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Quantification of Nitrous Oxide, Methane, and Carbon Dioxide Emissions from Agricultural Machinery in Tropical Lowland Rice Farming Systems

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ABSTRACT

The study quantified nitrous oxide (N_2O), methane (CH_4), and carbon dioxide (CO_2) emissions from key agricultural machineries used in rice farming systems across the tropical lowland regions, particularly Cagayan Valley. Fuel consumption and machinery data were obtained from the Department of Agriculture – Regional Agricultural Engineering Division (DA-RAED). Emissions were estimated using IPCC Inventory Software (2006 Guidelines, Tier 1- 2 methodologies), with disaggregation by machinery, gas, and province. Total emissions from the agricultural machinery under study amounted to 143.66 Gg, dominated by hand tractors (130.71 Gg; 90.99%), followed by four-wheel drive tractors (8.37 Gg; 5.83%), rice combine harvesters (4.37 Gg; 3.04%), mechanical rice transplanters (0.10259 Gg; 0.07%), and precision seeders (0.09703 Gg 0.07%). At the provincial level of tropical lowland settings, Isabela and Cagayan recorded the highest emissions (77.75 Gg; 53.04% and 66.03 Gg; 45.02%, respectively), while Nueva Vizcaya and Quirino accounted for the lowest (1.80 Gg; 1.23% and 1.06 Gg; 0.72%, respectively). These findings highlight the environmental impact of mechanization in rice farming and emphasize the need for climate-smart strategies, including improved energy efficiency, adoption of low-emission technologies, and integration of renewable energy sources.

Keywords: *agricultural machinery, nitrous oxide, methane, carbon dioxide, IPCC inventory software*

Introduction

Rice production is a major contributor to greenhouse gas (GHG) emissions in the Philippines, primarily from irrigated paddy fields that release methane (CH_4), alongside emissions from soil processes, fertilizer use, and mechanized operations (Bautista et al., 2015; Kraus et al., 2022; Maraseni et al., 2009). National estimates of rice-related GHG emissions vary widely, from 13.3 Tg CO_2 eq. yr^{-1} (Bautista et al., 2015) to 1,180 ± 163 Gg CH_4 yr^{-1} (Kraus et al., 2022), with irrigated systems consistently showing higher emissions than rainfed fields. In a tropical lowland setting like Cagayan Valley, rice cultivation alone contributed 80.61 Gg CH_4 in 2021 (Aquino & Galamgam, 2025).

Moreover, field-level mitigation strategies such as alternate wetting and drying (AWD), conservation tillage, and optimized fertilizer application have been extensively studied to reduce CH_4 and N_2O emissions (Kraus et al., 2022; Ryu et al., 2013). However, emissions from agricultural machinery remain poorly quantified, despite the increasing mechanization of rice farming in the Philippines. Farm machinery powered by fossil fuels emits CO_2, CH_4, and N_2O during land preparation, planting, and harvesting (Ryu et al., 2013), yet most research has focused on operational efficiency or adoption rates rather than emissions (De Jesus & Leyesa, 2023; Tado & Bautista, 2022).

Recent studies in other rice-producing regions illustrate both progress and gaps in understanding mechanization-related emissions. In Nigeria, mechanized harvesting and threshing reduced GHG emissions by approximately 1,696 kg CO_2-eq per hectare, largely by reducing post-harvest losses, even after accounting for machinery fuel consumption (2022). In the Mekong Delta, Vietnam, mechanized rice systems produced direct CO_2-eq emissions of ~0.22 ton/ha per cropping season, with additional indirect emissions (~0.02 ton/ha), highlighting the measurable contribution of mechanization to the carbon footprint of rice production (2023). Furthermore, a 2025 study on large-scale mechanized rice systems in the Mekong Delta found that fuel-based emissions increased, but net emissions per ton of rice could decrease by 15.5% through improved water management, fertilizer optimization, land leveling, and straw management. Another recent carbon footprint assessment of smallholder rice farms reported ~5,018 kg CO_2-eq/ha per season (2025), emphasizing variability across system types and management practices.

These studies collectively demonstrate that while mechanization can influence GHG emissions both positively and negatively, there remains a lack of region-specific, comprehensive emission inventories that capture both field and machinery emissions in Southeast Asia, and particularly in the Philippines. Context-specific assessments are needed because mechanization intensity, fuel type, cropping practices, and local environmental conditions differ significantly across regions. In Cagayan Valley—the site of this study—mechanization is among the highest in the country (3.51 hp/ha; Cordero & Park, 2023), yet machinery-related emissions are unquantified. Without this information, national GHG inventories and climate-smart mechanization policies may underestimate the contribution of agricultural machinery to emissions.

Beyond the national context, this study aligns with broader Southeast Asian efforts to decarbonize agriculture. ASEAN countries face rising emissions due to intensified rice production, expanding mechanization, and continued reliance on diesel-powered operations (ASEAN-CRN, 2015). Regional initiatives, including the ASEAN Climate Resilience Network (ASEAN-CRN) and IRRI's carbon-neutrality and methane-reduction programs, highlight the importance of detailed, machinery-specific emission inventories to support mitigation planning and policy formulation (IRRI, 2024; IRRI, 2025; SEARCA, 2023).

To address this gap, the present study expands the existing methane inventory for rice cultivation and livestock in Cagayan Valley (Aquino & Galamgam, 2025) by incorporating emissions from various rice farm machinery. Specifically, it quantifies CO_2, CH_4, and N_2O emissions across machinery types, compares provincial variations, and provides scientific evidence to support climate-smart mechanization. The study also informs policy interventions and contributes to both national and regional GHG mitigation efforts, ensuring that mechanization is integrated into sustainable rice production strategies.

Methods

Data Sources and Research Design

A descriptive–quantitative research design was used to estimate greenhouse gas (GHG) emissions from agricultural machinery in a tropical lowland setting, particularly Cagayan Valley. Secondary data were obtained from the DA-RAED provincial machinery database, which included annual fuel consumption, machinery type, and distribution by province. These datasets were processed using the IPCC Inventory Software (Version 2.98, 64-bit) under the Energy Sector module (1.A.4.c: Off-road vehicles and other machinery).

Table 1. Inventory of GHG from Agricultural Machinery by Type, Gas, and Province (Gg)

Machinery Type	CO_2 (Gg)	CH_4 (Gg)	N_2O (Gg)	Total (Gg)
1. Four-Wheel Drive Tractor	8.37374	0.00047	0.00324	8.37745
2. Hand Tractor	130.65439	0.00734	0.05044	130.71217
3. Mechanical Rice Transplanter	0.10256	0.00000	0.00003	0.10259
4. Precision Seeder	0.09700	0.00000	0.00003	0.09703
5. Rice Combine Harvester	4.37176	0.00023	0.00168	4.37367
Total:	**143.59945**	**0.00804**	**0.05542**	**143.66291**
Province				
1. Cagayan	63.00823	0.00354	0.02432	63.03609
2. Isabela	77.72389	0.00434	0.03001	77.75824
3. Nueva Vizcaya	1.80451	0.00011	0.00069	1.80531
4. Quirino	1.06282	0.00005	0.0004	1.06327
Total:	**143.59945**	**0.00804**	**0.05542**	**143.66291**

Respondents of the Study

Technical personnel and data analysts configured the IPCC Inventory Software, encoded activity data, and performed data validation. Provincial-level datasets were supplied by the Department of Agriculture–Regional Agricultural Engineering Division (DA-RAED), Tuguegarao City, Cagayan.

Locale of the Study

The study was conducted in a tropical lowland setting, particulalry in Cagayan Valley, Philippines, a region recognized as the country's second rice-producing area and the most mechanized with a level of 3.51 hp/ha (Lagare, 2023). Specifically, the provinces of Cagayan, Isabela, Nueva Vizcaya, and Quirino served as the geographical scope of the analysis. The DA-RAED database from this region provided detailed records on agricultural machinery, including tractors, seeders, transplanters, and harvesters. Provincial disaggregation allowed the study to generate localized emission estimates and identify emission hotspots across the region.

Data Collection Procedure

Only the necessary configuration steps of the IPCC Inventory Software were undertaken, which included setting the inventory year, selecting the appropriate fuel type and unit conversions, encoding fuel consumption according to machinery type, and applying the default emission factors specified under the Energy Sector guidelines. The DA-RAED provided annual records detailing machinery type, fuel type, and fuel consumption, which were processed accordingly. Fuel quantities were converted into gigagrams (Gg) using the IPCC default fuel densities before being encoded into the software worksheets for emissions computation.

Data Analysis

Tier 1 and Tier 2 methodologies from the 2006 IPCC Guidelines were applied. The software generated estimates for CO_2, CH_4, and N_2O emissions by gas and machinery type. Results were disaggregated by province to identify spatial variations and emission hotspots. This study adopted a descriptive–quantitative approach consistent with the methodological framework prescribed in the 2006 IPCC Guidelines and the 2019 Refinement for estimating greenhouse gas emissions. The activity data used (fuel consumption and machinery counts) represent complete provincial-level records obtained from DA-RAED, rather than sampled observations. Emission estimates are computed deterministically through the formula Activity Data × Emission Factor, using standardized IPCC coefficients. As such, the analysis does not involve experimental treatments, randomization, or stochastic variation that would warrant the use of inferential statistical tests such as ANOVA. Because the dataset reflects the full population of machinery in the region and the emissions are generated through fixed computational rules rather than sampling-based variability, descriptive statistics and disaggregation are the appropriate analytical tools, in accordance with international GHG inventory practice under UNFCCC reporting.

Ethical Considerations

Ethical standards were upheld with data collection from official and authorized sources only. Prior permission was sought for the use of institutional records, and confidentiality of sensitive data was maintained. No personal or individual-level data were collected. In addition, results were reported objectively and without manipulation to uphold research integrity and transparency.

Results and Discussion

Fuel Consumption (Mass Basis)

The study revealed that agricultural machinery in Cagayan Valley consumed a total of 45.06 Gg of fuel in 2022. Among the machinery, hand tractors accounted for the largest share (41.00 Gg), highlighting their dominant role in land preparation across the provinces. This was followed by four-wheel drive tractors (2.62 Gg) and rice combine harvesters (1.37 Gg). In contrast, precision seeders (0.03 Gg) and mechanical rice transplanters (0.03 Gg) contributed only minimally to overall consumption. From the analysis in Figure 1, it is evident that hand tractors overwhelmingly dominate provincial fuel consumption in the region, with four-wheel drive tractors and rice combine harvesters making up the next significant shares.

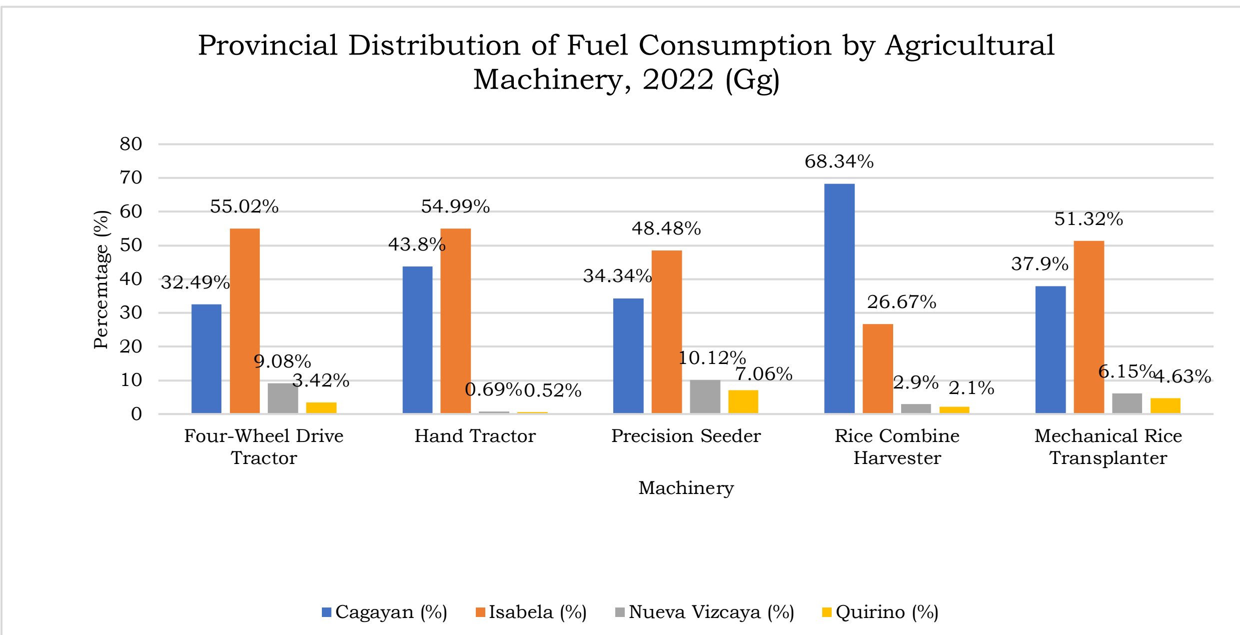

Figure 1. *Provincial Distribution of Agricultural Machinery Fuel Consumption (Gg) and Percentage Share by Machinery Type*

At the provincial level, fuel consumption patterns are summarized in Table 2, with Isabela recording the highest values (24.39 Gg), largely attributable to its extensive irrigated lands and intensive rice cultivation, followed by Cagayan (19.77 Gg). Nueva Vizcaya (0.56 Gg) exhibited moderate consumption, whereas Quirino (0.33 Gg) reported negligible values due to limited mechanization.

Research on farm mechanization in the Philippines reveals significant regional variations and adoption patterns. In Northern Philippines, mechanization levels vary considerably across provinces, with studies showing low overall mechanization in Nueva Vizcaya despite government promotion efforts (Damayon et al., 2025). Isabela demonstrates higher mechanization adoption, particularly for rice combine harvesters, with approximately 90% of rice farmers using this technology, driven by factors including larger farm holdings, higher education levels, and irrigated lowland conditions

(Malanon & Pabuayon, 2022). Hand tractors appear to be widely adopted across regions for land preparation activities. Economic modeling suggests that while mechanization may reduce direct employment, indirect effects and irrigation intensification can partially offset these impacts (Ahammed & Herdt, 1983). Regional studies in Nueva Ecija have examined mechanization's effects on yield, inputs, and cropping intensity across different farming systems (Shields, 1985). The research indicates that topography, farm size, and infrastructure access are key determinants of mechanization adoption patterns.

Table 2. Fuel Consumption (Gg) Dataset for Agricultural Machinery in Different Provinces

Machinery Type	Cagayan	Isabela	Nueva Vizcaya	Quirino	Fuel Consumption
1. Four Wheel Drive Tractor	0.85373	1.44601	0.23851	0.08979	2.62805
2. Hand Tractor	17.96066	22.54999	0.28303	0.21137	41.00505
3. Mechanical Rice Transplanter	0.01220	0.01652	0.00198	0.00149	0.03219
4. Precision Seeder	0.01046	0.01476	0.00308	0.00215	0.03044
5. Rice Combine Harvester	0.93769	0.36587	0.03974	0.02875	1.37205
Total:	**19.77473**	**24.39315**	**0.56634**	**0.33356**	**45.06778**

The predominance of four-wheel drive tractors (4WDT) and rice combine harvesters (RC) in fuel use is consistent with Mandal et al. (2018), who emphasized that heavy-duty tractors and harvesters significantly drive fuel demand in mechanized rice production. These findings suggest that while modernization enhances efficiency, it also intensifies fossil fuel dependence. Future research could explore alternative fuels or hybrid machinery technologies to reduce reliance on fossil fuels, particularly in fuel-intensive provinces like Isabela.

Total Energy Consumption (TJ)

When expressed in energy equivalents, total fuel consumption amounted to 1,937.91 TJ, with hand tractors overwhelmingly dominating at 1,763.22 TJ, followed by four-wheel drive tractors (113.00 TJ) and rice combine harvesters (58.99 TJ). In contrast, mechanical rice transplanters (1.38 TJ) and precision seeders (1.30 TJ) contributed minimally, together accounting for less than 2 TJ. Based on the results in Figure 2, Isabela emerged as the highest consumer (1,048.90 TJ), largely due to extensive use of hand tractors, while Cagayan (850.31 TJ) also exhibited substantial consumption from both hand tractors and rice combine harvesters. Nueva Vizcaya (24.35 TJ) showed moderate values, whereas Quirino (14.34 TJ) registered negligible levels owing to limited mechanization.

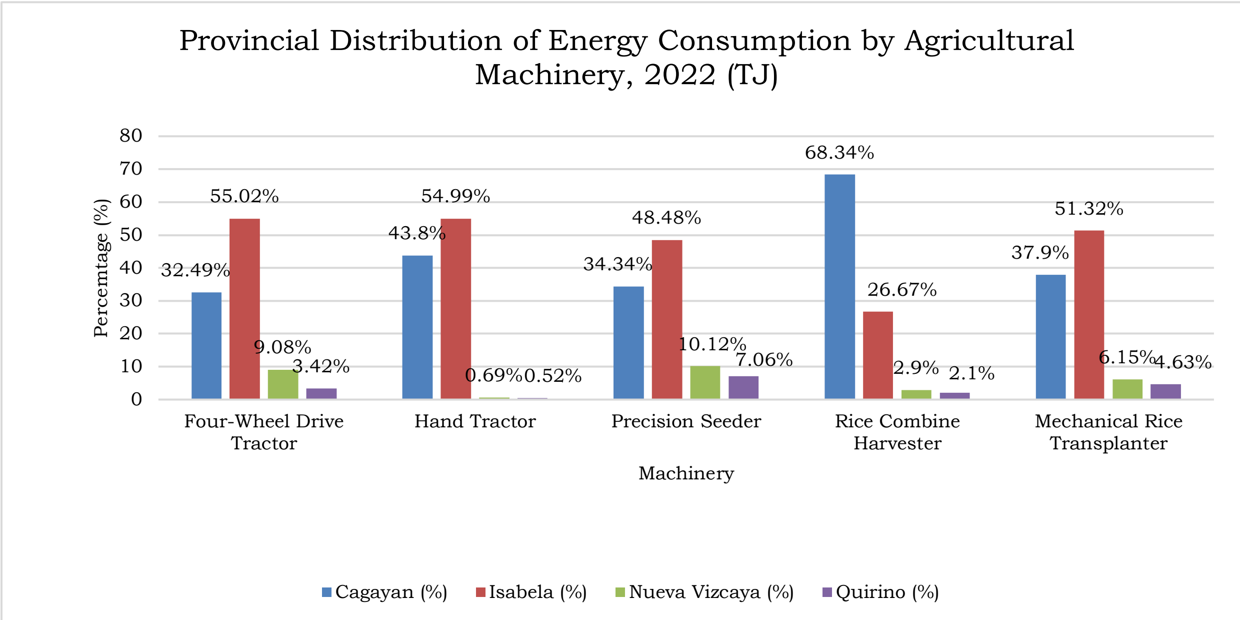

Figure 2. *Provincial Distribution of Agricultural Machinery Energy Usage (TJ) with Percentage Shares*

Agricultural mechanization significantly impacts energy consumption patterns across different regions and farming systems. In the Philippines, provincial energy consumption varies dramatically, with mechanized rice-producing areas like Isabela and Cagayan showing substantially higher energy use than less mechanized provinces (Malanon & Pabuayon, 2022). Rice production systems demonstrate varying energy efficiencies, with manual systems achieving higher output-input ratios (8.50-10.39) compared to mechanized systems, though mechanization reduces labor requirements and climate risks (Bautista & Minowa, 2010). The environmental footprint of agricultural machinery is substantial, with energy demands ranging from 259-685 GJ for tractors and 400-3500 GJ for specialized equipment like harvesters, while carbon steel comprises 30-70% of total energy demand in machinery manufacturing (Mantoam et al., 2020). Precise energy calculations require incorporating specific operational parameters and commercially available machinery rather than relying solely on reference values (Lampridi et al., 2020).

Provincial disaggregation revealed that Isabela accounted for the largest share of the region's total energy consumption (1,048.90 TJ; 54.1%), followed by Cagayan (850.31 TJ; 43.9%), reflecting their vast rice plains and higher levels of mechanization. In contrast, Nueva Vizcaya (24.35 TJ; 1.3%) consumed considerably less energy, while Quirino (14.34 TJ; 0.7%) recorded the lowest share due to limited mechanization. The total energy consumption (TJ) of agricultural machinery by province and type is reported in Table 3, showing that hand tractors overwhelmingly dominated energy use across all provinces. Meanwhile, four-wheel drive tractors (113.00 TJ) and rice combine harvesters (58.99 TJ) also contributed notably, particularly in Isabela and Cagayan during peak cultivation and harvest operations.

Table 3. Energy Consumption (TJ) of Agricultural Machinery by Province and Type in Cagayan Valley

Machinery Type	Cagayan	Isabela	Nueva Vizcaya	Quirino	Total Consumption
1. Four Wheel Drive Tractor	36.71039	62.17852	10.25598	3.86110	113.00599
2. Hand Tractor	772.30822	969.64963	12.17039	9.08890	1763.21714
3. Mechanical Rice Transplanter	0.52451	0.71027	0.08531	0.06398	1.38407
4. Precision Seeder	0.44957	0.63472	0.13223	0.09258	1.30910
5. Rice Combine Harvester	40.32046	15.73250	1.70865	1.23642	58.99803
Total:	**850.31315**	**1048.90564**	**24.35256**	**14.34298**	**1937.91433**

Total Greenhouse Gas Emissions (Gg) by Agricultural Machinery Type

The analysis of greenhouse gas (GHG) emissions from agricultural machinery in Cagayan Valley revealed a total of 143.66 Gg, of which carbon dioxide (CO_2) was the dominant gas (143.59 Gg), followed by minor contributions of methane (CH_4, 0.008 Gg) and nitrous oxide (N_2O, 0.055 Gg). By machinery type, hand tractors overwhelmingly accounted for the largest share (130.71 Gg; 91%), underscoring their intensive use in land preparation across the region. This was followed by four-wheel drive tractors (8.37 Gg; 6%) and rice combine harvesters (4.37 Gg; 3%), while mechanical rice transplanters (0.10 Gg) and precision seeders (0.09 Gg) together contributed less than 1%.

Agricultural machinery represents a significant source of greenhouse gas emissions in rice production systems across various regions. In the Philippines, total GHG emissions from rice production reach 13.3 Tg CO_2 eq. yr^{-1}, with fuel and farming activities contributing 140 kg CO_2 eq. ha^{-1} $crop^{-1}$ in irrigated areas and 111 kg CO_2 eq. ha^{-1} $crop^{-1}$ in rainfed areas (Bautista et al., 2015). Cross-country assessments reveal that farm machinery accounts for approximately 0.018 of total agricultural emissions, while fuels contribute 0.307, with tubewell irrigation systems producing 1.64 times greater emissions than canal systems (Maraseni et al., 2009).

The primary GHGs from agricultural activities include carbon dioxide, methane, and nitrous oxide (Mumu et al., 2024). Advanced methodologies for emission estimation now incorporate satellite data, soil information, and spatial-temporal patterns of machinery usage, enabling high-resolution inventories that better capture real-world emissions from agricultural machinery operations (Zhang et al., 2020). Water-saving techniques like alternate wetting and drying can reduce methane emissions by an average of 36.5-43% (Sander et al., 2016) and with reductions of 73% in the dry season and 21% in the wet season observed in farmer-managed fields (Sander et al., 2020).

As indicated in Figure 3 and detailed in Table 4, the emissions profile highlights the disproportionate impact of hand tractors as the primary source of GHG emissions, with four-wheel drive tractors and rice combine harvesters contributing substantially during peak cultivation and harvest operations in Isabela and Cagayan.

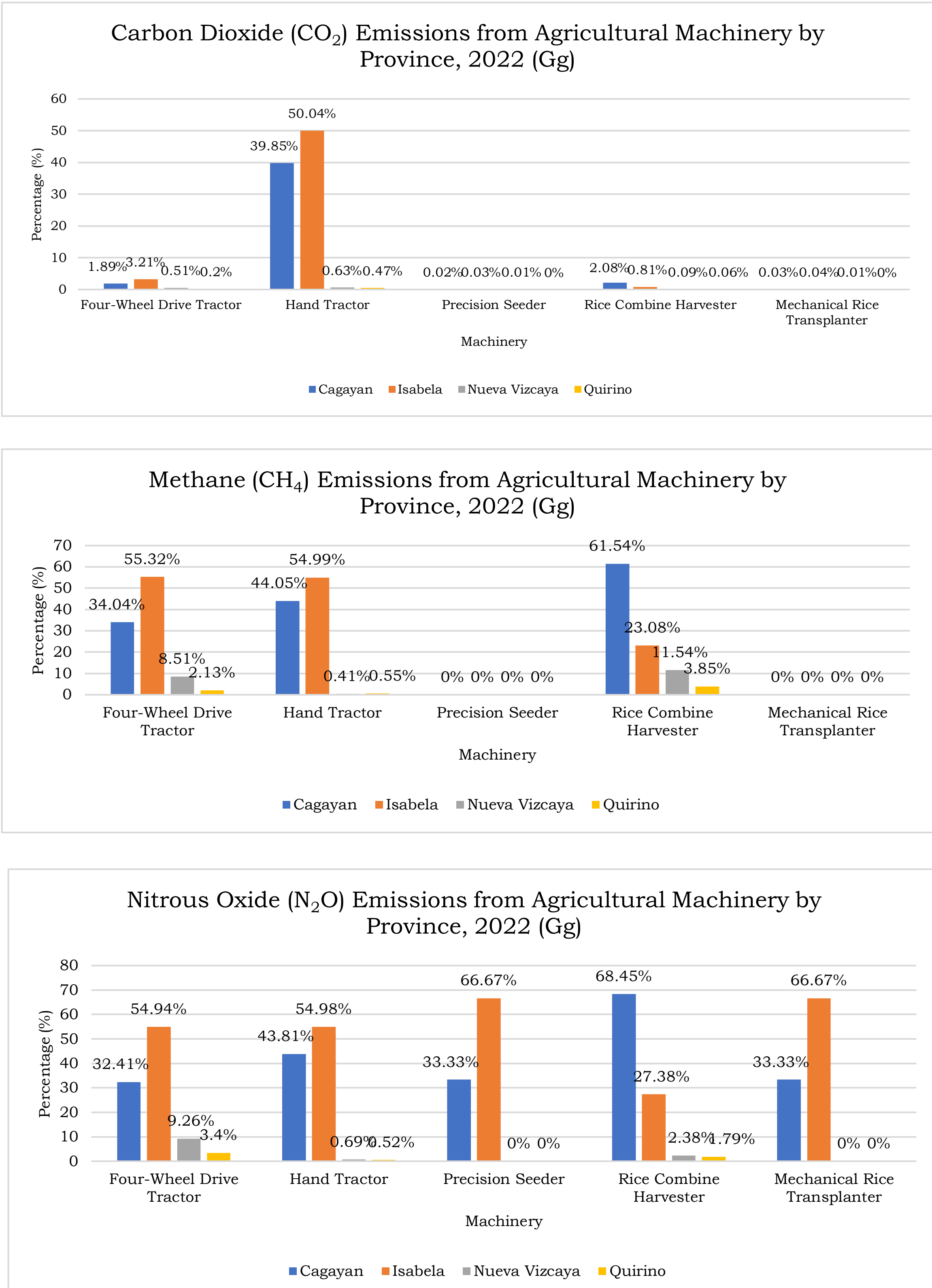

Figure 3. *Comparative Greenhouse Gas Emissions (CO_2, CH_4, and N_2O) of Agricultural Machinery Types in Cagayan Valley*

At the provincial level, Isabela (77.72 Gg) and Cagayan (63.01 Gg) recorded the highest machinery-related emissions, together accounting for more than 98% of the regional total, reflecting their dominance in both fuel and energy consumption. By contrast, Nueva Vizcaya (1.80 Gg) contributed only marginally, while Quirino (1.06 Gg) registered negligible values due to limited mechanization. Emissions inventories detailed in Table 4 indicate that hand tractors overwhelmingly accounted for the largest share across all provinces, underscoring their intensive use in land preparation.

Meanwhile, four-wheel drive tractors (8.37 Gg) and rice combine harvesters (4.37 Gg) also contributed notably, particularly in Isabela and Cagayan during peak cultivation and harvest operations.

Table 4. Inventory of GHG from Agricultural Machinery by Type, Gas, and Province (Gg)

Machinery Type	CO_2 (Gg)	CH_4 (Gg)	N_2O (Gg)	Total (Gg)
1. Four Wheel Drive Tractor	8.37374	0.00047	0.00324	8.37745
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5. Rice Combine Harvester	4.37176	0.00023	0.00168	4.37367
Total:	**143.59945**	**0.00804**	**0.05542**	**143.66291**
Province				
1. Cagayan	63.00823	0.00354	0.02432	63.03609
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4. Quirino	1.06282	0.00005	0.0004	1.06327
Total:	**143.59945**	**0.00804**	**0.05542**	**143.66291**

The contextual comparison across provinces demonstrates that emission patterns are not solely a function of machinery counts or fuel use but are strongly shaped by structural factors. Provinces with larger irrigated lowland areas and widespread mechanization (Isabela, Cagayan) exhibit substantially higher emissions due to intensive cultivation and reliance on tractors and combine harvesters.

In contrast, upland and rainfed provinces with limited mechanization, smaller farms, and reduced access to capital (Nueva Vizcaya, Quirino) show significantly lower emissions. These socio-economic and agro-ecological gradients explain the clear spatial differences in machinery-related GHG emissions across Cagayan Valley as presented in Table 5.

Table 5. Agro-Ecological and Socio-Economic Drivers Influencing Machinery Fuel Use and Emissions in Cagayan Valley Provinces

Province	Topography	Irrigation Coverage & Cropping Intensity	Average Farm Size	Mechanization Adoption Level	Credit/ Capital Access	Implications for Emissions
Isabela	Predominantly lowland plains	High irrigation intensity; 2–3 cropping cycles	Larger than the regional average	Very high; ~90% adoption of combine harvesters; extensive tractor use	High due to cooperative networks and DA investment	Highest emissions due to intensive cultivation, larger farms, and widespread use of mechanized equipment
Cagayan	A mix of plains and rolling terrain	Moderate-high irrigation; 2 cropping cycles	Medium	High, especially for land preparation	Moderate	Second-highest emissions from high-hand tractor use and expanding mechanization
Nueva Vizcaya	Mostly upland and mountainous	Low irrigation; predominantly rainfed	Small	Low mechaniza-tion; limited harvester adoption	Low	Moderate emissions due to topographical constraints and limited mechanization
Quirino	Mountainous, limited flat areas	Very low irrigation; subsistence-level farming	Small	Very low mechaniza-tion; few tractors and harvesters	Low	Lowest emissions resulting from low mechanization and limited cropping area

Conclusion and Future Works

This study provides one of the first comprehensive, machinery-specific assessments of fuel use, energy demand, and greenhouse gas emissions in Cagayan Valley, offering valuable insights into the environmental consequences of agricultural mechanization. The findings underscore the need for policies and practices that balance productivity gains with sustainability goals, highlighting the importance of energy-efficient machinery, low-emission technologies, and renewable energy integration. By establishing a baseline for machinery-related emissions, the study informs climate-smart mechanization strategies and supports regional and national GHG reporting initiatives.

Future research should focus on life-cycle assessments (Eraña et al., 2024) to capture indirect emissions from machinery production, maintenance, and disposal, as well as comparative evaluations to identify low-emission, energy-efficient practices. Long-term monitoring of fuel use and emissions, coupled with socio-economic analyses of adoption behavior and cost-benefit considerations, would further support sustainable mechanization planning. Addressing these areas can guide evidence-based strategies for transitioning toward low-emission, climate-resilient, and environmentally sustainable rice production systems in the Philippines and similar agricultural regions.

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Conflict of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Artificial Intelligence (AI) Declaration Statement

The authors acknowledge the use of OpenAI's ChatGPT in formatting suggestions during manuscript preparation, and Grammarly AI tool for assistance in language refinement, and Scribbr for proper APA citation formatting. The said tools were not used for data analysis, interpretation of results, or the writing of original scientific content. All AI-assisted content was thoroughly reviewed and edited by the authors to ensure accuracy and integrity of the manuscript.