ISO 14044. Within this framework, it is described that LCA consists of four main stages, namely (a) goal and scope definition, (b) life cycle inventory analysis of input and output, (c) life cycle impact assessment of all input and output, and (d) life cycle interpretation of the results.

2.4.1 Goal and scope definition

Determining the goal and scope is the initial LCA analysis stage. In this phase, the objectives and boundaries of the LCA study are defined. The functional units to be used in the LCA assessment are also determined. Establishing the goal and scope makes the LCA assessment more focused and systematic, as it solely relies on predetermined boundaries.

2.4.2 Life cycle inventory analysis

The next stage in LCA is inventory analysis, which involves identifying the product life cycle, collecting the necessary data, and quantifying the data for analysis in the subsequent stage, which is the impact assessment. The data to be collected and processed in this stage are aligned with the scope or boundaries defined in the previous stage. In this stage, an inventory of data is constructed and developed, consisting of three main activities: cultivation, rice production, and transportation.

2.4.3 Life cycle impact assessment

The environmental impact assessment evaluates the environmental impacts generated based on the inventory analysis results. The objective of this stage is to calculate the environmental burdens based on the data obtained from the inventory [6].

2.4.3.1 The calculation of greenhouse gas impacts (GHG)

The calculation of CO_2 emissions per ton of rice based on the IPCC method can be obtained by multiplying human activity information over a specific period (activity data, AD) with emissions/absorption per unit activity (emission/absorption factor, EF). In general, the equations for estimating greenhouse gas emissions and absorptions can be written in the following form:

Emissions/Absorption GHG = AD × EF..(i)

Where:

AD stands for Activity Data, which refers to data on human activities or development activities that result in greenhouse gas emissions or absorption. This includes data on land area.

EF represents Emission Factor or Absorption Factor, indicating the magnitude of emissions or absorption per unit of the conducted activity.

The method used for calculating net energy is converting energy usage into standard energy units (Joules). The energy requirement value for each production of 1 ton of rice is calculated using the following equation:

En = n × CV...(ii)

Where:

En = Energy

n = Inventory volume

CV = Calorific Value (energy conversion value)

Anaerobic decomposition of organic matter in paddy fields emits methane gas into the atmosphere. The amount of CH_4 emitted is a function of plant age, water regime before and during the cultivation period, and the use of organic and inorganic materials. CH_4 emissions are also influenced by soil type, temperature, and rice varieties. CH_4 emissions are calculated by multiplying the daily emission factor with the rice cultivation duration and the harvested area using the following equation:

CH_4 *Rice* = ∑ijk (EFi,j,k × ti,j,k × Ai,j,k × 10^{-6})...............................(iii)

Where:

CH_4*Rice* = Methane emissions from paddy rice cultivation (Gg CH_4 per year)

EFi,j,k = Emission factor for conditions i, j, and k (kg CH_4 per day)

ti,j,k = Rice cultivation duration for conditions i, j, and k (days)

Ai,j,k = Harvested area of paddy rice for conditions i, j, and k (hectares per year).

i,j, dan k = Representing different ecosystems: (i) water regime, (j) type and amount of soil organic matter input, and (k) other conditions in which CH4 emissions from paddy rice can vary [7]

The equation to correct the baseline emission factor is shown as follows:

EFi = (EFc × SFw × SFp × SFo × SFs,r)..............................(iv)

Where:

EFi = Corrected daily emission factor for a specific harvested area (kg CH4 per day)

EFc = Baseline emission factor for continuously irrigated paddy rice without organic matter return

SFw = Scale factor explaining the differences in water regime during the cultivation period

SFp = Scale factor explaining the differences in water regime before the cultivation period

SFo = Scale factor explaining the type and amount of organic matter return applied during the paddy rice cultivation period

SFs,r =Scale factors for soil type, rice varieties, and other factors, if available [7]

The CO_2 emissions from the use of urea fertilizer are calculated using the following equation:

CO_2-*Emission* = (MUrea × EFUrea)..................................... (v)

Where:

CO_2-*Emission* = The annual C emissions from the application of urea (tons of CO_2 per year)

MUrea = The amount of urea fertilizer applied (tons per year)

EFUrea = The emission factor (tons of C per urea). The default IPCC (Tier 1) emission factor for urea is 0.20, equivalent to the carbon content in urea fertilizer based on the atomic weight (20% of $CO(NH_2)_2$). [7]

The equation to estimate indirect N_2O emissions from managed soil is shown in the following equation, which describes the process of N volatilization to the atmosphere (N_2OATD):

N_2O (ATD)-N = [(FSN × FracGASF) +((FON + FPRP) FracGASM)] × EF_4…..(vi)

Where:

N_2O(ATD)-N = The annual amount of N_2O-N generated from N volatilization to the atmosphere from managed soil (kg N_2O-N per year).

FSN = The annual amount of synthetic N fertilizer applied to the soil (kg of N per year).

FracGASF = The fraction of synthetic N fertilizer volatilized as NH3 and NOx (kg of N volatilized per kg of N applied)

FON = The annual amount of manure, compost, urine, feces, and other organic materials applied to the soil (kg of N per year).

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FPRP = The annual amount of urine and feces from livestock deposited in pasture or grazing fields (kg of N per year).

FracGASM = The fraction of organic N fertilizer (FON) and urine and feces from livestock deposited (FPRP) that is volatilized as NH_3 and NO_X (kg of non-CO_2 emissions from biomass burning per kg of N applied or deposited).

EF_4 = The emission factor of N_2O from N deposition n soil and water surface [(kg of N-N_2O per kg of NH_3-N + NO_X-N volatilized)] [7]

The equation used to calculate non-CO2 emissions from biomass burning is as follows:

$$L_{fire} = A \times M_B \times C_f \times G_{ef} \times 10^{-3} \text{...(vii)}$$

Where:

L_{fire} = The total greenhouse gas emissions from combustion (tons of CH_4, N_2O, CO, and NO_X).

A = Area burned (ha)

M_B = Available biomass for combustion (tons/ha) (including biomass, litter, and deadwood)

C_f = Combustion factor

G_{ef} = Emission factor (g/kg dry matter burned). [7]

The general equation used to calculate GHG emissions from fuel combustion is as follows:

Emission GRK (kg/year) = Energy Consumption (TJ/year) × Emission factor(kg/TJ)…..... (viii)

2.4.3.2 Acidification Impact Calculation

Pollutants that can cause acidification are SO_2, NO_x, and NH_3. The impact on acidification is analyzed and converted based on the content of SO_2eq (sulfur dioxide equivalent). The sources of pollutants causing acidification that contain SO_2 come from using fuels such as diesel and electricity consumption.

The calculation of SO_2 emissions from fuels according to AIP (1996) can be obtained through the following equation:

Emissions SO_2 (fuel) = QF × NK × FE…...............................(ix)

Where:

QF = Fuel consumption (l)

NK = Net Calorific Value (0.037 TJ/kL)

FE = Emission Factor (59.61 kg SO_2/TJ) [8]

SO_2 Emissions (electricity) = QL × FE…..............................(x)

Where:

QL = Electricity consumption (kWh)

FE = Emission Factor (8.1 g SO_2/kWh) [9]

Nox Emissions (fuel) = QF × NK × FE…..............................(xi)

Where:

QF = Fuel consumption (l)

NK = Net Calorific Value (0.037 TJ/kL)

FE = Emission Factor (1.322 kg Nox/TJ) [8]

The Emission of Nox (electricity) = QL × FE……............(xii)

Where:

QL = Electricity consumption (kWh)

FE = Emission factor (4.17 g NO_x/kWh) [9]

Emission of Nox (fertilizer) = QP × N × FE…...........................(xiii)

Where:

QP = Fertilizer consumption (kg)

N = Nitrogen content in the fertilizer (46%)

FE = Emission factor (0.005 kg NO_X/kg N) [10]

Emission Nox (*leaching*) = QP × N × FE….......................(xiv)

Where:

QP = Fertilizer consumption (kg)

N = Nitrogen content in the fertilizer (46%)

FE = Emission factor (0.3 kg NO_X/kg N) [10]

Emission of NH_3 (urea) = QU × N × FE...........................(xv)

Where:

QU = Urea fertilizer consumption (kg)

N = Nitrogen content (46%)

FE = Emission factor (0.1 kg NH_3/kg N) [10]

2.3.4.3 Eutrophication Impact Calculation

Eutrophication is a phenomenon that can affect both terrestrial and aquatic ecosystems. Nitrogen and phosphorus are two nutrients heavily involved in eutrophication. The pollutants causing eutrophication include NO_x, NH_3, PO_4^{3-}, and nutrients (N and P). NO^x pollutants contributing to eutrophication arise from fuel combustion, electricity consumption, fertilizer use, crop residue, and NO^3 leaching (IPCC, 2002). Fertilizer use also has an impact on eutrophication. Pollutant sources that cause eutrophication include NH3 (urea volatilization), PO_4^{3-}, and liquid waste.

The calculation of eutrophication impact from NH3 emissions originating from the use of urea fertilizer, based on EEA (2006), can be obtained through the equation:

Emission of NH_3 (urea) = QU × N × FE............................(xvi)

Where:

Qu = Urea fertilizer consumption (kg)

N = Nitrogen content (46%)

FE = Emission factor (0.1 kg NH_3/kg N) …. [10]

Emission of PO_4^{3-} (fertilizer). = QP × P × FE..................(xvii)

Where:

Qp = Fertilizer consumption (kg)

P = Phosphorus content (36%)

FE = Emission factor (0.128 kg $PO4^{3-}$/kg P) [11]

2.4.4 Interpretation of Results

In this stage, the interpretation of results, evaluation, and validation of the impact analysis are conducted to improve and reduce negative environmental impacts. Based on the evaluation of the impact analysis, the process stages that significantly contribute to environmental changes are identified. Through process improvement and utilization efforts, it is expected that not only the environmental impact on greenhouse gases, acidification, and eutrophication can be reduced, but also the efficiency of the Solok rice production system can be enhanced.

2.5. Data processing and presentation

Data processing and presentation were done using Microsoft Excel, involving calculations and displaying results in tables, diagrams, and graphs. The data collected from the data collection process was input into predetermined formulas from literature studies, and impact analysis was conducted. The impacts in the form of quantitative data for each component were then grouped based on impact types, namely greenhouse gases (GHG), acidification, and eutrophication. In the interpretation phase, the impact analysis results were analyzed descriptively to identify the impact sources and explore alternative improvements to reduce environmental impacts.

3. RESULT AND DISCUSSION

3.1. Life cycle assessment analysis

3.1.1 Objective and Scope

The data inventory process in the field provides information on the entire stages of the Solok rice production process, starting from cultivation activities and production until the production of rice ready for consumption. Figure 1 illustrates the life cycle of Solok rice production.

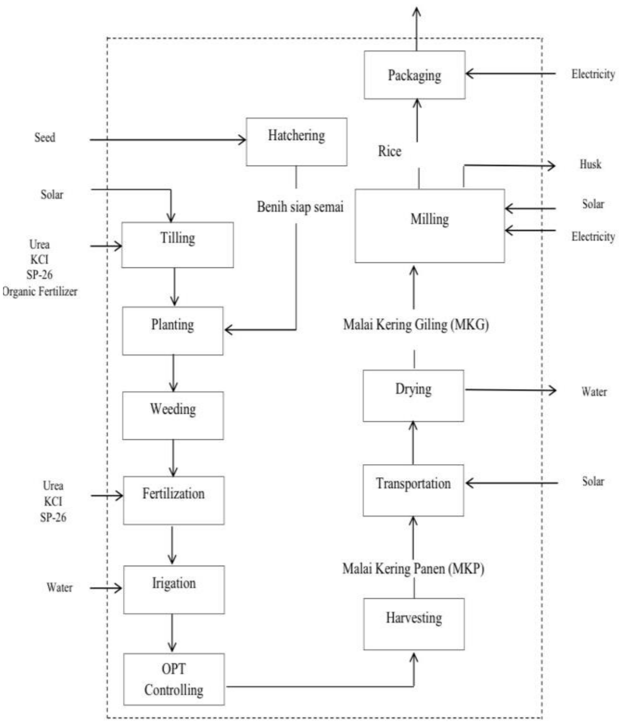

Figure 1. Life cycle of solok rice production

3.1.2 Life cycle inventory

The development of the inventory database begins with the inventory of resources and raw material usage throughout the entire cycle, including production, transportation, utilization, and product disposal. The life cycle of a product involves various processes within its cycle. Creating a life cycle model requires data collection from all the processes involved. Table 2 shows the Solok rice production system's Life Cycle Inventory (LCI).

3.1.3 The energy requirement of the Solok rice production system

In the life cycle of Solok rice, the energy input (energy required) is 2.793,66 MJ/ton of rice. The stages that require energy are the cultivation process, which uses fertilizers and fuel. In addition to the cultivation process, the post-harvest stage also requires energy for fuel and electricity consumption. Table 12 shows that the largest energy contribution comes from N fertilizers.

The energy output from the life cycle of Solok rice is 21.150 MJ/ton of rice. This energy is derived from the products produced and the by-products utilized. The Net Energy Value (NEV) obtained is 18.36 GJ/ton of rice with a Net Energy Ratio (NER) of 7.57. The Net Energy Ratio (NER) of technology is useful in indicating how efficient the technology is in providing energy for society. The net energy performance achieved is favourable since the NER value is greater than 1, and the NEV is positive.

Table 2. Life Cycle Inventory (LCI) Solok Rice

Inventory	**Unit**	**Total (per ha)**	**Total (per ton yield)**
Seeding			
Seeds	Kg	25	4.46
Tilling			
Urea Fertilizer	Kg	57.3	10.23
SP-36 Fertilizer	Kg	100	17.86
KCI Fertilizer	Kg	25	4.46
Solar	Litre	23	4.1
Organic Fertilizer	Kg	1000	178.57
Fertilization			
Urea Fertilizer	Kg	114.7	20.48
KCI Fertilizer	Kg	25	4.46
Harvesting			
Dry panicles (MKP)	Ton	9.25	1.65
Transportation			
Solar	Litre	14.8	2.64
Milling			
Solar	Litre	52.05	9.29
Electricity	Kwh	6,53	1,16
Husks	Kg	1400	250
Packaging			
Electricity	Kwh	3.36	0,6

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Table 3. System energy requirements Solok Rice Production

Inventory	Unit	Total (per ton yield)	Emission (kg CO_2eq/ton Rice)
Cultivation- Harvesting			
N	Kg	30.71	180.57
P	Kg	17.86	18.04
K	Kg	8.92	5.08
Solar	Litre	4.1	10.95
Annual Emission			1390.62
Transportation			
Solar	Litre	2.64	7.05
Production Process			
Solar	Litre	9.29	24.8
Electricity	Kwh	1.16	1.04
Packaging			
Electricity	Kwh	0.17	0.15
Total			1.638.3

3.1.4 Life cycle impact assessment

3.1.4.1 Greenhouse gas impact calculation

Based on the emission calculations, the total emission value from 1 ton of Solok rice production is 1,638.3 kg CO_2eq/ton of rice or 1.64 kg CO_2eq/kg of rice. The emission values obtained from the calculations are presented in Table 4.

Table 4. Carbon Emission value of Solok Rice Production

Inventory	Total Energy (MJ/ton Rice)
Input	**2.793.66**
Cultivation- Harvesting	
N	1996.15
P	160.74
K	53.52
Solar	147.56
Transportation	
Solar	95.01
Production Process	
Solar	334.35
Electricity	4.17
Packaging	
Electricity	2.16
Output	**21.150**
Rice	17400
Waste Production (Husks)	3750

Based on previous research, the emission values generated in rice production systems are generally calculated based on the input of raw materials and the output of the final product in terms of CO_2 equivalent value.

When compared to LCA studies of rice in other countries, there are differences in the values. For instance, Ref. [12] obtained an emission value of 2.92 kg CO2eq/kg of rice. Ref. [13] studied the environmental impact of paddy cultivation irrigation and obtained an emission value of 2.2 CO_2eq/kg of rice. Ref. [14] found an emission value of 1.59 CO_2eq/kg of rice. The difference in these values is influenced by several factors, including the scope limitations in the analysis and the observed variables adjusted to the specific conditions of the research location. On average, these studies focused on the rice milling process, as seen in the research conducted by Ref. [12] in Thailand and Ref. [14] analyzed the environmental impact of rice milling processes in Malaysia by comparing coal energy with natural gas. Ref. [15] limited the scope of their environmental impact analysis to rice production in the Shiga region of Japan, covering the stages from seedling to production without considering land use, waste management, and post-harvest activities like consumption.

Among the three main stages in the Solok rice production process, the cultivation stage yields relatively higher emission values than the production stage and the biomass residue burning process (straw burning). The calculation of greenhouse gas (GHG) emissions indicates that non-CO_2 emissions, specifically CH_4 emissions, have the highest value, which is 1.16 Gg CH_4 per year in the cultivation stage. The grouping of CO_2 emissions and non-CO_2 emissions in each stage of the Solok rice production process is presented in Table 5.

Table 5. Emission value in each Stage of Process Solok Rice Production

	Emission (Gg Emission/ year)				
Stage	CO_2	CH_4	N_2O	CO	Nox
Cultivation	0.12	1,16	49,8 x 10^{-6}	-	-
Production and TransPortation	491,3 x 10^{-9}	20,1 x 10^{-9}	4,02 x 10^{-9}	-	-
Biomass Burning	-	5,07 x 10^{-3}	131,4 x 10^{-3}	172,7 x 10^{-3}	4,79 x 10^{-3}

Table 5 overviews the CO_2 and non-CO_2 emissions generated from all Sokan rice production system stages over one year. The LCA approach developed based on the default IPCC can yield emission values in CO2eq, representing greenhouse gas emissions as GWP_{100} (Global Warming Potential) over 100 years, by the conversion factors of 25 for CH4 emission and 298 for N2O emission.

The emission conversion calculations in the cultivation stage result in a CO_2eq value of 28.75 Gg CO_2eq per year. Then, in the production and transportation stage, the CO_2eq value is 0.32 Gg CO_2eq per year. Meanwhile, during the biomass straw-burning activity, the CO_2eq value is 39.27 Gg CO_2eq per year. In the cultivation stage, the CH_4 emissions are relatively higher than CO_2 and N_2O emissions. The use of urea fertilizer influences the high CH4 value. Figure 2 illustrates the emission values resulting from the cultivation stage of Cisokan rice.

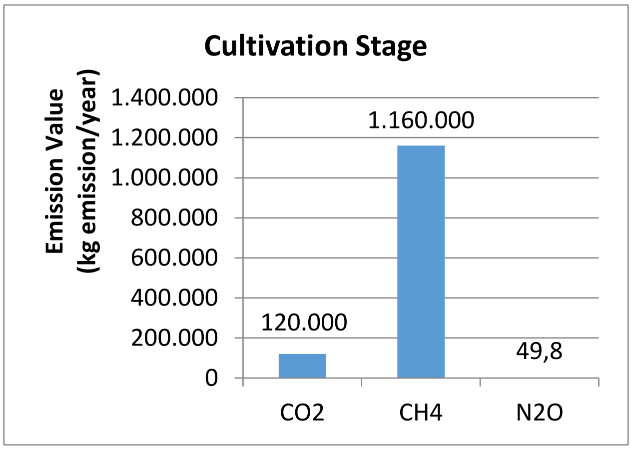

Figure 2. Emission Value of Solok Rice Cultivation

The production process that plays a role in producing rice as the final product is the milling process. The Solok rice milling process uses diesel fuel as the energy source. Emission calculations carried out at this stage also include emissions from transportation. The analysis results show that CO_2 emissions are higher than non-CO_2 emissions, such as CH_4 and N_2O. Figure 3 shows the emission values resulting from the production and transportation processes of Solok rice.

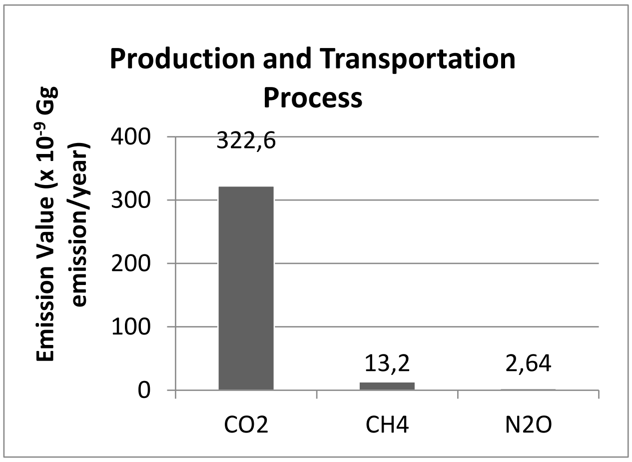

Figure 3. Emission value from the production and transportation process

The production process of Solok rice generates solid waste in the form of straw in the field after the cultivation period ends. Some farmers burn this straw in the field, which can potentially result in emissions, both into the soil and into the atmosphere in the form of greenhouse gas emissions. CO_2 emissions from the burned biomass are not accounted for because the carbon released during the combustion process is assumed to be reabsorbed by plants in the following season. Non-CO_2 emissions dominate the estimated emission values, with CO emissions from straw-burning activities being part of the post-harvest process. The emission potential from biomass-burning activities in the field is shown in Figure 4.

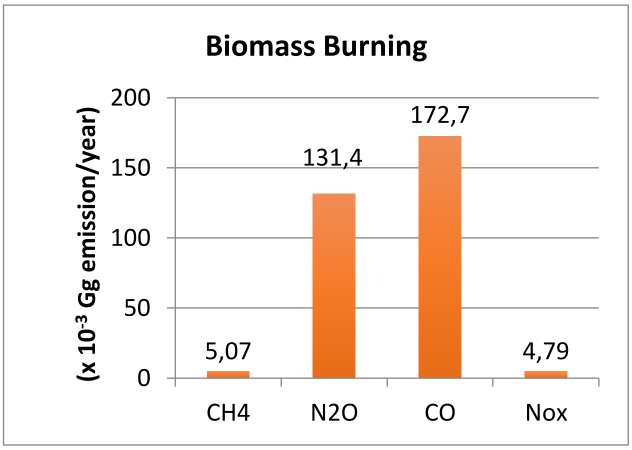

Figure 4. Emission Value of Straw Biomass Burning

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3.1.4.2 Acidification impact calculation

The results of the acidification impact category calculation based on pollutant sources in rice production in Gunung Talang District can be seen in Figure 5.

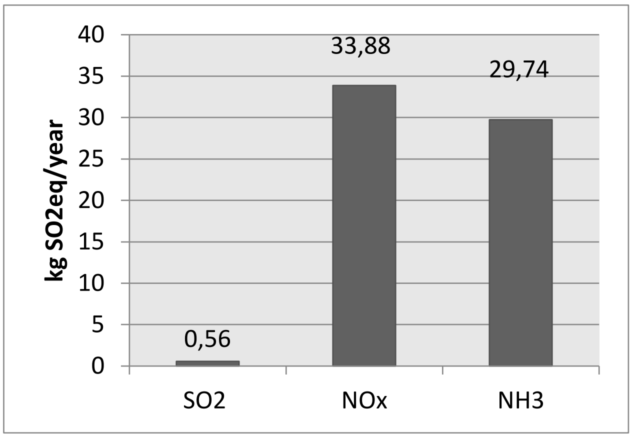

Figure 5. Acidification impact based on pollutant sources

Figure 5 shows that NO_x is the pollutant that contributes the most to the acidification impact compared to other pollutants. NO_x emissions come from urea fertilizer, nitrate (NO_3) leaching, diesel fuel, and electricity consumption. NH_3 emissions arise from urea volatilization, while SO_2 emissions come from diesel fuel and electricity consumption. Based on the emission calculations, the total emission value from 1 ton of Solok rice production is 64.176 kg SO^{2eq}/ton of rice or 0.064 kg SO^{2eq}/kg of rice. The data on acidification impact analysis based on emission sources in the production system of Solok rice can be seen in Table 17.'

Table 6. Acidification impact analysis based on emission sources

Polutant	Sources	kg SO_2eq/ ton Rice
SO_2	Solar	0.4
	Electricity	0.16
NO_x	Fertilizer urea	0.56
	Solar	0.006
	Electricity	0.06
	NO_3 *leaching*	33.25
NH_3	*Urea volatilization*	29.74
Total		64.176

Based on Table 6, it is evident that *Nitrate (*NO_3) leaching is the major contributor to NOx emissions due to the use of synthetic fertilizers. *Urea volatilization* is the primary source of NH_3 emissions arising from the application of urea fertilizer, while diesel fuel causes the highest impact on SO_2 emissions.

3.1.4.2 Eutrophication impact calculation

In the LCA study conducted on rice, the sources of pollutants causing eutrophication are NO_x, NH_3, and PO_4^{3-}. NOx emissions are generated from urea fertilizer, fuel in the form of diesel, and electricity consumption. NH_3 emissions originate from *urea volatilization*, while PO_4^{3-} emissions are derived from using phosphorus-containing fertilizers. The results of the impact assessment on eutrophication based on pollutant sources in rice production in Gunung Talang District can be seen in Figure 6.

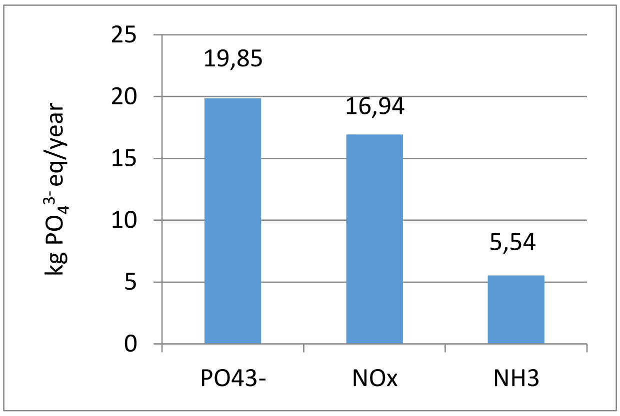

Figure 6. Impact assessment on eutrophication based on pollutant sources

Figure 6 shows that PO_4^{3-} is the pollutant that contributes the most to the eutrophication impact compared to other pollutants, and NH_3 tends to be higher than NO_x. This indicates that nutrients containing phosphorus (P) in the water body are higher than nutrients containing nitrogen (N). Based on the emission calculations, the total emission value from the production process of 1 ton of Solok rice is 42.33 kg PO_4^{3-} eq/ton of rice or 0.042 kg PO_4^{3-} eq/kg of rice. The data on eutrophication impact analysis based on emission sources in the production system of Solok rice can be seen in Table 7.

Table 7. Eutrophication impact analysis based on emission sources

Polutant	Sources	kg PO_4^{3-} eq/ ton Rice
PO_4^{3-}	SP-36 Fertilizer	19.85
NO_x	Urea Fertilizer	0.28
	Solar	0.003
	Electricity	0.03
	NO_3 *leaching*	16.63
NH_3	*Urea volatilization*	5.54
Total		42.33

Table 7 shows NO_3 leaching as the main contributor to NOx emissions caused by synthetic fertilizers. Urea volatilization is the primary source of NH_3 emissions resulting from the application of urea fertilizer while using phosphorus-containing fertilizers has the most significant impact on PO_4^{3-} emissions.

3.2. *Improvement of the production system*

The main issue in Cisokan rice cultivation lies in the excessive use of synthetic fertilizers and urea, which contribute significantly to CH_4 emissions. Another problem in the production process of Solok rice is the ineffective management of irrigation and drainage systems, as farmers still rely on natural spring sources for irrigation. Furthermore, the current evaluation of Solok rice production cannot overlook the management of production waste, specifically straw, which significantly contributes to air emissions through biomass burning in the fields by some farmers in the Gunung Talang District.

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Considering the current cultivation practices, there are still opportunities for optimizing raw materials, substituting environmentally friendly raw materials, and enhancing efficiency in irrigation and drainage systems in the fields. These measures can help reduce the emissions generated during the production process of Solok rice. Several alternative processes that can be proposed to mitigate the environmental impact in the production system of Solok rice are as follows:

3.2.1. Well-controlled irrigation and drainage systems.

In the reduction of total emissions, the findings of this research demonstrate that land emissions, particularly CH_4, contribute significantly to CO_2eq emissions. The agricultural sector plays a crucial role in methane production [16]. Ecosystems with predominantly anaerobic conditions, especially due to waterlogging as found in paddy fields and other wetlands, are the main sources of methane emissions. Waterlogging is a characteristic of paddy field irrigation systems. Essentially, rice plants do not require flooded conditions throughout their growth process. Intermediate drainage in paddy fields during the rainy season reduces CH_4 emissions [17].

3.2.2. Optimization of fertilizer use, particularly nitrogen (N) fertilizer.

Maximizing the efficiency of fertilizer use and applying only the necessary amount of nitrogen (N) required by the crops during the harvest season is also an essential pathway to reduce life cycle emissions. The research results by Brodt et al. (2014) [18] demonstrate that reducing fertilizer application decreases emissions and reduces substream emissions to a greater extent, as substantial CO2eq emissions are associated with synthetic N fixation and fertilizer formulations. Although farmers already have incentives to optimize fertilizer use to save input costs, the fertilization level still varies among rice farmers [18]. Further research and extension activities are needed to clarify the N nutrient requirements for different soil types, rice varieties, and land conditions.

3.2.3. Management of by-products (straw and rice husks)

The life cycle of Solok rice produces secondary products in the form of solid waste, namely straw and rice husks. Straw is generated in two process stages: the harvesting and threshing stages. The straw produced during the harvesting stage is commonly reused as a nutrient supplement for the subsequent planting season. Utilizing straw waste from the harvest can fulfill the soil's nitrogen (N) nutrient requirements for the next crop season, approximately 19-25 kg N/ha in various soil types, leading to a potential saving of around 15% in N fertilizer usage.

From the rice milling process, typically, around 20-30% of rice husks, 8-12% of rice bran, and 50-63.5% of milled rice are obtained based on the initial weight of the paddy. Several alternative uses for rice husk include biochar production, animal feed, electricity generation, and utilization in horticultural plantations.

4. CONCLUSION

The production system of Solok rice using the Cisokan variety encompasses various activities, ranging from cultivation to rice milling, to obtain the final product of rice, requiring inputs and energy consumption in the form of seeds, fertilizers, and diesel fuel as the energy source. Developing a Life Cycle Inventory (LCI) in LCA analysis assists in facilitating the data inventory process to identify the flow of raw materials within one product's production cycle. The chosen *scope* in the LCA method conducted in this research is *cradle-to-gate* to ease the research as the product use phase is particularly challenging to evaluate. The impact analysis results indicate that the greenhouse gas emissions amount to 1.94 kg CO^{2eq} / kg of rice. The subsequent potential impacts include acidification of 0.064 kg SO^{2eq} / kg of rice and eutrophication of 0.042 kg PO_4^{3-eq} / kg of rice. The largest CO_2 emissions originate from production and transportation activities, while the highest non-CO_2 emissions stem from the rice cultivation phase in the form of CH_4 emissions. The magnitude of CH_4 emissions is influenced by the extensive use of fertilizers on the fields. NO_x emissions contribute significantly more to acidification's impact than other pollutants. NO_x emissions originate from urea fertilizer, nitrate (NO_3) leaching, the utilization of diesel fuel, and electricity consumption. NH_3 emissions result from urea volatilization, while SO_2 emissions stem from diesel fuel and electricity. PO_4^{3-} emissions significantly impact eutrophication compared to other emissions, and NO_x emissions tend to be higher than NH_3. This indicates that nutrients containing phosphorus (P) in water bodies are higher than nutrients containing nitrogen (N). The net energy calculation yields an input energy value of 2,793.66 MJ/ton of rice and an output energy value of 21,150 MJ/ton. From these two values, the Net Energy Value (NEV) is determined to be 18.36 GJ, and the Net Energy Ratio (NER) is 7.57. This indicates that the net energy performance generated is quite favourable. The current system development focuses primarily on decreasing synthetic fertilizers, increasing the use of organic materials, and recycling production waste to reduce land and environmental emission values.

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