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Participatory Approaches to Rice Field Greenhouse Gas Mitigation: Inventory and Farmer Perceptions in Indonesia

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ABSTRACT

This paper presents a combination of a spatial greenhouse gas (GHG) emission inventory and a survey of farmers in North Sulawesi, Indonesia, with the perspective of estimating CH_4 and N_2O emissions of rice paddies by IPCC Tier-2, which reached a peak in 2015 and a decline in 2024, partly due to a conversion of paddy fields and gradual adoption of more sustainable methods. The concentration of the emission lies in the central rice-producing districts. In comparison, a single survey of 148 rice farmers who had already implemented mitigation measures indicates that low-cost interventions (e.g., changing planting schedules, straw composting) are generally acceptable. But 66 percent believe they will lose yield, and 85 percent worry they will lose income. The main focus of all responders is on government subsidies and training; their readiness to mitigate is very conditional on incentives. In nonparametric tests, older and less well-educated farmers are less prepared. Balancing between mitigation measures and the economic reality of the farmers and addressing knowledge gaps is essential. We suggest that the possible fill-in between technically feasible mitigation measures and implementation on farmland could involve economic protection, customized capacity building, and use of demonstration plots.

1. INTRODUCTION

Climate change is complicating a continuum of environmental stressors such as floods, droughts, heat waves, wildfires, water shortages, melting glaciers, and sea level rise, leading to ecosystem changes that trigger species migration or extinction and increase the risk of plant-disease interactions [1]. Rising greenhouse gas (GHG) levels across sectors like agriculture drive these trends. Among the gases emitted by agriculture, methane (CH_4) and nitrous oxide (N_2O) are the most common, with irrigated rice paddies being a significant source. According to estimates from the Intergovernmental Panel on Climate Change (IPCC), rice farming releases about 60 million tonnes of CH_4 annually, accounting for roughly 10-12 percent of the world's total methane emissions [2].

The same can be said of Indonesia, a prominent rice producer; paddies are the basis of national food security but also comprise a significant source of emissions. By excluding forestry and land use, agriculture is the most critical contributor to national GHGs (some 14%); rice farming is the largest: paddies represent approximately 39-40% of agricultural emissions, or tens of millions of tonnes of CO_2, and mitigation in rice systems is a strategic priority [3].

The study of GHGs in paddy fields and mitigation methods has grown exponentially over the last ten years. Uncautious work anticipated biophysical drivers, including continuous flooding, organic matter additions, and other field conditions [4-6]. Indian and Vietnamese studies emphasized the role of residue burning and flooding regimes in influencing methane fluxes [7, 8]. This establishment stimulated the transition to agronomic innovations [9, 10]. Intermittent irrigation, specifically Alternate Wetting and Drying (AWD), was extensively piloted in Southeast Asia; AWD can suppress CH_4 by 30-70% with no risk in yield reduction [11] and can potentially reduce the use of irrigation water by 30% [12]. Simultaneously, fertilizer policies, such as rate manipulation and nutrient rotation, have similarly been demonstrated to inhibit N_2O and CH_4 [13], and field studies of Thailand and Vietnam have shown that fertilizer optimization in conjunction with water management can decrease the carbon footprint without loss of productivity [14-16]. Late in the 2010s, rice-based biochar came into the limelight as another lever; two-year field experiments in eastern China have shown CH_4 reductions up to 86 percent, and an increase in yields of over 13 percent [17, 18]. Still other climate-smart alternatives, such as rice-fish/duck co-cultures, low-emission lines, and direct dry seeding, are increasingly popular [19-21]. Taken together, the literature demonstrates that various agronomic approaches can reduce paddy emissions and enhance water efficiency and soil quality, and usually, they do not cause a reduction in yield [22].

But uptake at the farm level is the ultimate challenge. While the evidence heavily emphasizes technical and biophysical efficacy, it does not thoroughly investigate factors like farmer behavior, social norms, and economic trade-offs [23]. Research on attitudes and perceptions regarding mitigation is scarce, both internationally and in specific country contexts [24]. There is still a lack of knowledge regarding technologies and skepticism regarding their efficacy; the risk of yield and unpredictable economic profits tends to discourage adoption. As a result, there is always a gap between scientific developments and field applications.

Being unable to meet these shortcomings is a problem of external validity. Many experiments are conducted in controlled conditions that do not fully represent a real farm, making it important to explore how water management, cultivar selection, soil types, and fertilization interact under typical constraints. Limited literature on integrative studies in Indonesia combines spatially explicit emission estimates and farmers' socio-economic realities. The streams of research have become decoupled: environmental scientists map emissions and test technologies, and social scientists study perceptions and strategies of adaptation separately, but not simultaneously [6, 22-26].

This paper addresses this gap by combining a spatial GHG inventory of rice paddies with farmers' views in one participatory mitigation framework. We produce geospatial CH_4 and N_2O emissions estimates and maps and survey farmers on their knowledge, perceptions, and preferences of mitigation options, including AWD, organic amendments, and mitigation practices. In contrast to the completely top-down methods, the participatory lens considers farmers as co-creators whose experience and priorities shape the viability of suggestions. The synthesis that follows—matching the most active emissions with those most willing and able to change—is the essence of the novelty and usefulness of our work. Therefore, the study will: (i) approximate and map paddy-field GHG emission and source distribution; (ii) describe the acceptance and perceived limitations of farmers to candidate strategies; and (iii) co-develop a specific, participatory mitigation plan that promotes better environmental performance without violating agronomic and economic realities.

2. MATERIALS AND METHOD

2.1 Study area and setting

The study was conducted in North Sulawesi Province, Indonesia, at the northern tip of Sulawesi Island. It is one of three provinces in Indonesia located north of the equator. Geographically, this region is situated at 0°N-3°N and 123°E-126°E. This region has 11 regencies and four cities (Figure 1).

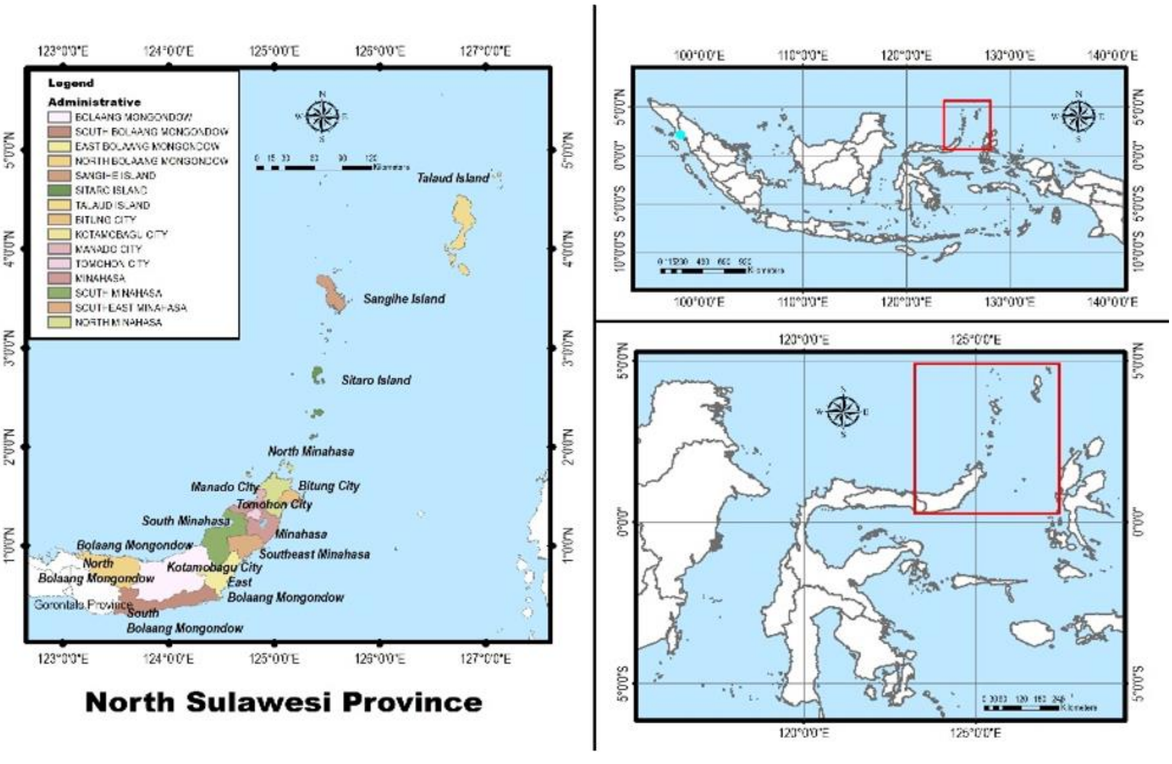

Figure 1. Study area (North Sulawesi, Indonesia)

2.2 Data source

This research uses both secondary and primary data. The secondary data will cover 2010-2024 and will be acquired at the Central Statistics Agency (BPS) and the local agricultural offices. The variables can be the area of rice paddies and other croplands, area harvested, quality and application rates of the fertilizers, and agricultural production per year in North Sulawesi. The 2006 IPCC Guidelines, the 2019 Refinement, and the sources of the Ministry of Environment were used to obtain the emission factors of CH_4, N_2O, and CO_2. These include direct and indirect soil N_2O, CH_4 produced by rice farming, and CO_2 produced by land use and management of rice residues.

Purposive sampling was used to sample primary data, where 148 farmers were sampled based on groups that had already applied mitigation measures in six regencies, namely, Bolaang Mongondow, East Bolaang Mongondow, North Bolaang Mongondow, South Bolaang Mongondow, Minahasa, and South Minahasa. Intentionally, participants were selected based on farmers who had prior experience with at least one mitigation practice, such as changes to the planting schedules and patterns, partial replacement of urea with organic fertilizers, the use of low-emission rice varieties (Mekongga, Inpari 32, IR 67), and intermittent irrigation. These measures are the proven best mitigation measures [27]. Consequently, sample is not representative of the general farming population in North Sulawesi but rather a sub-group of *early adopters*. This selection bias likely results in a more positive outlook on mitigation and a higher readiness for adoption than might be found in the broader farmer population. Therefore, the findings regarding farmer perceptions and attitudes should be interpreted with caution and cannot be directly generalized to all farmers. This study provides insights into the challenges and opportunities for scaling up adoption among already-engaged farmers, rather than an initial assessment of the entire farming community.

A structured questionnaire with 25 statements measured farmers' perceptions on a five-point Likert scale. The tool assessed four variables: knowledge, attitude, technical ease, and willingness to persist with adoption. Some of the items were reverse-coded to make the responses reliable. This integrated data offers socio-economic and temporal-spatial emission factor data required to facilitate participatory mitigation modelling.

2.3 Emission calculation method

The Tier-2 method [28] was used to estimate GHG emissions from 2012 to 2024, as it provides more accuracy compared to Tier-1 because it considers local climate, soil, crop varieties, and management practices. In line with rules provided by IPCC, inventories are calculated as a product of activity data (AD) and emission factors (EF). Most developing nations face two challenges: a lack of ability to collect credible AD and the use of generic IPCC default variables instead of country-specific variables. This research prioritizes local emission factors when they are available (Table A1).

The overall equation is Emission = AD × EF [28], where AD consists of the area of rice paddies, frequency of planting, type of crops, rate of fertilizer, management of irrigation, and use of straw residue. EF represents the factor of each source of emissions. Gases measured are CH_4 in flooded paddies, direct N_2O in managed soils, indirect N_2O in volatilization and leaching, and CO_2 in urea application, residue management, and other land use. All the gases were productively transformed into carbon dioxide equivalents (CO_2-eq) based on their Global Warming Potentials (GWP: $CO_2 = 1$, $CH_4 = 28$, $N_2O = 298$) [28]. The emissions are measured in tonnes CO_2-eq/y (CO_2-eq/y), which serves as a standard benchmark against which the contributions of gases and practices can be compared [29]. The approach provides stronger estimates of the regional inventories and complies with the international reporting standards.

1) CH_4 Emissions from Rice Paddies [30]:

$$E_{CH_4}^{rice} = \sum_i \left[A_i \times EF_c \times SF_{w,i} \times SF_{p,i} \times SF_{o,i} \times \frac{t_i}{365} \right] \quad (1)$$

where,

A_i: planted rice area (ha) for unit/location I;

EF_c: baseline emission factor (continuous flooding, no organic amendment) [1,30 kg/ha/day];

$SF_{w,i}$: scaling factor for in-season water regime (e.g., AWD);

$SF_{p,i}$: scaling factor for pre-season water regime;

$SF_{o,i}$: scaling factor for organic amendment (type and application rate);

t_i: flooded/active cultivation days (day) for i.

2) Carbon dioxide (CO_2) emission from urea and other applications [31]:

$$E_{CO_2}^{urea} = \sum_i \left[M_{urea} \times EF_{urea,i} \right] \quad (2)$$

where,

$M_{urea,i}$: urea applied (kg product/y);

$EF_{urea,i}$: CO_2 emission factor/kg urea.

3) Direct nitrous oxide (N_2O) from managed soils [31]:

$$E_{N_2O,direct} = \sum_i \left\{ \left[\begin{pmatrix} F_{SN,i} + F_{ON,i} + F_{PRP,i} \\ + F_{CR,i} + F_{OS,i} \end{pmatrix} EF_{1,i} \\ + F_{NM,i} EF_{1,FR,i} \right] \times \frac{44}{28} \right\} \quad (3)$$

where,

$F_{SN,i}$: synthetic fertilizer N (kg N/y);

$F_{ON,i}$: organic/compost N;

$F_{PRP,i}$: animal excreta N;

$F_{CR,i}$: crop residue N;

$F_{OS,i}$: soil N stock change;

$F_{NM,i}$: N subject to flooded-rice factor;

$EF_{1,FR,i}$: direct N_2O–N emission factor (flooded rice).

4) Indirect nitrous oxide (N_2O) from managed soils [31]:

$$E_{N_2O,indirect} = \sum_i \left\{ \left[\begin{pmatrix} F_{SN,i}\, Frac_{GASF} \\ + F_{ON,i} Frac_{GASM} \\ + F_{PRP,i}\, Frac_{GASM}) EF_4 \\ +(F_{CR,i} + F_{OS,i} \end{pmatrix} EF_4 \\ + (F_{SN,i} + F_{on,i} +) Frac_{LEACH} EF_5 \right] \times \frac{44}{28} \right\} \quad (4)$$

where,

$F_{SN,i}$: synthetic fertilizer N (kg N/y);

$F_{ON,i}$: organic/compost N;

$F_{PRP,i}$: animal excreta N;

$Frac_{GASF}$: volatilized fraction for synthetic N;

$Frac_{GASM}$: volatilized fraction for organic/excreta N;

$Frac_{LEACH}$: fraction of N leached/runoff;

EF_4: N_2O–N EF for atmospheric deposition;

EF_5: N_2O–N EF for leaching/ runoff.

The approximate GHG emissions will then be spatially analyzed using ArcGIS. Data on attributes of each region (paddy area, CH_4 emissions, and N_2O emissions) will be associated with the spatial data of the district/city administrative boundaries. The resulting maps will visually tackle the difference in emission levels of the regions to enable the identification of areas with a specific rate of emissions.

2.4 Statistical analysis

Descriptive and inferential statistics were analyzed to examine primary data. The answers to the 25-item Likert questionnaire were summarized as percentages of five categories, which gave a picture of farmers' perception. Before the survey, expert review ensured content validity, after which a pilot test was conducted to ensure that items were clear and understandable. Internal consistency was measured using Cronbach's alpha to determine reliability.

In line with inferential analysis, non-parametric analysis was used, according to ordinality measures of Likert data. The Kruskal-Wallis test was used to test the differences between the groups of respondents, with $p = 0.05$. We used Dunn's post-hoc test to detect differences between groups when we detected significant variation. All statistical analyses were conducted on SPSS v.29, whereas ArcGIS facilitated the spatial representation of emission patterns.

3. RESULTS AND DISCUSSION

3.1 Ricefield greenhouse gas (GHG) emission estimation

Eqs. (1)-(4) were used to calculate the emission of each GHG in the rice paddies, utilizing the input data of Tables A1 and 1.

The calculation of the cumulative GHG emission during the estimation period (2010-2024) led to 59,900,252.56 t CO_2-eq. As demonstrated in the results, the total GHG emission of rice fields shows an upward trend in the initial years of the period, but then a steep reduction that started in 2016. In 2010, the total reached 4,787,318.84 t CO_2-eq, which rose to 5,809,353.51 t CO_2-eq/y in 2015. Then the reduction was very steep; by 2018, the emissions had decreased to 3,560,080.89 t and may reach 2,672,436.43 t CO_2-eq/y by 2024 (Figure 2).

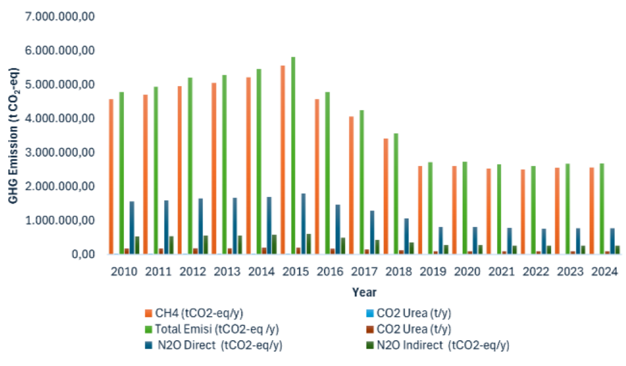

Figure 2. Ricefield greenhouse gas (GHG) emission inventory (2010-2024)

Indonesia's food self-sufficiency policy, which yielded successes in 2017–2018, closely correlated with the increase in emissions until 2015 [32]. The intensification relied on traditional practices, including constant flooding and high use of inorganic fertilizer (Table 1), which overlooked the environmental impact and indirectly increased methane emissions [33].

Table 1. Paddyland area and fertilizer consumption

Year	Ricefield Area (Ha)	Fertilizer (t)		
		Urea	NPK	Manure
2010	119,771.00	23,954.20	35,931.30	79,847.33
2011	122,108.00	24,421.60	36,632.40	81,405.33
2012	126,931.00	25,386.20	38,079.30	84,620.67
2013	127,413.00	25,482.60	38,223.90	84,942.00
2014	130,428.00	26,085.60	39,128.40	86,952.00
2015	137,438.00	27,487.60	41,231.40	91,625.33
2016	112,097.34	22,419.47	33,629.20	74,731.56
2017	98,726.87	19,745.37	29,618.06	65,817.91
2018	82,051.00	16,410.20	24,615.30	54,700.67
2019	62,020.39	12,404.08	18,606.12	41,346.93
2020	61,827.86	12,365.57	18,548.36	41,218.57
2021	59,514.72	11,902.94	17,854.42	39,676.48
2022	58,329.97	11,665.99	17,498.99	38,886.65
2023	59,120.00	11,824.00	17,736.00	39,413.33
2024	58,880.00	11,776.00	17,664.00	39,253.33

Field interviews made the use of fertilizer a recurrent practice. To obtain harvests earlier, farmers often spray more than the recommended amount, thereby contributing to the emission of GHG. This behavior validates previous results that high fertilizer additions increase N_2O and CO_2 emissions.

The recent reduction in rice-paddy land aligns with the overall decrease caused by socio-economic development, leading to land conversion. This decline correlates strongly with the contraction of rice paddy area in North Sulawesi, as shown in Table 2 and visualized in Figure 3 (Data from the Central Statistics Agency (BPS) reveal a 25.4% reduction in rice paddy area from 2015 to 2024.

Table 2. Land-use change statistics for rice paddies in North Sulawesi (2015-2024)

Year	Paddy Field Area (Ha)	Annual Change (%)
2015	137,438	-
2016	112,097	-18.4%
2017	98,727	-11.9%
2018	82,051	-16.9%
2019	62,020	-24.4%
2020	61,828	-0.3%
2021	59,515	-3.7%
2022	58,330	-2.0%
2023	59,120	+1.4%
2024	58,880	-0.4%

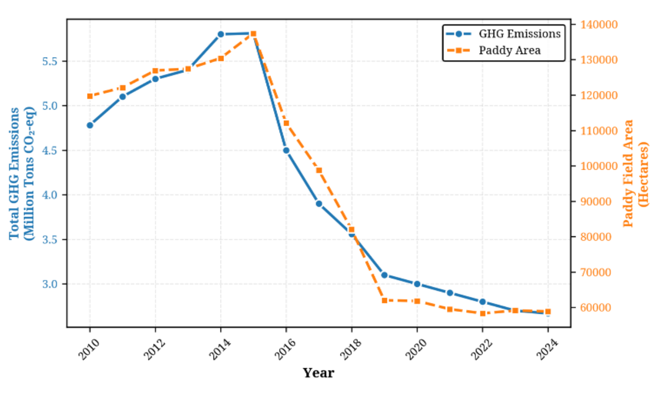

Figure 3. Correlation between GHG emissions and paddy field area in North Sulawesi (2010-2024)

Figure 3 visually illustrates the relationship between the decline in total GHG emissions (blue line, left Y-axis) and the contraction of paddy field area (orange line, right Y-axis). The emissions peak in 2015 coincides with the maximum land area, and the sharp decline thereafter parallels the significant rate of land conversion, providing strong evidence that land-use change is a primary driver of the emissions reduction in the study region.

The increase in the living standard led to housing and infrastructure needs, which contributed to the loss of agricultural land, including 2404 hectares in North Minahasa in 2017 [34]. The rice paddies, primarily in the areas surrounding the urban corridors, are especially prone to these, as flat lands are favorable to settlements, roads, and industrial construction. Changes in the national policy also played a role in the reduction in emissions [35]. By 2020, sustainable agriculture and mitigation programs contributed to a reduction of 11,676.74 Gg CO_2-eq of GHG emissions. These align with the Indonesian target to cut GHG emissions by 26 percent, or 41% with international assistance, by 2030 [36]. Presidential Regulations 61 and 71 of 2011 solidified this agenda by forming national action plans and inventory frameworks.

The production of CH_4 is done under an anaerobic environment in which the methanogenic bacteria feed on decomposed organic matter. There are high positive relationships between fertilization, water availability, and CH_4 and CO_2 (Figure 4) [37]. Nitrogen fertilizer increases the rate of microbial development, leading to a higher decomposition of organic matter and release of gases [38]. In flooded soils, urea hydrolysis forms ammonium, hydroxyl ions, and bicarbonate [39].

The addition of crop residue also enhances the methanogen feedstock. Periodic irrigation has the potential to disturb the anaerobic environment, which can reduce CH_4 formation, and low-emission rice varieties also reduce the emissions [40].

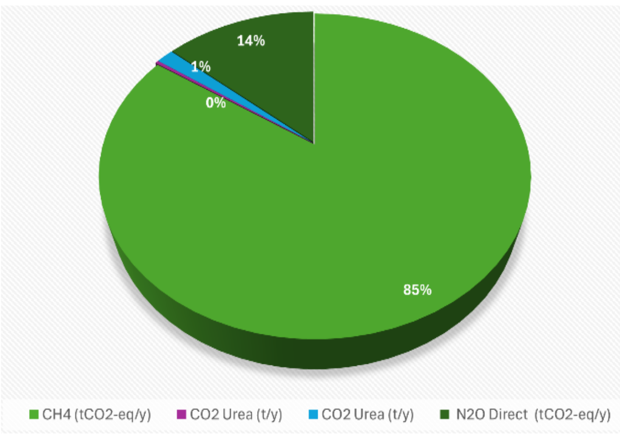

Figure 4. Contribution of CH_4, CO_2, N_2O

Inpari 32, IR 64 and Mekongga varieties exhibit lower methane yields, but availability is regionally and seasonally variable [27].

3.1.1 Uncertainty and sensitivity analysis

Recognizing that GHG inventories involve inherent uncertainty, we conducted a quantitative analysis to assess the confidence level of our estimates. A Monte Carlo simulation (10,000 iterations) was used to propagate uncertainty from activity data (e.g., annual variation in paddy area from BPS data) and emission factors (using the ranges provided in the IPCC 2019 guidelines). The results indicate that the total cumulative emissions over the study period were 59.9 ± 5.2 million t of CO_2-eq, at a 95% confidence interval (Table 3).

Table 3. Monte Carlo simulation results for total cumulative GHG emissions (2010-2024)

Statistic	Value	Unit
Mean	59.90	Million t CO_2-eq
Median	58.12	Million t CO_2-eq
Standard Deviation	5.23	Million t CO_2-eq
95% Confidence Interval (Lower)	50.12	Million t CO_2-eq
95% Confidence Interval (Upper)	69.68	Million t CO_2-eq
Minimum	38.45	Million t CO_2-eq
Maximum	78.92	Million t CO_2-eq
25th Percentile	56.34	Million t CO_2-eq
75th Percentile	63.46	Million t CO_2-eq
Coefficient of Variation	8.73	%

To identify the main drivers of this uncertainty, a sensitivity analysis was performed. As illustrated in Figure 5, the top three parameters that most significantly influence the total uncertainty are: (1) Annual Paddy Field Area, (2) the Baseline Emission Factor (EF_Ref) for CH_4, and (3) the Scaling Factor for Straw Burial (CF_Burial_Straw). This finding highlights the importance of acquiring accurate activity data and developing local-specific emission factors to reduce uncertainty in future GHG inventories.

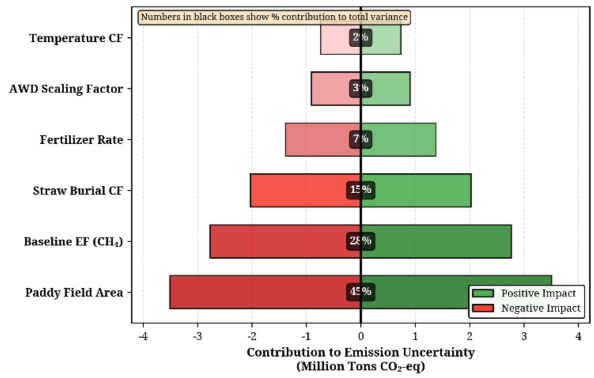

Figure 5. Sensitivity analysis: parameter contributions to total variance in GHG emission estimates

3.2 Emission distribution

The agricultural GHG emissions are not evenly distributed in the regions. Several districts/cities have been pointed out as the main contributors. According to ArcGIS data (with red denoting the most significant source of agricultural emissions, orange and yellow denoting the medium emission, and green denoting the lowest emissions), the Bolaang Mongondow Regency is the most significant source of agricultural emissions in North Sulawesi (Figure 6), with around 583.33 gg CO_2-eq/y, or 38.78% of the total provincial emissions. The other highly emitting districts are South Minahasa (~ 201.47 gg CO_2-eq, 13.4%) and Minahasa (~ 170.38 gg CO_2-eq, 11.3%). The large number of rice paddy fields and the intensity of agricultural activity in these areas contribute to the excessive emissions. These areas are a center of rice production and other food crops. Chemical fertilizers and other production inputs are more intensive than in different regions. The primary sources of GHG in the area are CH_4 emissions produced by rice paddies and N_2O by fertilizers in these districts. This is in line with other past studies that have indicated that the rise in CH_4 emission due to rice is primarily attributed to the expansion of paddy fields [41].

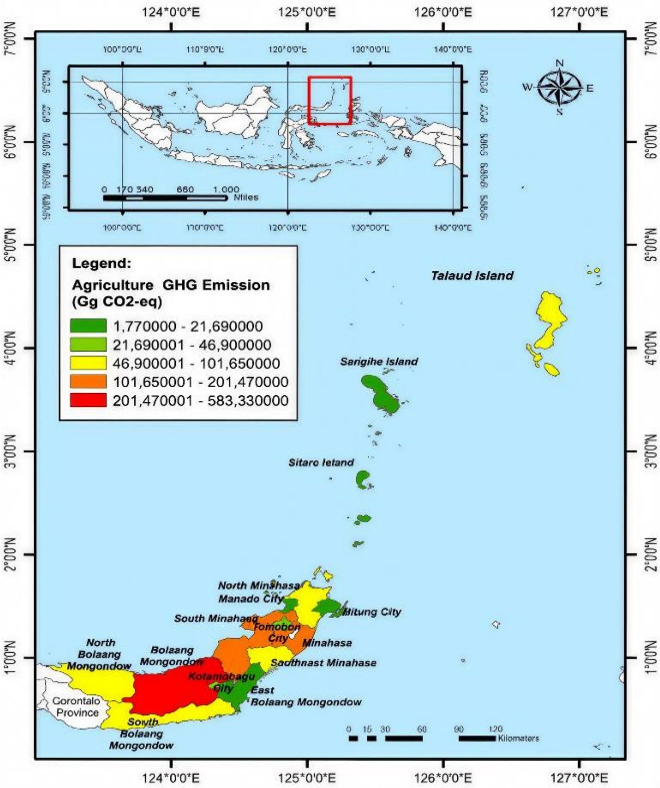

Figure 6. GHG spatial distribution

3.3 Participatory farmer approach

The participatory approach in this study is a method that actively involves the participants themselves (the community or farmers) in the research. Under this approach, farmers are treated as subjects and active participants in identifying and evaluating the mitigation strategies. This concept is based on the idea that direct community participation in the research process will enhance the relevance, acceptance, sustainability, and effectiveness of mitigation implementation. Several farmers' opinions on GHG mitigation and adaptation were gathered through the questionnaire. A detailed discussion of the attitudes of rice farmers toward the various GHG emission mitigation measures they have adopted shows that farmer attitudes and actions vary widely and depend on economic, knowledge, and demographic factors.

In line with the espoused participatory framework, farmer engagement in this research extended beyond mere survey completion. The process included several interactive stages to ensure that farmer voices were meaningfully integrated: (1) Prior to finalizing the questionnaire, we conducted FGDs with representatives from farmer groups. The purpose of these sessions was to co-develop and validate the survey items, ensuring cultural relevance, linguistic clarity, and contextual appropriateness. Farmer feedback was used to revise several technical terms to be more easily understood; (2) Following the initial data analysis, workshops were held in each study district. In these workshops, preliminary findings were presented back to the participating farmers. This process, known as *member checking*, allowed farmers to validate, challenge, or add nuance to the researchers' interpretations, thereby enhancing the validity of the findings; (3) The policy and practice recommendations presented in this study were not derived solely from the researchers' analysis. A significant portion was co-formulated with farmers during the validation workshops. Farmers provided practical input on the feasibility, barriers, and necessary incentives for each recommendation, making them more grounded and actionable.

This multi-stage approach ensured that farmers were not just subjects of the research but active participants who co-shaped the research process and outcomes, consistent with the core principles of participatory research.

3.4 Respondent profile

Based on the data processed from the collected questionnaires, it was found that majority of the respondents fell into the productive age group of 26–55 years (51.35%), the older (above 55 years) group (38.51%), and the youngest age group (under 25 years) (10.14%). 79.05% had a high school education, 18.24% had a diploma, and a mere 2.70% graduated from universities. The IDR 3,000,000-IDR 5,000,000 category (64.86%) was the highest income earner, but 20.95% earned less than IDR 3,000,000, and 14.19% earned more than IDR 5,000,000. They owned 71.62% of the rice, while others owned only 28.38% of the land. Overall, the respondents were mostly of working age, middle-to-lower income, and had moderate education. The level of land ownership illustrates that agrarian independence is relatively high. Still, the level of education and income can limit the farmers' opportunities to employ the latest greenhouse gas reduction technologies and sustainable agricultural innovations.

3.5 Descriptive analysis

This analysis explains how respondents perceived the items of the statement in the questionnaire. To ensure the robustness of the survey instrument, a series of construct validity tests were conducted prior to the main data analysis. The Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy yielded a value of 0.82, indicating that the sampling was 'good' for factor analysis. Bartlett’s test of sphericity was also statistically significant (χ^2 (300) = 2150.4, $p < 0.001$), suggesting that the correlations between items were large enough to proceed with factor analysis. Subsequently, an Exploratory Factor Analysis (EFA) with Varimax rotation was performed, which extracted four latent factors corresponding to the designed dimensions: (1) Knowledge, (2) Attitude, (3) Technical Ease, and (4) Willingness to Continue. These four factors cumulatively explained 68% of the total variance. The Cronbach's alpha for the overall scale was 0.88, and for the individual sub-scales ranged from 0.79 to 0.91, demonstrating excellent internal consistency. These results collectively confirm the validity and reliability of the survey instrument used.

Among the brightest results of Table 4, one may name farmers' high level of concern about the economic effectiveness of mitigation measures. A considerable number of respondents (66.2%) agree that mitigation efforts can reduce rice production, with an even higher majority (85.7%) thinking that such efforts will result in a decline in revenue.

Farmers’ perceptions reflect a substantial psychological and economic barrier to climate change mitigation. Operating on narrow profit margins, they are reluctant to adopt practices perceived as risky to their production or income stability, a finding consistent with studies emphasising the need for financial safeguards in mitigation initiatives [42].

Table 4. Farmers' perceptions of GHG mitigation

No.	Statement	SD (%)	D (%)	N (%)	A (%)	SA (%)
1	GHG mitigation reduces rice production.	0.00	26,20	7.60	42.50	23.70
2	GHG mitigation reduces farmers' income.	0.00	13,15	1.15	48.45	37.25
3	Adjusting planting time.	0.00	0.00	0.00	58.85	41.15
4	Adjusting planting patterns.	0.00	0.00	13.40	35.10	51.50
5	Reduce the use of chemical pesticides.	2.70	28.50	6.00	31.50	31,30
6	Using low-emission rice varieties.	2.00	18.00	4.00	49.80	26,20
7	Substitute urea fertilizer with organic fertilizer.	6.00	39.60	3.40	33.20	17.80
8	Implementing intermittent irrigation in rice fields.	2.00	18.00	29.70	30.30	20.00
9	Do not burn crop residue after harvest.	0.00	0.00	11.50	41.20	47.30
10	Processing plant waste into compost/ animal feed.	0.00	0.00	1970	40.30	40.00
11	Minimize soil processing.	10.00	49.50	30.50	10.00	0.00
12	Processing livestock waste into biogas.	0.00	19.30	38.70	28.80	13.20
13	Agroforestry on agricultural land.	0.00	20.00	20.00	39.80	20.20
14	Climate change mitigation training for farmers is needed.	0.00	3.70	39.30	39.00	18.00
15	Government subsidies are needed to implement mitigation.	0.00	0.00	0.00	20.75	79.25
16	Climate change mitigation training for farmers is needed.	0.00	0.00	0.00	25.70	74.30
17	Climate change mitigation is the responsibility of farmers.	10.00	39.80	20.00	20.20	10.00
18	Mitigation benefits farmers (long term).	0.00	10.00	20.00	49.70	20.30
19	Willing to implement mitigation practices if incentives exist.	0.00	2.00	8.00	59.60	30.40
20	Willing to reduce GHG emissions even without incentives.	10.00	40.50	20.00	19.50	10.00
21	Knowledge of GHG mitigation practices is adequate.	35.00	39.30	15.70	10.00	0.00
22	GHG mitigation is not that important.	29.80	40.20	12.50	17.50	0.00
23	Climate change mitigation increases soil fertility.	0.00	10.00	49.50	30.50	10.00
24	Concerns that agricultural activities contribute to GHG emissions.	10.00	30.30	30.00	19.70	10.00
25	Willing to change farming methods to reduce GHG emissions.	8:30	31.70	30.00	20.00	10.00

Not all practices, however, face equal resistance. Adjusting planting time (100% agreement), modifying cropping patterns (86.6%), and adopting residue management through straw non-burning (88.5%) or composting (80.3%) are highly accepted. These methods align with traditional knowledge, require minimal investment, and often generate tangible benefits such as improved soil fertility. In contrast, techniques demanding structural changes or higher upfront costs—such as minimum tillage (59.5% rejection) or substituting urea with organic fertiliser (45.6% rejection)—encounter greater resistance. This pattern aligns with risk-avoidance theory, where farmers prefer established, proven methods over uncertain innovations [43].

Although most respondents (70%) recognise the long-term importance of climate mitigation, 74.3% acknowledge limited understanding of mitigation practices. This gap between awareness and action suggests that farmers view mitigation as an abstract policy issue rather than a personal responsibility. Nearly half (49.8%) rejected the notion that mitigation lies within farmers' obligations. Furthermore, there was unanimous agreement (100%) that government support—through subsidies and training—is essential for the adoption of low-emission practices. Willingness to implement mitigation strongly depends on economic incentives: 90% expressed readiness if financial support were available, while 50.5% would refuse without it. These findings affirm prior studies showing that adoption hinges not only on willingness but also on farmers' financial capacity and perceived feasibility [44].

3.6 The influence of socio-demographic factors

A deeper analysis of the demographic data, supported by non-parametric statistical tests, reveals that the individual characteristics of farmers play a crucial role in shaping their perceptions and their readiness to adopt mitigation practices. The Kruskal-Wallis test for the age variable yielded a p-value of 0.033, which is statistically significant, with a medium effect size ($\eta^2 = 0.13$), and indicates a meaningful difference in attitudes among age groups (Table 5).

Table 5. Statistical test of farmer socio-demographic

Demographic Variables	Statistical Test	P-Value	Effect Size (η^2 or r)	95% CI for Median Difference	Conclusion
Age	Kruskal-Wallis	0.033*	$\eta^2 = 0.13$	[-1.2, -0.3]	Significant difference with a medium effect size. Farmers >55 years are significantly more reluctant.
Education	Kruskal-Wallis	0.028*	$\eta^2 = 0.15$	[0.4, 1.5]	Significant difference with a medium effect size. Higher education correlates with higher readiness.
Land ownership	Mann Whitney U	0.027*	r = 0.31	[0.2, 1.1]	Significant difference with a medium effect size. Landowners are more ready than tenants.
Income	Kruskal-Wallis	0.127	$\eta^2 = 0.05$	[-0.5, 0.8]	No significant difference in income level.

*Note: $p < 0.05$. η^2 (eta-squared) is reported for Kruskal-Wallis. r (rank-biserial correlation) is reported for Mann-Whitney U. The post-hoc multiple comparison adjustment method used was Dunn-Bonferroni to control the family-wise error rate.

Education also emerged as a distinguishing factor, with a *p*-value of 0.028 suggesting that farmers with higher education levels—diploma or bachelor's degrees—are more prepared to adopt mitigation practices than those with only secondary education. This finding implies that formal education enhances farmers' ability to comprehend and assess agricultural innovations. Land ownership status likewise showed significance; the Mann–Whitney U test returned a *p*-value of 0.027, confirming that landowners exhibit greater readiness to adopt new practices than tenant farmers due to higher land tenure security and autonomy. Meanwhile, the Kruskal-Wallis test for the income variable yielded a p-value of 0.127 ($p > 0.05$) (Table 5), indicating no statistically significant difference in perception across income groups. Nearly all respondents held the same opinion that mitigation measures would lower their income. However, this finding suggests that in this context, non-economic barriers such as knowledge, tradition (as reflected in age), and land tenure security have an influence equivalent to that of financial capacity.

Post-hoc analysis with Dunn-Bonferroni correction clarified that farmers over 55 years old are significantly more reluctant to change (95% CI for median difference: [-1.2, -0.3]) compared to their younger counterparts.

However, it should be noted that purposive sampling in this study has the potential for bias because the selected samples cannot fully represent farmers in North Sulawesi, they are more a subgroup of early adopters. Therefore, the findings on farmer perceptions are specific to early adopters of mitigation practices and caution is needed in generalizing to the broader farming population.

4. CONCLUSIONS AND IMPLICATIONS

4.1 Conclusions

The current research combines spatial greenhouse gas emission inventory and farmer perceptions to develop a comprehensive view of participatory mitigation strategies in North Sulawesi, Indonesia. The spatial analysis indicated that rice paddies' emissions were the highest in 2015 and decreased to 2024 with 59.9 million tons of CO_2-equivalent. Bolaang Mongondow's district became the largest emitter, with a share of 38.78% of provincial agricultural emissions. The time trend shows that the intensity of rice production is necessary for Indonesia to achieve food self-sufficiency, which creates pressure for land conversion and slows the transition to sustainable agricultural development.

The participatory method indicated that economic issues prevail in farmers' decisions, with 66.2% expecting to yield and 85.7% afraid of losing income due to mitigation measures. But different practices were differently accepted. Little costly interventions, such as modifying the planting schedule (100% agreement) and managing crop residues (88.5% agreement), were more accepted, whereas those requiring system-level modification were less acceptable. The statistical analysis revealed that age, education, and land ownership were significant determinants of adoption readiness, where farmers older than 55 years had lower readiness to abandon traditional ways. Amazingly, income had no significant impact, suggesting that factors beyond financial capacity greatly influence adoption decisions and may be non-economic. Farmers unanimously support participating in the government's program, and their adoption of it greatly depends on the availability of incentives.

4.2 Implications and limitations

The evidence shows that effective mitigation implementation requires specific intervention strategies. Low-cost, high-acceptance practices should be the main entry points that policymakers should focus on. Extension programs should be age differentiated, offering older farmers extra support, and youthful farmers should become technology champions. Given the strong correlation between the level of education and adoption preparedness, we can cite capacity building and education as essential investments. We must also tighten the policy for land tenure security to encourage long-term sustainable investments.

Economic protections are essential for the success of programs, as high incomes have demonstrated the necessity for mitigation programs that include protection measures such as yield insurance, price premiums on sustainably produced rice, or direct compensation during transitional periods. Mitigation can be converted to revenue by developing climate-smart agricultural products and using carbon credit schemes or certification schemes to support market development of such products. Community-based methods are necessary because farmers view mitigation as a government responsibility rather than their own, which necessitates personal investment.

Limitations of the study are a small sample size (148 farmers), a geographical focus in North Sulawesi, and purposive sampling, which could have resulted in selection bias. Further studies should undertake longitudinal research, broaden geographical regions, include extensive economic examination, and adopt mixed-method research techniques to comprehend farmers' decisions better and devise more productive participatory mitigation measures.

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APPENDIX

Table A1. Origin and justification of scaling factors used in emission calculations

Scaling Factor	Value	Source	Justification for Use
EF_Ref	1.3	IPCC	IPCC default baseline emission factor for continuously flooded rice fields without organic amendments. Used as the reference value for all scaling adjustments.
GWP_CH_4	28	IPCC AR5 [45]	Global Warming Potential for methane over a 100-year time horizon, used to convert CH_4 emissions to CO_2-equivalents for standardized reporting.
GWP_N_2O	298	IPCC AR5 [45]	Global Warming Potential for nitrous oxide over a 100-year time horizon, used to convert N_2O emissions to CO_2-equivalents for standardized reporting.
CF_Tech_ Irrigation	1	IPCC	Scaling factor for technical irrigation systems with controlled water management. Value of 1 indicates no adjustment from baseline as this represents standard conditions.
CF_Simple_ Irrigation	1	IPCC	Scaling factor for simple irrigation systems. Value of 1 indicates emissions comparable to baseline conditions.
CF_RWH	1	IPCC	Scaling factor for rainwater harvesting systems in swamp rice cultivation. No adjustment from baseline as water regime remains similar.
CF_Cont. Flooding	1	IPCC	Scaling factor for continuously flooded fields. Value of 1 as this represents the baseline condition against which other water regimes are compared.
CF_Weekly AWD	0.8	IPCC	Scaling factor for Alternate Wetting and Drying with weekly drainage intervals. Reduces CH_4 emissions by 20% compared to continuous flooding by limiting anaerobic conditions.
CF_Month-ly AWD	0.85	IPCC	Scaling factor for AWD with monthly drainage intervals. Provides moderate emission reduction (15%) compared to continuous flooding, less effective than weekly AWD.
CF_Rain-fed_Water	0.9	IPCC	Scaling factor for rainfed rice systems. Lower emissions (10% reduction) due to intermittent flooding patterns compared to irrigated systems.
CF_Burnt_ Straw	0.65	IPCC [46]	Scaling factor when rice straw is burned. Significantly reduces CH_4 emissions (35% reduction) as organic matter is not incorporated into soil for anaerobic decomposition.
CF_Burial_Straw	1.5	IPCC [46]	Scaling factor when rice straw is incorporated into soil. Increases CH_4 emissions by 50% due to additional organic substrate for methanogenic bacteria under anaerobic conditions.
CF_Removal_Straw	1	IPCC [46]	Scaling factor when rice straw is removed from the field. No adjustment from baseline as organic input remains at standard levels.
CF_Var_ Mekongga	1	MoEF Indonesia [47]	Scaling factor for Mekongga rice variety. Neutral factor (1.0) indicates standard emission levels for this locally adapted variety.
CF_Var_ Inpari32	0.9	MoEF Indonesia [47]	Scaling factor for Inpari 32, a low-emission rice variety. Reduces CH_4 emissions by 10% through improved root exudate characteristics and reduced substrate for methanogens.
CF_Var_ IR64	1.1	MoEF Indonesia [47]	Scaling factor for IR64 variety. Slightly higher emissions (10% increase) compared to baseline due to higher root biomass and exudation patterns.
CF_Var_ Others	1.05	MoEF Indonesia [47]	Scaling factor for other local rice varieties. Slight increase (5%) in emissions representing the average of various traditional cultivars.
CF_Drying_0_15	1	IPCC	Scaling factor for pre-season drying period of 0-15 days. No adjustment as this represents minimal drying with standard emission levels.
CF_Drying_16_25	0.88	IPCC	Scaling factor for pre-season drying of 16-25 days. Reduces emissions by 12% through oxidation of soil organic matter and reduced methanogen populations.
CF_Drying_26_plus	0.78	IPCC	Scaling factor for pre-season drying exceeding 25 days. Significant emission reduction (22%) due to prolonged aerobic conditions that suppress methanogenic activity.
CF_Tem-perature	1.08	IPCC, BMKG Data	Scaling factor for average temperature of 25-30°C in North Sulawesi. Increases emissions by 8% as higher temperatures enhance microbial activity and methane production rates.
CF_pH	1	IPCC [48]	Scaling factor for soil pH 6-7 in North Sulawesi. Neutral factor as this pH range represents optimal conditions for both methanogenic and methanotrophic bacteria.
CF_C_Or-ganic	1.05	IPCC [48]	Scaling factor for soil organic carbon content of 2-3% in North Sulawesi. Slight increase (5%) in emissions due to additional substrate availability for methane production.
CF_Tex-ture	1	IPCC [48]	Scaling factor for silty loam soil texture in North Sulawesi. Neutral factor as this texture provides moderate drainage and standard anaerobic conditions.

Notes:

- All IPCC references are from the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 4: Agriculture, Forestry and Other Land Use.
- Local data sources include measurements from the Indonesian Meteorological, Climatological, and Geophysical Agency (BMKG) and soil surveys conducted by local agricultural offices.
- MoEF = Ministry of Environment and Forestry, Republic of Indonesia.
- Scaling factors are multiplicative adjustments to the baseline emission factor (EF_Ref) to account for specific management practices, environmental conditions, and crop varieties.

NOMENCLATURE

CH_4:	Methane gas
CO_2:	Carbon dioxide
GHGs:	Greenhouse gases
Gg/y:	Gigagram per year
Gg CO_2-eq/y:	Gigagram CO_2 equivalent per year
GIS:	Geographic Information System
IPCC:	Intergovernmental Panel on Climate Change
N_2O:	Nitrous oxide
t/y:	Tonnes per year
t CO_2-eq/y:	Tonnes CO_2 equivalent per year
Tier-2:	Method of GHG emission estimation (one of three methods from IPCC)