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Life Cycle Assessment of Rice Cultivation in Acid Sulfate Tidal Swamplands: A Case Study from Barito Kuala, South Kalimantan, Indonesia

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Abstract

Rice cultivation in acid sulfate tidal swamplands is agronomically and biogeochemically distinct from irrigated lowland systems, yet site-specific life-cycle greenhouse gas (GHG) assessments of this agroecosystem remain scarce. This study developed a site-specific, secondary-data life-cycle assessment of rice cultivation in Barito Kuala, South Kalimantan, Indonesia, comparing four management scenarios derived from a factorial field experiment: current farmer practice (S1), a conventional nitrogen-phosphorus-potassium (NPK)-only treatment (S2), an improved compost-amended practice (S3), and a low-input biochar-amended alternative (S4). Cradle-to-gate global warming potential (GWP) was quantified on both an area (kg CO_2-equivalent per hectare) and yield-scaled (kg CO_2-equivalent per tonne) basis using IPCC Tier 1 emission factors for direct N_2O estimation and openLCA for life-cycle modelling. Farmer Practice exhibited the highest GWP under both functional units, with methane as its dominant emission source. The Low-Input scenario minimised area-based GWP (425.5 kg CO_2-eq ha^{-1}) but not yield-scaled intensity, owing to its low yield, whereas the Improved scenario achieved the lowest yield-scaled GWP (204.6 kg CO_2-eq t^{-1}) under a base compost-nitrogen assumption, an advantage not retained under an alternative, higher nitrogen estimate. Direct N_2O and upstream fertilizer production dominated emissions in fertilized scenarios (63.8–76.4% of total GWP), indicating improved nitrogen-use efficiency as a potentially important mitigation pathway for fertilized management under tidal acid-sulfate conditions. These findings demonstrate that GHG mitigation strategies in this system depend on both the functional unit applied and the characterisation of organic amendment nitrogen, with implications for management decisions in acid sulfate tidal rice systems.

Keywords Life cycle assessment; Greenhouse gas emissions; Acid sulfate soil; Tidal swampland; Rice cultivation

1. Introduction

Rice (*Oryza sativa* L.) underpins food security for a substantial share of the world's population, yet paddy cultivation is also a major source of anthropogenic methane (IPCC 2019), and its expanding production must be reconciled with the need to mitigate its greenhouse gas (GHG) burden.

In Indonesia, mounting pressure on irrigated sawah land, particularly through conversion to non-agricultural uses on Java, has renewed national interest in tidal swamplands (lahan rawa pasang surut) as a frontier for rice extensification and food security. South Kalimantan's Barito Kuala Regency is among the most prominent of these areas: it has consistently recorded the largest rice harvested area and production among regencies in the province in recent years (2017–2022) (Azis et al. 2024), cultivated almost entirely on non-irrigated, tidally influenced land.

Unlike irrigated rice systems where water regimes can be relatively controlled, tidal rice cultivation on acid sulfate soils is governed by dynamic interactions between tidal flooding, drainage, and soil redox status. In Barito Kuala, tidal channel studies have documented temporal and spatial variation in water level and acidity along secondary and tertiary channels (Bhakty 2005), while field studies have mapped shallow pyrite depth and associated soil acidification, noting particular agronomic risk where pyrite depth coincides with the rice root zone (Ahmad et al. 2024). These water–soil interactions affect crop productivity and create management constraints that may influence fertilizer and amendment requirements, choices that, in turn, influence the system's methanogenic and nitrogen-cycling processes and, ultimately, its GHG performance. Water regime is therefore treated in this study as an inherent characteristic of the production environment, while contrasting fertilizer and amelioration practices constitute the management scenarios evaluated.

Most published rice life-cycle assessments (LCAs), however, have focused on conventional irrigated systems, and the environmental performance of rice cultivated under the coupled constraints of tidal hydrology and acid sulfate soils remains poorly characterized. To the best of our knowledge, no site-specific, cradle-to-gate LCA has been reported for rice production in the acid sulfate tidal swamplands of Barito Kuala. This study addresses that gap by developing a site-specific, secondary-data LCA of rice cultivation in this agroecosystem. Based on the factorial management treatments reported by Annisa and Nursyamsi (2016), four scenarios were selected to represent contrasting management strategies relevant to practical management decisions in tidal acid-sulfate environments: current farmer practice (S1), a conventional nitrogen-phosphorus-potassium (NPK)-only treatment (S2), the evidence-based recommended practice explicitly identified by the original authors (S3), and a low-external-input alternative combining reduced land intensification with biochar amendment (S4). The objective of this study is to quantify and compare the cradle-to-gate GHG performance of these four scenarios on both an area (per hectare) and yield-scaled (per tonne) basis, and to identify the dominant emission sources and key uncertainties relevant to future management decisions in this agroecosystem.

2. Materials and methods

2.1 Study area and system boundary

This study evaluates the life-cycle GHG emissions of rice cultivation in acid sulfate tidal swampland in Barito Kuala Regency, South Kalimantan, Indonesia. The area is characterised by non-irrigated, tidally influenced paddy fields on acid sulfate soils. A cradle-to-gate system boundary was adopted, encompassing the production of agricultural inputs (nitrogen, phosphate and potassium fertilizers, and diesel fuel for land preparation) and on-field GHG emissions (methane and nitrous oxide) up to the farm gate (harvested unmilled grain, gabah kering panen). Post-harvest processes (drying, milling, transport, and distribution) were excluded from the system boundary.

2.2 Functional units

Two complementary functional units (FU) were used throughout this study: (i) kg CO_2-eq per hectare per season, representing the area-based environmental burden of production, and (ii) kg CO_2-eq per tonne of harvested grain, representing the environmental intensity (efficiency) of production. The dual FU approach was adopted because area-based and yield-based burdens can rank management scenarios differently, and both perspectives carry distinct policy relevance (see Section 3).

2.3 Scenario selection and data source

The primary source of site-specific activity data and direct field-measured emissions was a split-split-plot factorial field experiment conducted in acid sulfate soil in South Kalimantan (Annisa and Nursyamsi 2016), which reported methane emissions, grain yield, and fertilizer application rates for 16 factorial treatment combinations (2 land-use types × 2 NPK fertilization rates × 4 ameliorant treatments).

Of the 16 factorial combinations reported in the primary source, four were selected to represent management contrasts relevant to practical management decisions: current farmer practice (S1), a conventional NPK-only treatment (S2), the evidence-based recommended practice explicitly identified by the original authors (S3), and a low-external-input alternative combining reduced land intensification with biochar amendment (S4). This subset was chosen to span a coherent management gradient rather than to exhaustively replicate the full factorial design. Table 1 summarises the four scenarios and their corresponding treatment codes from the primary source.

Table 1. Summary of the four rice cultivation scenarios and their corresponding treatment codes from the primary source (Annisa and Nursyamsi 2016)

LCA scenario[a]	Original treatment code	Land management	NPK dose (%)	Ameliorant
S1: Farmer Practice	S2P1B1	Intensive	100	Farmer's practice (fresh straw + local weed)
S2: Conventional	S2P1B0	Intensive	100	None
S3: Improved	S2P2B2	Intensive	75	Compost (30% straw + 30% Purun + 40% cattle manure)
S4: Low-Input	S1P2B3	Traditional/natural	75	Rice husk biochar

[a]*S1–S4 are scenario labels assigned in the present LCA; treatment codes refer to the original factorial field experiment.*

S1 is referred to as the farmer-practice treatment because it was designated as such in the primary experimental source; it should not be interpreted as a representative, survey-based average of farming practices across Barito Kuala.

Nitrogen input from the farmer-practice ameliorant (B1, S1) was not quantified in the primary source, as its composition and application rate were not reported. This organic-N input was therefore set to zero in the base inventory as an explicit, conservative modelling assumption; the implications of this assumption for the interpretation of GWP estimates are discussed in Section 4.6.

2.4 Foreground inventory: field GHG

2.4.1 Methane

Seasonal methane (CH_4) emissions per scenario were taken directly from field flux-chamber measurements reported in the primary source (Annisa and Nursyamsi 2016), ranging from 2.33 to 30.40 kg CH_4 ha^{-1} $season^{-1}$ across the four scenarios.

2.4.2 Direct nitrous oxide

Direct nitrous oxide (N_2O) emissions were estimated using the IPCC (2019) Tier 1 approach, applying the emission factor for N inputs to flooded rice fields (EF1FR) to total anthropogenic nitrogen inputs (synthetic and organic):

$$\mathrm{N2O-N} = \left(\mathrm{N_{synthetic}} + \mathrm{N_{organic}}\right) \times \mathrm{EF1FR}$$

$$\mathrm{N2O} = \mathrm{N2O-N} \times \left(\frac{44}{28}\right)$$

A primary EF1FR of 0.5% was applied, corresponding to the IPCC single/multiple drainage category, considered more representative of the non-continuously flooded tidal water regime of the study area than the continuous-flooding category. A sensitivity value of 0.3% (continuous flooding category) was evaluated in parallel. Nitrogen inputs from compost (S3) and biochar (S4) were derived from literature-derived total-N content of the respective amendments, expressed as discrete base-case and alternative-case values (Section 2.5) rather than a single point estimate, to propagate parameter uncertainty transparently through the inventory.

This approach follows a Tier 1 estimate of direct N_2O emissions from total anthropogenic nitrogen inputs; it does not capture site-, soil-, or management-specific N_2O dynamics that higher-tier methods would require.

2.4.3 Indirect nitrous oxide (scope exclusion)

Indirect N_2O emissions arising from volatilisation-redeposition (NH_3/NOx) and leaching-runoff pathways were not quantified, as the site-specific fractions required (FracGASF, FracGASM, FracLEACH-H) have not been established for tidal acid sulfate rice systems in South Kalimantan. Applying generic IPCC default fractions in the absence of local validation would introduce an additional layer of proxy-based uncertainty without a clear local basis; this pathway is therefore excluded from the foreground inventory rather than assumed to be negligible; the implications of this exclusion for total GWP estimates are discussed in Section 4.6.

2.5 Compost and biochar nitrogen content

Total nitrogen content of the compost amendment (straw:Purun weed:cattle manure, 30:30:40) used in scenario S3 was derived from two independent literature reports of the same underlying 2012 field dataset (Annisa et al. 2014; Annisa et al. 2017) (1.456% N; treated as one consistent dataset rather than two independent replications) and an alternative estimate from a separate composting trial using a bioactivator and lime (Santri et al. 2021) (4.326% N). The two values were propagated as discrete base-case and alternative-case scenarios rather than combined into a statistical distribution, as the difference reflects distinct composting processes rather than random measurement variability. Biochar (rice husk) nitrogen content for scenario S4 was estimated at 0.3–0.5% N from a low-confidence regional wood-charcoal comparator study conducted at the Belandean Experimental Station, Barito Kuala (Soedarmanto et al. 2020), pending a more direct measurement source specific to rice husk biochar.

2.6 Background inventory: upstream input production

Because ecoinvent/Agribalyse licensing was not available to the research team, upstream (background) emissions associated with fertilizer production, together with direct diesel combustion emissions, were represented using published, literature-derived emission factors rather than a full commercial life-cycle inventory database. This hybrid approach was adopted as a transparent methodological strategy in the absence of a licensed, geographically resolved background inventory database, while retaining site-specific foreground data wherever available. Table 2 summarises the primary and sensitivity emission factors used for each input.

Table 2. Primary and sensitivity parameters for upstream inputs and diesel use

Input	Primary factor (source)	Value	Sensitivity factor (source)
Urea	Brentrup et al. (2018), South-East Asia regional value	0.93 kg CO_2-eq kg^{-1}	Katiyar et al. (2025), conventional Haber-Bosch technology, Northern India
SP-36	Brentrup et al. (2018), Triple Super Phosphate (proxy)	0.25 kg CO_2-eq kg^{-1}	Single Super Phosphate (proxy) / linear P_2O_5-content interpolation
KCl	Brentrup et al. (2018), global default factor	0.25 kg CO_2-eq kg^{-1}	—
Diesel consumption (tillage)	SNI 738:2023, midpoint	2.0 L ha^{-1}	1.5–2.5 L ha^{-1} (SNI range) / 15.17 L ha^{-1} (high-mechanization case, Habiburrohman et al. 2018)
Diesel combustion emission factor	IPCC (2006) default, gas/diesel oil	2.68 kg CO_2-eq L^{-1}	—

SP-36 (36% P_2O_5) is produced via a mixed-acid (phosphoric and sulfuric acid) process; Triple Super Phosphate (pure phosphoric-acid route) was used as the closest available proxy on the basis of P_2O_5 content, while Single Super Phosphate and a linear P_2O_5-content interpolation were retained as bracketing sensitivity values. Potassium chloride was represented using a global-average default factor, as the source did not provide region-specific production data. Diesel use for tillage was represented using a primary consumption rate of 2.0 L ha^{-1}, corresponding to the midpoint of the 1.5–2.5 L ha^{-1} range specified in SNI 738:2023 for two-wheel agricultural tractors, a range also cited by Syahputra et al. (2025). This rate was applied uniformly across all four scenarios rather than as scenario-specific values. Diesel combustion emissions were characterised using an independent emission factor derived from the IPCC (2006) default for gas/diesel oil (2.68 kg CO_2-eq L^{-1}), rather than from the

SNI standard, which addresses fuel consumption rather than combustion emissions. Alternative mechanisation cases, spanning minimal/manual tillage and a high-mechanisation floating-wheel tractor case relevant to waterlogged tidal soils, were evaluated through variation in diesel consumption rather than through changes in the combustion emission factor, in order to test whether the ranking of scenarios is sensitive to the assumed level of mechanisation. The complete life-cycle inventory, including all activity data, emission factors, and literature sources, is provided in Online Resource 1.

2.6.1 Herbicide and pesticide inputs (scope exclusion)

Herbicide and pesticide inputs were excluded from the inventory. The primary experimental source did not report herbicide use, while available regional evidence indicated that herbicide application occurs among some farmers in Barito Kuala. However, the available data were insufficiently resolved for quantitative inventory modelling because the reported application rate was based on a single-farmer observation, while the active ingredient, formulation, product concentration, and product density were not specified. In addition, the available literature-derived pesticide emission factors were expressed on an active-ingredient basis and could not be reliably reconciled with the reported commercial-product application rate. Herbicide use was therefore excluded rather than parameterized using multiple unverified assumptions; this exclusion is discussed further as an inventory data gap, rather than evidence of zero herbicide use, in Section 4.6.

2.7 Characterization and software

Global warming potential (GWP100) characterization factors from IPCC AR6 (IPCC 2021) were applied (CH_4 = 27 kg CO_2-eq kg^{-1}; N_2O = 273 kg CO_2-eq kg^{-1}; CO_2 = 1 kg CO_2-eq kg^{-1}). Life-cycle modelling and impact calculation were performed in openLCA 2.6.2 (GreenDelta), using a custom characterization method configured with the above factors. Foreground processes representing each of the four cultivation scenarios were linked to individually modelled background processes representing upstream production of urea, SP-36, KCl, and diesel combustion, each parameterised with a single-flow proxy process representing the aggregated cradle-to-gate emission factor, rather than an elementary flow derived from a fully resolved background inventory. Model outputs were cross-validated against independent manual calculations for all 12 scenario/EF1FR combinations (6 scenario variants × 2 EF1FR levels), with exact numerical agreement confirmed in all cases. Figures were generated in R (version 4.6.0) using the ggplot2, patchwork, and ggpattern packages.

2.8 Sensitivity analysis

Three parameters with documented uncertainty were propagated through discrete sensitivity scenarios rather than a single point estimate: (i) EF1FR for direct N_2O (0.5% primary vs. 0.3% sensitivity); (ii) compost nitrogen content for scenario S3 (1.456% base vs. 4.326% alternative); and (iii) biochar nitrogen content for scenario S4 (0.3% base vs. 0.5% alternative). Background emission factors for urea, phosphate fertilizer, and diesel were additionally evaluated against literature-derived alternative values (Table 2) to assess whether the comparative ranking of scenarios is robust to background-data selection. Formal probabilistic uncertainty propagation (e.g., Monte Carlo simulation) was outside the scope of the present analysis.

2.9 Terminology and scope statement

Given that the core foreground inventory (methane, yield, and fertilizer application rates) originates from a single field experiment at one location (Mandastana, Barito Kuala), while several background parameters are literature-derived proxies, this study is presented as a site-specific, secondary-data life-cycle assessment model representing rice production in acid sulfate tidal swamplands of Barito Kuala, rather than as a comprehensive survey-based inventory of regional farming practice.

3. Results

3.1 Agricultural production and field emission inventory

Grain yield across the four scenarios ranged from 1.30 t ha^{-1} (S4, Low-Input) to 3.40 t ha^{-1} (S3, Improved), while seasonal methane emissions ranged from 2.33 kg CH_4 ha^{-1} (S4) to 30.40 kg CH_4 ha^{-1} (S1, Farmer Practice). Total nitrogen input (synthetic plus organic) ranged from 84.0 kg N ha^{-1} (S4, base biochar-N assumption) to 285.3 kg N ha^{-1} (S3, alternative compost-N assumption), driving corresponding direct N_2O emissions of 0.66–2.24 kg N_2O ha^{-1} (Table 3). Notably, S1 combined the highest methane emissions of all scenarios with a synthetic-nitrogen input identical to S2, and involved fresh organic amendments under the farmer-practice treatment.

Table 3. Yield, methane, nitrogen input, and direct N_2O emissions across the four cultivation scenarios

LCA scenario	Yield (t ha^{-1})	CH_4 (kg ha^{-1})	N input (kg N ha^{-1})	Direct N_2O (kg ha^{-1})
S1: Farmer Practice	2.52	30.40	92.0	0.723
S2: Conventional	1.95	2.47	92.0	0.723
S3: Improved (base)	3.40	7.75	141.8	1.114
S3: Improved (alt.)	3.40	7.75	285.3	2.242
S4: Low-Input (base)	1.30	2.33	84.0	0.660
S4: Low-Input (alt.)	1.30	2.33	94.0	0.739

3.2 Life-cycle greenhouse gas emissions

Total cradle-to-gate GWP (primary EF1FR = 0.5%) ranged from 425.5 kg CO_2-eq ha^{-1} (S4, Low-Input, base case) to 1259.5 kg CO_2-eq ha^{-1} (S1, Farmer Practice) (Table 4; Fig. 1a). Farmer Practice (S1) produced the highest area-based burden across all six scenario variants evaluated, more than twice that of the Conventional (S2) and Improved-base (S3) scenarios, driven principally by its high field methane emissions (Section 3.3).

Expressed per unit of harvested grain, GWP intensity followed a markedly different pattern (Fig. 1b): the Improved scenario under the base compost-nitrogen assumption (S3-base) showed the lowest GWP intensity (204.6 kg CO_2-eq t^{-1}) among all scenarios, while Farmer Practice (S1) remained the highest under both functional units (499.8 kg CO_2-eq t^{-1}). The Low-Input scenario (S4), despite having the lowest area-based burden, ranked only fourth of six on a per-tonne basis (327.3 kg CO_2-eq t^{-1}) owing to its comparatively low yield (Table 4).

Table 4. Total cradle-to-gate GWP and GWP intensity across the four cultivation scenarios (primary EF1FR = 0.5%)

LCA scenario	Total GWP (kg CO_2-eq ha^{-1})	GWP intensity (kg CO_2-eq t^{-1})	Rank (per ha)	Rank (per t)
S1: Farmer Practice	1259.5	499.8	6 (highest)	6 (highest)
S2: Conventional	505.4	259.2	3	2
S3: Improved (base)	695.8	204.6	4	1 (lowest)
S3: Improved (alt.)	1003.6	295.2	5	3
S4: Low-Input (base)	425.5	327.3	1 (lowest)	4
S4: Low-Input (alt.)	446.9	343.8	2	5

These results illustrate that area-based and yield-based functional units convey distinct, non-substitutable information: S4 exhibited the lowest environmental burden per hectare, whereas S3 (under its base assumption) exhibited the lowest environmental intensity per unit of harvested rice. Reporting a single scenario as unconditionally 'best' would misrepresent this trade-off; the appropriate scenario depends on whether the management objective is to minimise total field-level emissions or to minimise emissions per unit of food produced.

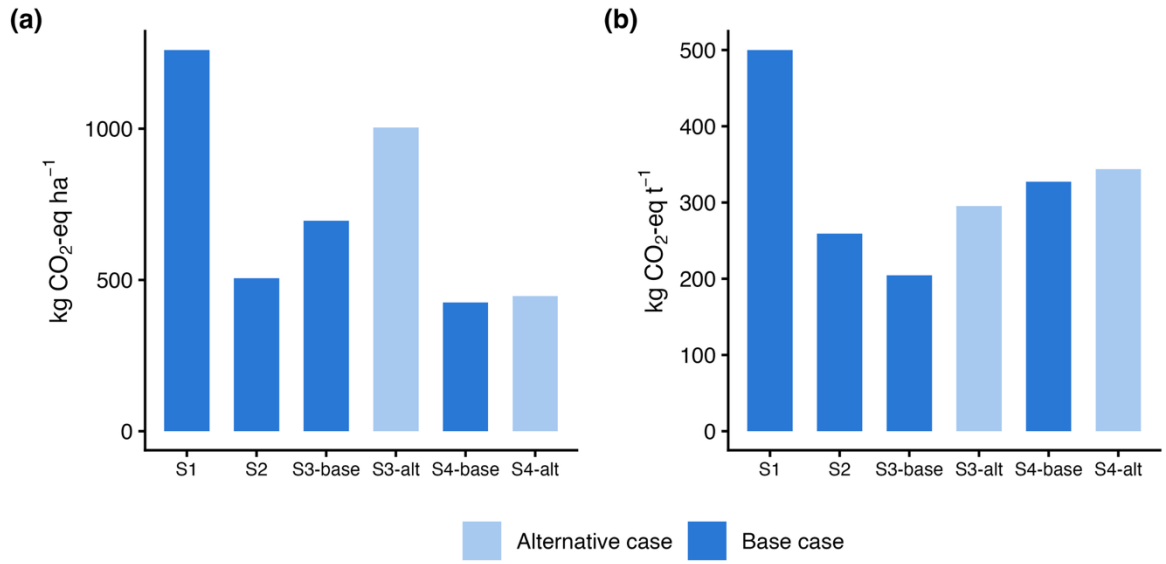


Fig. 1 Cradle-to-gate greenhouse gas emissions of the four rice management scenarios expressed as (a) area-based emissions (kg CO_2-eq ha^{-1}) and (b) yield-scaled emissions (kg CO_2-eq t^{-1}); dark and light bars represent base and alternative (sensitivity) cases, respectively

3.3 Contribution of emission sources

The relative contribution of individual emission sources to total GWP differed substantially between Farmer Practice (S1) and the remaining scenarios (Table 5; Fig. 2). In S1, field methane emissions dominated the total (65.1%), with direct N_2O and fertilizer production together contributing the remainder. In contrast, S2–S4 were dominated by a combination of direct N_2O and upstream urea production, which together accounted for 63.8–76.4% of total GWP depending on scenario and compost/biochar-nitrogen assumption. This contrast indicates that mitigation priorities differ systematically between the two groups: for Farmer Practice, the dominant emission source was field methane associated with the farmer-practice organic-amendment regime, whereas for the remaining scenarios, nitrogen-use efficiency and upstream fertilizer emissions are the dominant concern.

Table 5. Percentage contribution of individual emission sources to total GWP (primary EF1FR = 0.5%)

LCA scenario	CH_4 (%)	N_2O (%)	Urea prod. (%)	SP-36 prod. (%)	KCl prod. (%)	Diesel (%)
S1: Farmer Practice	65.1	15.7	14.8	2.0	2.0	0.4
S2: Conventional	13.2	39.1	36.8	5.0	5.0	1.1
S3: Improved (base)	30.0	43.7	20.1	2.7	2.7	0.8
S3: Improved (alt.)	20.9	61.0	13.9	1.9	1.9	0.5
S4: Low-Input (base)	14.7	42.4	32.8	4.4	4.4	1.3
S4: Low-Input (alt.)	14.0	45.2	31.2	4.2	4.2	1.2

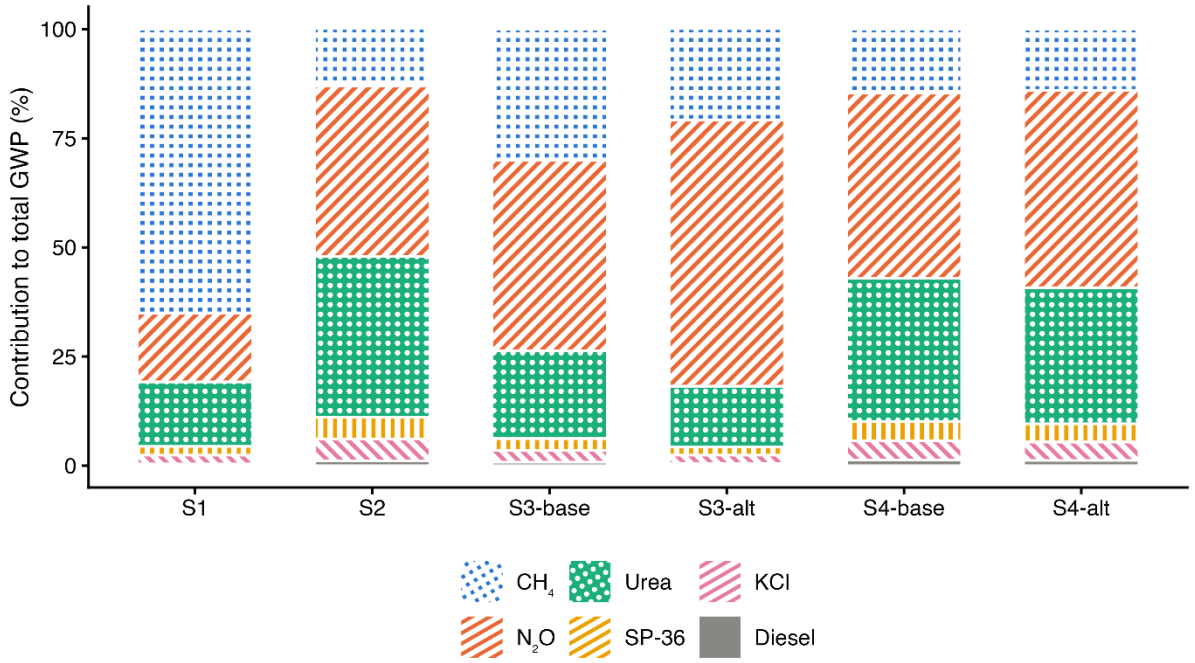


Fig. 2 Relative contribution (%) of individual emission sources: methane (CH_4), nitrous oxide (N_2O), and production of urea, SP-36, KCl, and diesel to total cradle-to-gate GWP across the six scenario variants

The contribution of direct N_2O was particularly sensitive to the assumed nitrogen content of the organic amendment: under the alternative (higher) compost-nitrogen assumption, direct N_2O alone accounted for 61.0% of total GWP in S3, compared with 43.7% under the base assumption (Section 3.4).

3.4 Sensitivity of GHG intensity to uncertain parameters

3.4.1 EF1FR (direct N_2O emission factor)

Applying the lower, continuous-flooding EF1FR (0.3%) in place of the primary single/multiple-drainage value (0.5%) reduced GWP intensity by 6.3–24.4% across scenarios, with the largest absolute and relative reduction occurring in the compost- and biochar-amended scenarios (S3, S4), reflecting their comparatively larger nitrogen inputs (Table 6). Critically, the comparative ranking of scenarios was unchanged between the two EF1FR values: S1 remained highest and S3-base remained lowest in GWP intensity under both assumptions, indicating that the study's comparative ranking is robust to the EF1FR assumption, though not to the alternative compost-nitrogen estimate (Section 3.4.2).

Table 6. GWP intensity under primary (EF1FR 0.5%) and sensitivity (EF1FR 0.3%) assumptions

LCA scenario	EF1FR 0.5% (primary), kg CO_2-eq t^{-1}	EF1FR 0.3% (sensitivity), kg CO_2-eq t^{-1}
S1: Farmer Practice	499.8	468.5
S2: Conventional	259.2	218.7
S3: Improved (base, 1.456% N)	204.6	168.9
S3: Improved (alt., 4.326% N)	295.2	223.2
S4: Low-Input (base, 0.3% N)	327.3	271.8
S4: Low-Input (alt., 0.5% N)	343.8	281.7

3.4.2 Compost and biochar nitrogen content

The choice between base-case and alternative-case nitrogen content for the compost amendment (S3) had a substantial effect on absolute results: GWP intensity increased from 204.6 to 295.2 kg CO_2-eq t^{-1} (a 44.3% increase) when the alternative (4.326% N) compost value was applied instead of the base (1.456% N) value. Under this alternative assumption, the GWP intensity advantage of S3 relative to S2 (Conventional) was substantially reduced (295.2 vs. 259.2 kg CO_2-eq t^{-1}), indicating that the apparent benefit of the Improved scenario is contingent

on the assumed nitrogen content of the compost amendment and should not be generalised without qualification. The corresponding biochar-nitrogen sensitivity for S4 (0.3% vs. 0.5% N) produced a smaller relative change (327.3 to 343.8 kg CO_2-eq t^{-1}, a 5.0% increase), consistent with the lower total nitrogen input associated with biochar amendment relative to compost.

The Improved scenario (S3) showed the lowest GWP intensity per unit of harvested rice under the base compost-nitrogen assumption, although this advantage was not retained under the alternative higher-nitrogen assumption.

3.4.3 Background emission factors (diesel, fertilizer proxies)

Because the diesel emission factor was applied uniformly across all four scenarios (Section 2.6), its influence on the comparative ranking between scenarios was necessarily limited; its contribution to total GWP was consistently minor (0.4–1.3% of total, Table 5) across all scenarios and both EF1FR levels. Varying the background factors for urea and phosphate fertilizer production, and the diesel-use assumptions (Table 2), altered absolute GWP values but did not reverse the relative ranking of scenarios, consistent with the robustness observed for EF1FR (Section 3.4.1).

4. Discussion

4.1 Methane dominance under farmer-practice management

Farmer Practice (S1) exhibited the highest seasonal methane emissions of all scenarios (30.40 kg CH_4 ha^{-1}) despite receiving the same synthetic nitrogen input as the Conventional scenario (S2), indicating that its elevated GHG burden was primarily associated with its methane-intensive emission profile rather than fertilizer-related emissions (Section 3.3). This pattern may reflect the influence of the fresh, undecomposed organic amendment characteristic of the farmer-practice treatment: fresh straw and crop residues are consistent with the mechanism whereby readily available carbon substrate promotes methanogenic activity under the anaerobic conditions of flooded rice cultivation, whereas partially decomposed or aerobically processed organic matter is generally associated with lower methane emission (Song et al. 2019). In a multi-site field study, Song et al. (2019) reported that fresh straw incorporated shortly before transplanting increased seasonal methane flux by approximately 120% relative to a no-straw control, considerably more than straw that had undergone aerobic decomposition during the fallow season. This is consistent with the comparatively low methane emissions observed in the Conventional (S2) and Improved (S3) scenarios, which did not receive fresh organic amendments.

The tidal, non-continuously-flooded water regime of the study area may further influence methane dynamics through its effects on soil redox status and the timing of anaerobic conditions relative to organic matter decomposition (Section 1); however, water table depth and redox potential were not measured directly within the foreground experiment, and this interaction cannot be quantified from the available data. Site-specific measurements of soil redox dynamics under tidal wetting–drying cycles, combined with characterization of organic amendment quality, would be needed to establish this mechanism more directly.

4.2 Area-based versus yield-scaled GHG performance: a management trade-off

The comparative ranking of scenarios depended fundamentally on the choice of functional unit. On an area basis, the Low-Input scenario (S4-base) exhibited the lowest cradle-to-gate GWP (425.5 kg CO_2-eq ha^{-1}), reflecting its minimal fertilizer and amendment inputs. However, when emissions were expressed per unit of harvested grain, S4-base ranked only fourth of six scenario variants (327.3 kg CO_2-eq t^{-1}), because its low external input was accompanied by the lowest grain yield of all scenarios (1.30 t ha^{-1}). Conversely, the Improved scenario under its base compost-nitrogen assumption (S3-base) exhibited the lowest yield-scaled GWP (204.6 kg CO_2-eq t^{-1}) despite a comparatively higher area-based burden (695.8 kg CO_2-eq ha^{-1}, rank 4 of 6), because its substantially higher yield (3.40 t ha^{-1}) diluted the per-hectare emissions across a larger harvested output. Neither scenario can therefore be described as unconditionally superior: S4's area-based advantage was contingent on its markedly lower productivity, while S3-base's yield-scaled advantage was itself conditional on the assumed compost-nitrogen content (Section 4.4).

This functional-unit dependency is consistent with previous rice LCA that have reported reversed rankings between area-based and yield-scaled functional units when comparing management intensities. Maruyama et al. (2010) found that a super-high-yield rice production system in Japan generated higher GWP per hectare than a conventional system, owing to greater fertilizer and fuel inputs, but lower GWP per kilogram of brown rice, because the yield increase outpaced the increase in absolute emissions. The present findings extend

this pattern to a tidal acid-sulfate rice system, where the yield-scaled advantage of an intensified, amendment-based scenario over a minimal-input alternative was driven not by lower absolute emissions, but by substantially higher productivity per unit area.

These results indicate that area-based mitigation strategies and production-efficiency mitigation strategies are not necessarily aligned in this system. A scenario that minimises the total field-level GHG burden (S4) is not the same scenario that minimises the GHG cost of the rice actually produced (S3-base), and the appropriate choice between them depends on whether the management objective prioritises total regional emissions from a fixed land area or the GHG intensity of food production.

4.3 Nitrogen inputs as a major emission driver in fertilized scenarios

Across the fertilized scenarios (S2–S4), the combination of direct N_2O and upstream urea production accounted for 63.8–76.4% of total GWP, substantially exceeding the contribution of methane in these scenarios (13.2–30.1%; Section 3.3). This pattern indicates that, in contrast to Farmer Practice, nitrogen-related processes, encompassing both direct N_2O emissions and upstream fertilizer production, became the dominant emission sources once synthetic fertilization was applied at conventional or reduced rates. As shown in Section 4.4, the magnitude of this nitrogen-related burden depended on both the synthetic fertilizer rate and the nitrogen content of any organic amendment applied. The contribution of direct N_2O was itself sensitive to total nitrogen input, rising from 39.1% in the Conventional scenario (S2) to 61.0% in the Improved scenario under its alternative, higher compost-nitrogen assumption (S3-alt), reflecting the additive nitrogen loading from mineral fertilizer and organic amendment combined.

These estimates should be interpreted with the methodological limitations of the Tier 1 approach in mind. The EF1FR-based method applied here provides an aggregate seasonal estimate of direct N_2O emissions from total nitrogen input, but does not resolve the temporal dynamics of N_2O flux in response to tidal drainage cycles, soil redox fluctuations, or interactions between nitrogen form and amendment type; higher-tier, field-measured N_2O data would be needed to characterise these processes directly in this system (Section 2.4.2).

Because upstream urea production and direct N_2O together represented the largest emission sources in S2–S4, nitrogen-use efficiency is a plausible entry point for GHG mitigation in fertilized management systems in this agroecosystem. Improved nitrogen management, such as fertilizer placement methods that reduce N losses while maintaining yield, has been shown to lower yield-scaled GHG emissions in other rice systems; for example, Yao et al. (2017) reported that deep placement of urea, relative to surface broadcasting, reduced yield-scaled GHG emissions from 377 to 222 kg CO_2-eq Mg^{-1} in a ground-cover rice production system in China, primarily through reduced N_2O emissions without yield penalty. This suggests that the relevant management objective in this system is not simply to reduce nitrogen input, but to improve nitrogen-use efficiency while maintaining or increasing yield: reducing synthetic nitrogen losses while maintaining rice yield may therefore offer a potentially important mitigation pathway for the conventional and improved scenarios evaluated here, although this study did not test nitrogen management interventions directly and this conclusion remains to be verified under local tidal acid-sulfate conditions.

4.4 Organic-amendment nitrogen uncertainty constrains the interpretation of compost-based mitigation

The apparent environmental advantage of the Improved scenario (S3) was conditional on the assumed nitrogen content of its compost amendment. Under the base compost-nitrogen estimate (1.456% N), S3 exhibited the lowest yield-scaled GWP of all scenarios (204.6 kg CO_2-eq t^{-1}), 21.1% lower than the Conventional scenario (S2, 259.2 kg CO_2-eq t^{-1}). Under the alternative, higher compost-nitrogen estimate (4.326% N), however, S3's yield-scaled GWP rose to 295.2 kg CO_2-eq t^{-1}, exceeding that of S2 by 13.9%. This reversal illustrates that the comparative environmental performance of compost-based management cannot be established independently of how the amendment's nitrogen content is characterised.

It is important to distinguish the nature of this uncertainty from a statistical confidence interval. The base and alternative estimates were derived from two separate composting trials employing distinct processes, a straw-Purun-manure mixture without bioactivator addition versus a composting process incorporating a bioactivator and lime, rather than from repeated measurements of the same material (Section 2.5). The two values therefore represent scenario-based parameter uncertainty, reflecting genuine variability in compost quality depending on production method, rather than random measurement error around a single true value. This distinction matters for interpretation: the finding is not that the nitrogen content of "the" compost used in S3 is uncertain within a defined

range, but that different, plausible compost production pathways would yield materially different environmental outcomes.

This form of uncertainty is not unique to the present study. Brockmann et al. (2018), in a review of approximately 100 life-cycle assessments involving organic residue application, reported that the nitrogen mineral fertilizer equivalent used to characterise organic amendments is rarely documented in published LCA studies, despite its potential to substantially affect reported results. The present findings reinforce this concern in the context of rice cultivation: without direct characterisation of the specific compost applied in a given production system, the yield-scaled GHG advantage attributed to compost-based management should be regarded as conditional rather than established.

By comparison, the corresponding nitrogen-content uncertainty for the biochar amendment in the Low-Input scenario (S4) produced a substantially smaller relative effect on GWP intensity (5.0%, Section 3.4.2), consistent with the lower total nitrogen input associated with biochar relative to compost application. This suggests that the sensitivity of a scenario's GHG performance to amendment-nitrogen uncertainty scales with the magnitude of the nitrogen input itself, and that scenarios relying on nitrogen-rich organic amendments warrant particular caution in this regard.

4.5 Implications for management of rice production in tidal acid-sulfate environments

The four scenarios evaluated here suggest distinct management implications rather than a single preferred strategy. Farmer Practice (S1) exhibited the highest GHG burden under both functional units, characterised primarily by methane emissions plausibly associated with its fresh organic amendment (Section 4.1); this points toward the quality and timing of organic matter incorporation, rather than fertilizer input, as the most relevant target for emission reduction under this management configuration. The Improved scenario (S3) combined the highest grain yield with the lowest yield-scaled GHG intensity under its base compost-nitrogen assumption, indicating that compost-based amendment may warrant further evaluation as a potentially GHG-efficient strategy for reducing the yield-scaled cost of rice production in this system, contingent on direct characterisation of the nitrogen content of the compost used (Section 4.4). The Low-Input scenario (S4) minimised the area-based GHG burden but did not translate this into the lowest yield-scaled performance, owing to its comparatively low yield; it may therefore be more relevant to management objectives that prioritise minimising total emissions from a given land area than to objectives focused on production efficiency. The Conventional scenario (S2), while not optimal under either functional unit, provides a useful benchmark against which the amendment-based scenarios can be evaluated, and its higher yield-scaled GHG intensity relative to S3-base indicates that fertilizer-only management may not represent the most GHG-efficient option available within this system.

These implications should be interpreted within the scope of the underlying data. The scenarios evaluated represent specific treatment combinations reported in a single field experiment (Annisa and Nursyamsi 2016) rather than a statistical sample of farming practices across Barito Kuala; in particular, Farmer Practice (S1) should be understood as the treatment representing current farmer practice within that experiment, not as a representative average of the diverse practices employed by farmers throughout the region (Section 2.9).

More broadly, management recommendations for rice cultivation in this system cannot be transferred uncritically from evidence based on continuously irrigated, non-acid-sulfate lowland rice, because the tidal hydrology and acid sulfate soil chemistry of Barito Kuala impose agronomic constraints, including periodic Fe toxicity, fluctuating redox conditions, and dependence on tidal water exchange, that are largely absent from those systems (Section 1). Management strategies that appear favourable under controlled irrigation, including some approaches to organic amendment and nitrogen timing, may perform differently under tidal wetting-drying cycles, and this warrants site-specific verification before extrapolation.

4.6 Limitations and future research needs

Several aspects of the present inventory constrain the interpretation of these findings and identify priorities for future site-specific research in this agroecosystem.

The core foreground inventory, comprising methane emissions, grain yield, and fertilizer application rates, originates from a single field experiment conducted at one location (Mandastana, Barito Kuala; Annisa and Nursyamsi 2016). This study is accordingly presented as a site-specific, secondary-data life-cycle assessment model rather than a survey-based inventory representative of regional farming practice (Section 2.9), and its comparative findings should be understood as applying to the specific management treatments evaluated rather than to the full diversity of practices across the region.

Direct nitrous oxide emissions were estimated using the IPCC Tier 1 EF1FR approach, which provides an aggregate seasonal estimate but does not resolve the temporal response of N_2O flux to tidal drainage cycles, soil redox fluctuations, or interactions between nitrogen source and amendment type (Section 4.3). Indirect N_2O emissions arising from volatilisation-redeposition and leaching-runoff pathways were excluded entirely, because the site-specific fractions required for their estimation have not been established for tidal acid sulfate rice systems, and applying generic default values without local validation would have introduced additional unvalidated uncertainty rather than resolved it (Section 2.4.3).

These exclusions and uncertainties do not all point in the same direction. The exclusion of indirect N_2O and herbicide production likely results in some underestimation of total GHG emissions (Section 2.4.3, 2.6.1). However, the additive treatment of biochar-derived nitrogen within the Tier 1 EF1FR framework may not fully capture the documented tendency of biochar amendments to suppress N2O emissions through adsorption and altered microbial activity, which would instead imply a potential overestimation of N_2O for the biochar-amended scenario (S4); and uncertainty in organic-amendment nitrogen content and background emission factors may affect the estimates in either direction (Section 4.4, 3.4.3). Accordingly, the reported GWP values should be interpreted as estimates subject to multiple, not uniformly directional, sources of uncertainty, rather than as strict lower-bound values of total life-cycle GHG emissions.

Nitrogen inputs from organic amendments were subject to substantial uncertainty, most notably for compost nitrogen content (Section 4.4), and the organic-amendment input associated with Farmer Practice (B1, S1) was not quantified in the primary source and was therefore set to zero as an explicit, conservative modelling assumption rather than evidence of its absence (Section 2.3). Herbicide and pesticide inputs were excluded from the inventory entirely, not because they are known to be absent from the regional production system, but because the available regional evidence (a single-farmer observation, unknown active ingredient and formulation) was insufficiently resolved to support even a bounded sensitivity estimate (Section 2.6.1).

Background emission factors for fertilizer production, together with the diesel combustion emission factor, were derived from published literature rather than from a licensed regional life-cycle inventory database, representing single-flow proxy processes for aggregated cradle-to-gate factors rather than a fully resolved background inventory (Section 2.6, 2.7). While these factors were assessed against alternative values without reversing the comparative ranking of scenarios (Section 3.4.3), higher-resolution, Indonesia-specific background data would improve the precision of absolute GWP estimates. The diesel emission factor specifically represents direct combustion emissions only (IPCC 2006), excluding upstream fuel production and distribution; because diesel contributed only a minor share of total GWP across all scenarios (Table 5), this scope simplification is expected to have negligible influence on the comparative results.

These limitations point toward four priorities for future research in this system: site-specific measurement of direct and indirect N_2O emissions under tidal wetting-drying cycles, to replace the Tier 1 estimates used here; direct characterisation of the nitrogen content and mineralisation dynamics of locally used compost and biochar amendments, including the mechanistic effect of biochar on N_2O suppression; field-scale data on herbicide and mechanization practices actually employed by farmers in Barito Kuala; and development of higher-resolution background emission factor databases for Indonesian agricultural inputs. Addressing these gaps would allow future assessments to move from a site-specific, secondary-data model toward a more fully resolved, locally validated life-cycle inventory for rice production in acid sulfate tidal swamplands.

5. Conclusion

This study developed a site-specific, secondary-data LCA of rice cultivation across four management scenarios in the acid sulfate tidal swamplands of Barito Kuala, South Kalimantan, quantifying cradle-to-gate GHG performance on both an area and yield-scaled basis. Farmer Practice (S1) consistently exhibited the highest GHG burden under both functional units, characterised primarily by its high methane emissions, which were plausibly associated with the fresh organic amendment used in this treatment. This suggests that the quality and timing of organic matter incorporation warrant further evaluation as potential emission-reduction targets in traditionally managed systems. Beyond this, no single scenario emerged as unconditionally superior: the Low-Input scenario (S4) minimised area-based emissions but not yield-scaled intensity, owing to its comparatively low yield, whereas the Improved scenario (S3) achieved the lowest yield-scaled GHG intensity under its base compost-nitrogen assumption, although this advantage was not retained under the alternative higher compost-nitrogen estimate. This

dependence on functional unit and uncertain parameters demonstrates that GHG mitigation strategies for rice production in this system cannot be evaluated using a single metric or point estimate, and that area-based and production-efficiency objectives may favour different management choices.

Across the fertilized scenarios, direct nitrous oxide emissions and upstream fertilizer production together accounted for the majority of total GWP, suggesting that improving nitrogen-use efficiency, rather than simply reducing nitrogen input, represents a plausible mitigation pathway warranting further evaluation under local conditions. Because the foreground inventory was derived from a single field experiment and several background and amendment parameters relied on literature-derived proxies, these findings should be interpreted as a site-specific evaluation of the treatments assessed rather than a comprehensive characterisation of regional farming practice. Future research should prioritise direct measurement of N_2O dynamics under tidal wetting-drying cycles, direct characterisation of organic-amendment nitrogen content, and improved resolution of background emission factors to strengthen LCA-based assessment of rice production in acid sulfate tidal environments.

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