



## **Greenhouse Gas and Air Pollutant Mitigation Strategies for Sustainable Agriculture in Grobogan District, Indonesia**

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### **ABSTRACT**

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This research emphasizes how combined emission reduction approaches play a vital part in developing sustainable farming practices across Grobogan District which represents an important rice-producing region with rising greenhouse gas (GHG) and air pollutant emissions. The intensification of agricultural activities in this region has generated increased methane emissions from rice paddies and nitrous oxide (N<sub>2</sub>O) from fertilizer usage and sulfur oxides (SO<sub>x</sub>) and nitrogen oxides (NO<sub>x</sub>) from diesel-operated farm equipment which damages both environmental conditions and public health. The research focuses on creating a customized climate and air quality mitigation framework that serves the Grobogan District. The emission inventories for the study were developed through IPCC Tier 1 and Tier 2 guidelines, while conventional air pollutant dispersion was modeled using a Box Model approach. The research evaluates the environmental consequences of three low-carbon agricultural methods which include biochar application and alternate wetting and drying (AWD) irrigation and biosolar fuel substitution. The study demonstrates that biochar and AWD implementation results in a 27.5% reduction of total GHG emissions while biosolar substitution lowers SO<sub>x</sub> emissions by 75% and NO<sub>x</sub> by 48.5%. Integrated mitigation approaches demonstrate technical viability and environmental advantages which prove how agricultural development can meet Indonesian climate objectives. The research advances the development of sustainable low-emission agricultural systems which will benefit Southeast Asia.

## **1. INTRODUCTION**

The agricultural industry serves as an essential base for food protection but simultaneously creates substantial environmental harm [1, 2]. Globally, agriculture accounts for 10-12% of global greenhouse gas (GHG) emissions because methane (CH<sub>4</sub>) escapes from rice paddies, while nitrous oxide (N<sub>2</sub>O) emerges from synthetic fertilizer usage, and carbon dioxide (CO<sub>2</sub>) results from mechanized farming operations that use fossil fuels [3]. The increasing use of diesel-powered agricultural machinery has resulted in increasing emissions of nitrogen oxides (NO<sub>x</sub>), sulfur oxides (SO<sub>x</sub>) and particulate matter, which are conventional air pollutants [4]. In Indonesia, these environmental challenges are particularly evident in Grobogan Regency, Central Java, which is recognized as one of the major rice-producing regions contributing to national food supply. Grobogan's agricultural system is characterized by extensive irrigated and rainfed paddy fields, high cropping intensity, and substantial nitrogen fertilizer inputs, which collectively increase the region's emission intensity compared to less intensive agricultural areas [5]. The combination of

excessive urea fertilizer use, uncontrolled crop residue burning, and continuous diesel fuel usage generates rising emissions that endanger both nearby air quality and worldwide climate stability [6]. The country is facing increasing pressure to meet its Nationally Determined Contribution (NDC) goal of 31.89% unconditional GHG emission reduction by 2030 [7]. Regional emission control plays an essential role in supporting national climate objectives and promoting sustainable agricultural development.

Numerous studies have been conducted to determine and minimize agricultural emissions. The Intergovernmental Panel on Climate Change (IPCC) guidelines, including the 2006 and 2019 versions, establish universal methods to calculate emissions for different data resolution tiers [3]. These guidelines serve as a basis for emission inventories that estimate CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O emissions originating from land use, fertilizer application, and rice cultivation. Numerous mitigation strategies have been reported in literature. The alternate wetting and drying (AWD) method as an intermittent irrigation technique reduces CH<sub>4</sub> emissions by 48% by limiting the anaerobic conditions in rice fields [8]. Biochar,

which results from the pyrolysis of organic waste, produces a stable carbon-rich product that simultaneously reduces GHG emissions and benefits soil health [9]. The replacement of diesel with biosolar which is a renewable biofuel obtained from biomass or plastic waste shows great potential to lower NO<sub>x</sub> and SO<sub>x</sub> emissions produced by agricultural machinery [10]. The Box Model and other modeling techniques simulate air pollutant dispersion under atmospheric conditions, which allows researchers to understand the spatial patterns of emissions and their effects on human health [11]. However, existing studies predominantly examine these mitigation measures in isolation or at national scales, with limited attention to their combined effects and limited integration of GHG and conventional air pollutant mitigation at the local agricultural system level.

This study aims to fill these gaps by developing an integrated emission reduction framework specifically tailored to the agricultural characteristics of Grobogan Regency. The novelty of this study lies in its combined assessment of GHG and conventional air pollutant emissions using IPCC Tier 1 and Tier 2 methodologies alongside Box Model dispersion analysis, while simultaneously evaluating three interdependent mitigation strategies—biochar application, AWD, and biosolar fuel substitution—within a single scenario-based framework. Unlike previous studies that focus on individual mitigation options or generalized regional assessments, this research emphasizes the interaction between soil management, water management, and fuel use in an intensive rice-based production system. This research provides concrete findings that directly support policy development at the subnational level for Indonesia's NDC execution.

The research objective is to establish a scientifically robust emission reduction strategy for agricultural operations in the Grobogan Regency, which is suitable for regional implementation. The study has four main objectives: to measure GHG emissions together with conventional air pollutant levels through IPCC standard protocols and national guidelines; to model NO<sub>x</sub> and SO<sub>x</sub> emission spatial patterns by using the Box Model; to analyze three mitigation approaches (biochar and AWD and biosolar) for their environmental impact on reducing GHG and air pollutants; and to provide strategic regional-level policies that promote sustainable agricultural practices with minimal emissions.

## 2. MATERIALS AND METHODS

This study was conducted to create a combined emission reduction plan for Grobogan Regency agricultural operations in Central Java, Indonesia. The research methodology included four main components: (1) GHG emission inventory using the IPCC Guidelines, (2) modeling of conventional air pollutants using the Box Model, (3) data collection of primary and secondary activities, and (4) evaluation of three mitigation strategy scenarios. This sequence of steps enables complete emission evaluation and produces scientifically validated policy suggestions that fit local circumstances.

### 2.1 Study area

The Grobogan Regency is a major rice-producing region with extensive irrigated and rainfed rice fields, as shown in Figure 1. Farming practices in this region include the intensive

use of nitrogen fertilizers, open burning of crop residues, and widespread use of diesel-powered agricultural machinery, all of which contribute significantly to GHG and conventional air pollutant emissions. This study focused on quantifying emissions from these primary agricultural activities and evaluating feasible mitigation interventions.



Figure 1. Study area

### 2.2 Data collection

GHG emissions were calculated using the 2006 and 2019 IPCC Guidelines, applying both the Tier 1 and Tier 2 methods, where appropriate. Tier 1 uses default emission factors (EFs), whereas Tier 2 allows the inclusion of more localized or specific parameters. Activity data for the period 2018–2024 were obtained through a combination of primary field surveys and secondary statistical records to ensure temporal consistency and representativeness.

Primary activity data were collected through structured questionnaires administered to 120 rice farmers across six major rice-producing sub-districts in Grobogan Regency (Godong, Pulokulon, Toroh, Geyer, Tegowanu, and Purwodadi). These sub-districts were selected based on their dominant contribution to total paddy field area and agricultural output. The sample size represents approximately 5–7% of active rice farmers in each selected sub-district and was considered sufficient to capture variations in fertilizer application rates, irrigation practices, and machinery usage patterns. Secondary data were obtained from the Grobogan Regency Agriculture Office, including annual statistics on cultivated area, fertilizer distribution, cropping intensity, and machinery population.

Emissions were calculated for CO<sub>2</sub> (from urea fertilization and liming), CH<sub>4</sub> (from flooded rice cultivation), and N<sub>2</sub>O (from synthetic and organic nitrogen inputs). All emissions were converted to carbon dioxide equivalents (CO<sub>2</sub>-eq) using the IPCC AR5 Global Warming Potential (GWP) values: 1 for CO<sub>2</sub>, 28 for CH<sub>4</sub>, and 265 for N<sub>2</sub>O. The emission load was calculated using the following equation:

$$\text{Emission} = \text{Activity Data} \times \text{Emission Factor}$$

To address measurement uncertainty, this study adopted the uncertainty ranges recommended in the IPCC Guidelines, particularly for Tier 1 EFs, which typically range from ±10% to ±30% depending on the emission source. Variability in activity data, such as fertilizer application rates and diesel fuel consumption, was assessed using descriptive statistics (mean

and standard deviation) derived from farmer survey responses. Although a full Monte Carlo uncertainty analysis was beyond the scope of this study, the combined use of multi-year data, cross-validation with official agricultural statistics, and

conservative IPCC uncertainty ranges provides a reasonable level of confidence in the emission estimates. A summary of the main activity data and EFs used in this study are presented in Table 1.

**Table 1.** Summary of activity data and Intergovernmental Panel on Climate Change (IPCC) emission factors (EFs) used for greenhouse gas (GHG) estimation

Activity	Emission Source	Parameter	Value/ Unit	Emission Factor Source
Urea fertilization	CO <sub>2</sub>	CO <sub>2</sub> per kg urea	0.20 kg CO <sub>2</sub> / kg urea	IPCC 2006 Tier 1
Liming (CaCO <sub>3</sub> )	CO <sub>2</sub>	CO <sub>2</sub> per kg CaCO <sub>3</sub>	0.12 kg CO <sub>2</sub> / kg CaCO <sub>3</sub>	IPCC 2006 Tier 1
Rice cultivation (flooded)	CH <sub>4</sub>	CH <sub>4</sub> per ha/day	1.61 kg CH <sub>4</sub> / ha / day	IPCC 2006 Default
N fertilizer (direct N <sub>2</sub> O emissions)	N <sub>2</sub> O	N <sub>2</sub> O-N per kg N applied	0.003 kg N <sub>2</sub> O-N / kg N	IPCC 2006 Tier 1
N volatilization (indirect N <sub>2</sub> O)	N <sub>2</sub> O	N <sub>2</sub> O-N per kg N volatilized	0.01 kg N <sub>2</sub> O-N / kg N	IPCC 2006 Tier 1
N leaching (indirect N <sub>2</sub> O)	N <sub>2</sub> O	N <sub>2</sub> O-N per kg N leached	0.0075 kg N <sub>2</sub> O-N / kg N	IPCC 2006 Tier 1

### 2.3 Integrated assessment of soil-based and fuel-based emissions

The complete analysis of emissions from agricultural operations requires consideration of land management approaches together with equipment use [12]. The evaluation of emissions from "cropland remaining cropland" employed the gain loss approach from the IPCC Guidelines. The evaluation method includes carbon stock changes resulting from biomass growth and loss, together with emissions from crop residue burning, soil deterioration, and organic soil drainage. Carbon emission calculations for drained organic soils used tropical climate-specific EFs, which were multiplied by land area measurements obtained from satellite-based land classification and regional agricultural statistics. The study calculated conventional air pollutants emissions from diesel combustion specifically NO<sub>x</sub> and SO<sub>x</sub> during tractor operations and other agricultural machinery functions. The emission calculations depended on fuel usage statistics collected during field surveys, combined with EF standards from the Indonesian Ministry of Environment and IPCC default values [13]. A Box Model was used to predict the spatial distribution and ambient levels of these pollutants by simulating the homogeneous mixing of pollutants within a defined air volume. The emission rate, wind speed mixing height, and emission source zone area dimensions were the primary input parameters for this analysis.

### 2.4 Mitigation scenario design

This study examines three mitigation strategies to support emission reduction planning in the Grobogan Regency agricultural sector by evaluating their scientific effectiveness, implementation feasibility, and compatibility with local agricultural practices. These strategies focus on major emission sources, including fertilization, irrigation, and mechanized operations, because they demonstrate significant potential to decrease GHG emissions together with conventional air pollutant emissions. The mitigation scenarios developed in this study represent policy-oriented and technical potential cases rather than assumptions of full or immediate adoption by all farmers. The study modeled each strategy using region-specific activity data paired with EFs and literature-based assumptions, while running scenario simulations for both individual and combined interventions. To account for variability in farmer adoption and practical implementation constraints, a scenario-based sensitivity approach was applied by considering different levels of mitigation uptake (low, medium, and high adoption) rather than assuming idealized, uniform implementation across the entire agricultural area. These adoption levels reflect realistic differences in farmer willingness, access to resources, and institutional support.

**Table 2.** Mitigation strategies for agricultural emission reduction in Grobogan Regency

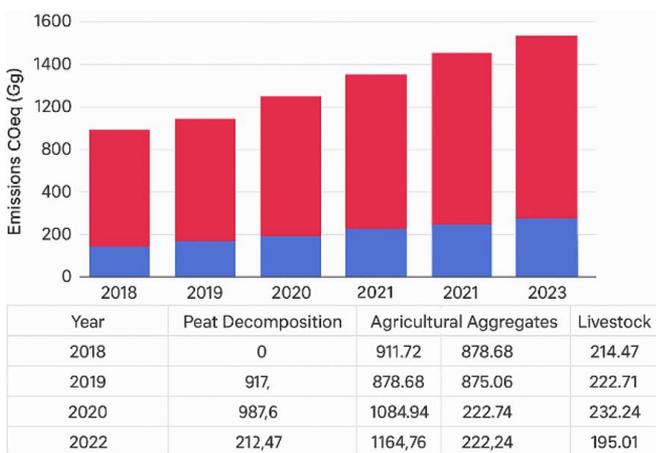
Mitigation Strategy	Mechanism of Action	Targeted Emission Source(s)	Expected Environmental Impact	Implementation Notes
Biochar Application	Application of biochar (produced via pyrolysis of crop residues) enhances soil carbon storage, reduces fertilizer dependency, and suppresses GHG emissions	N <sub>2</sub> O (fertilizer), CH <sub>4</sub> (rice cultivation)	↓ N <sub>2</sub> O and CH <sub>4</sub> emissions; ↑ soil fertility; ↓ synthetic fertilizer demand	Locally sourced from agricultural waste (e.g., rice husks); incorporated during land preparation
Alternate Wetting and Drying (AWD)	Introduces dry periods in rice fields to disrupt anaerobic conditions, thereby lowering CH <sub>4</sub> emissions	CH <sub>4</sub> (flooded paddy fields)	↓ CH <sub>4</sub> emissions by 30–70%; potential ↑ in water use efficiency	Requires control over irrigation frequency; can be implemented with current infrastructure
Biosolar Fuel Substitution	Replaces diesel with renewable biosolar fuel made from biomass or plastic pyrolysis, reducing combustion-related air pollutants	NO <sub>x</sub> , SO <sub>x</sub> (agricultural machinery)	↓ NO <sub>x</sub> and SO <sub>x</sub> emissions; supports renewable energy transition; ↑ waste valorization	Fuel compatibility and regional biosolar production capacity are key success factors

Although a detailed economic assessment was beyond the scope of this study, qualitative considerations related to implementation costs, availability of biochar production facilities, irrigation management capacity for AWD, and access to biosolar fuel were incorporated into the scenario design. The role of policy instruments, such as extension services, input subsidies, and renewable energy incentives, is therefore acknowledged as a key enabling factor for large-scale implementation. Table 2 summarizes the mitigation strategies by describing their mechanisms, targeted emission sources, expected environmental impacts, assumed adoption levels, and key implementation considerations.

### 3. RESULTS AND DISCUSSION

#### 3.1 Greenhouse gas emission inventory

Agricultural activities are a well-established source of GHG emissions, primarily owing to intensive land management practices, synthetic fertilizer use, and anaerobic conditions in flooded rice fields [14]. In Indonesia, the agricultural sector contributes significantly to national GHG totals, particularly through methane (CH<sub>4</sub>) from rice cultivation and N<sub>2</sub>O from soil fertilization [15-17]. These findings align with global assessments by the IPCC (2019), which attribute substantial emissions to paddy systems in Southeast Asia owing to high water usage and organic decomposition [18]. This study conducted a comprehensive GHG inventory for the agricultural sector in Grobogan Regency using the Tier 1 methodology from the 2006 IPCC Guidelines and the 100-year GWP conversion factors from IPCC AR5 (2019). Activity data were obtained from local surveys and secondary sources, provided by the Grobogan Department of Agriculture. A historical analysis of emissions from 2018 to 2023, as shown in Figure 2, shows a clear upward trend, with a sharp increase beginning in 2021. These results reflect a broader pattern reported in regional agricultural intensification studies, where increased fertilizer application and land expansion contributed to greater emission outputs [19].



**Figure 2.** GHG emission trends in the agriculture sector

In 2024, the total GHG emissions from agriculture in the region reached 1,054.13 tons of CO<sub>2</sub>-equivalent (CO<sub>2</sub>-eq). The emission breakdowns are presented in Table 3. The data confirmed that methane emissions from flooded paddy fields and direct N<sub>2</sub>O emissions from nitrogen-based fertilizers were the primary contributors, accounting for more than 93% of the

total agricultural GHG emissions in the region. These findings are consistent with similar studies in Central Java and reinforce concerns regarding inefficient nutrient management and water practices [20]. Although emissions from urea application and liming are relatively minor, they are still relevant to cumulative GHG accounting. The results of this inventory are related to the urgent need for mitigation strategies such as AWD, biochar application, and precision nitrogen management approaches, which have been shown to reduce emissions by 20–50% in field trials [21].

**Table 3.** GHG inventory results of the agricultural sector

No.	Emission Source	Gas Type	Emission (tons CO <sub>2</sub> -eq)
1	Direct N <sub>2</sub> O Emissions from Soil Management	N <sub>2</sub> O	437.31
2	Indirect N <sub>2</sub> O Emissions from Soil Management	N <sub>2</sub> O	14.58
3	Indirect N <sub>2</sub> O Emissions from Runoff and Leaching	N <sub>2</sub> O	32.80
4	Methane from Paddy Field Management	CH <sub>4</sub> → CO <sub>2</sub> -eq	552.38
5	Urea Fertilizer Application	CO <sub>2</sub>	5.08
6	Liming (Agricultural Lime Application)	CO <sub>2</sub>	11.99
<b>Total Emissions</b>			<b>1,054.13</b>

#### 3.2 Conventional air pollutants and dispersion modeling

In addition to GHG emissions, agricultural mechanization in Grobogan Regency contributes significantly to conventional air pollutants, particularly NO<sub>x</sub> and SO<sub>x</sub>. These pollutants primarily originate from the combustion of diesel fuel in agricultural machinery such as tractors. As the adoption of mechanized farming has expanded, fuel consumption has also increased, thus increasing the emission burden on the local air quality. The estimation of NO<sub>x</sub> and SO<sub>x</sub> emissions in this study was based on the bottom-up approach, incorporating district-level activity data (diesel fuel consumption per tractor) and EFs derived from the EMEP/EEA Air Pollutant Emission Inventory Guidebook (2019) [22]. The use of standardized EFs, such as 0.035 kg/L for NO<sub>x</sub> and 0.002 kg/L for SO<sub>x</sub> from diesel combustion, aligns with established methodologies in environmental impact assessments in agriculture [23]. Regency recorded an estimated total diesel consumption exceeding 12 million liters in 2024, driven by the operation of approximately 20,000 tractors. Sub-districts such as Godong and Pulokulon, where agricultural machinery density is the highest, were identified as emission hotspots. These findings are consistent with those reported who noted a strong correlation between mechanized land area and NO<sub>x</sub> emissions in Central Java’s agricultural zones [24]. To assess the spatial dispersion of these pollutants, this study employed a Box Model, which represents a screening-level atmospheric dispersion approach suitable for regions with limited monitoring data and relatively homogeneous terrain. The Box Model estimates average pollutant concentrations within a defined geographical area by assuming uniform horizontal mixing of emissions within a fixed atmospheric boundary layer, while accounting for key meteorological parameters such as wind speed and mixing height. For Grobogan Regency, an average wind speed of 2.5 m/s and a mixing height of 500 m were adopted based on BMKG climatological data.

It is acknowledged that the Box Model does not explicitly

account for complex atmospheric processes such as turbulent diffusion, vertical concentration gradients, or terrain-induced flow variations, which are better represented by advanced dispersion models such as AERMOD or CALPUFF. Consequently, the Box Model results should be interpreted as indicative regional averages rather than precise point-scale concentration predictions. Nevertheless, previous comparative studies have demonstrated that Box Model estimates are generally consistent with Gaussian and Lagrangian dispersion models when applied at the district or regional scale under relatively uniform land-use and meteorological conditions, supporting its application as an initial assessment tool [25]. Although no direct numerical calibration with AERMOD or CALPUFF was conducted, the concentration patterns obtained are consistent with emission hotspot distributions identified in studies using more advanced dispersion models in comparable semi-rural agricultural regions, indicating reasonable model performance for policy-screening purposes [26]. Standard pollution emissions from agricultural equipment pose major risks to the air quality standards within the Grobogan Regency. The combined approach of emission inventories with dispersion models and mitigation scenario evaluations established a complete system for creating environmentally friendly agricultural practices. These findings serve dual purposes by delivering important information for policy development and advancing knowledge about sustainable agricultural growth in the face of climate change and air quality challenges.

### 3.3 Impacts of mitigation scenarios

This section analyzes the projected outcomes of implementing selected mitigation strategies aimed at reducing GHG and conventional air pollutant emissions in the agricultural sector of Grobogan Regency. The mitigation scenarios evaluated in this study incorporated three low-

carbon technologies: biochar application, AWD irrigation, and biosolar substitution for diesel fuel. These interventions target emission sources associated with synthetic fertilizer use, anaerobic rice cultivation, and fossil fuel combustion in agricultural machinery. The rationale for selecting these strategies is based on their compatibility with regional agricultural practices and their demonstrated effectiveness in Southeast Asian agroecosystems. It should be noted that the mitigation outcomes presented in this section represent scenario-based estimates under varying levels of technology adoption rather than assumptions of full or immediate implementation across the entire agricultural system. The projected emission reductions therefore reflect upper-bound mitigation potential, which may vary depending on farmer adoption rates, access to inputs, and supporting policy mechanisms.

Previous studies have reported GHG reductions ranging from 26% to over 40% following the adoption of similar mitigation technologies in rice-dominated farming systems [27]. In this study, the magnitude of emission reduction is explicitly linked to the assumed adoption level of each mitigation strategy, with lower adoption scenarios yielding proportionally smaller emission reductions. To model the effects of these interventions, default EFs were adjusted in accordance with the IPCC (2019) Guidelines and aligned with Indonesia's Enhanced Nationally Determined Contribution (ENDC) targets, which aim to reduce GHG emissions by 29–41% by 2030 [3]. The revised EFs, summarized in Table 4, reflect reductions in N<sub>2</sub>O and CH<sub>4</sub> emissions attributed to improved nutrient management and water regulation, respectively. These adjusted factors were applied consistently across low-, medium-, and high-adoption scenarios to evaluate the sensitivity of total emission reductions to implementation assumptions, thereby providing a more realistic assessment of mitigation effectiveness under practical field conditions.

**Table 4.** Changes in emission factor values for GHG mitigation scenario

Activity	Parameter	Original EF	Adjusted EF (after Mitigation)
Direct N <sub>2</sub> O emissions from fertilization	N <sub>2</sub> O	0.003 kg N <sub>2</sub> O-N/kg input	0.0021 kg N <sub>2</sub> O-N/kg input
Indirect N <sub>2</sub> O from volatilization	N volatilized → N <sub>2</sub> O	0.01 kg N <sub>2</sub> O-N/kg N volatilized	0.007 kg N <sub>2</sub> O-N/kg N volatilized
Indirect N <sub>2</sub> O from leaching/runoff	N leached → N <sub>2</sub> O	0.0075 kg N <sub>2</sub> O-N/kg N leached	0.00525 kg N <sub>2</sub> O-N/kg N leached
Methane from flooded rice fields	CH <sub>4</sub>	1.61 kg CH <sub>4</sub> /ha/day	1.127 kg CH <sub>4</sub> /ha/day
Liming (CaCO <sub>3</sub> )	CO <sub>2</sub>	0.12 kg CO <sub>2</sub> /kg CaCO <sub>3</sub>	0.12 kg CO <sub>2</sub> /kg CaCO <sub>3</sub>
Urea fertilization	CO <sub>2</sub>	0.20 kg CO <sub>2</sub> /kg urea	0.20 kg CO <sub>2</sub> /kg urea

The recalculated emissions, derived using the adjusted EFs and 2024 activity data, revealed a substantial reduction in the total GHG output. The results, presented in Table 5, show a post-mitigation emission total of 764.58 tons CO<sub>2</sub>-eq, representing a 27.5% reduction compared to the pre-mitigation level of 1,054.13 tons CO<sub>2</sub>-eq. These results highlight the mitigation potential of climate-smart agricultural practices in a tropical context. Biochar application not only improved soil nutrient retention but also reduced direct and indirect N<sub>2</sub>O emissions. AWD irrigation is a proven strategy for minimizing CH<sub>4</sub> emissions under intermittently flooded conditions, contributing significantly to emission reduction from paddy fields. Finally, although biosolars did not directly impact GHG emissions in the accounting above (as CO<sub>2</sub> from bio-based fuels is considered biogenic), they were critical for reducing conventional air pollutants. In comparison with similar regional studies, a 27.5% reduction was achieved and a 28–35% reduction in GHGs was reported in paddy systems with

combined biochar and AWD application [8]. From a regional perspective, the effectiveness of these mitigation strategies is closely linked to the specific climatic and agricultural characteristics of Grobogan Regency. The dominance of irrigated rice fields under a tropical monsoon climate provides favorable conditions for AWD implementation, particularly during the main growing season when irrigation control is feasible. However, the widespread reliance on subsidized synthetic fertilizers and the predominance of smallholder farmers may constrain large-scale biochar adoption due to initial production and application costs. Similarly, the mitigation potential of biosolar substitution depends on fuel availability, price competitiveness, and policy incentives supporting renewable energy use in agricultural machinery. These interactions indicate that emission reduction outcomes in Grobogan are not solely driven by technical effectiveness, but also by institutional support, extension services, and economic feasibility at the farm level. Consequently,

integrating mitigation strategies with targeted policy instruments, such as fertilizer management programs, irrigation governance strengthening, and renewable energy incentives will be essential to translate technical mitigation potential into sustained, real-world emission reductions.

**Table 5.** GHG inventory results after mitigation implementation

No.	Emission Source	Gas Type	Emission (tons CO <sub>2</sub> -eq)
1	Direct N <sub>2</sub> O Emissions from Soil Management	N <sub>2</sub> O	306.12
2	Indirect N <sub>2</sub> O Emissions from Soil Management	N <sub>2</sub> O	10.20
3	Indirect N <sub>2</sub> O Emissions from Runoff/Leaching	N <sub>2</sub> O	22.96
4	Methane from Paddy Field Management (AWD)	CH <sub>4</sub> → CO <sub>2</sub> -eq	408.23
5	Urea Application	CO <sub>2</sub>	5.08
6	Liming	CO <sub>2</sub>	11.99
	<b>Total</b>		<b>764.58</b>

### 3.3.1 Greenhouse gas reductions: Biochar and alternate wetting and drying

The implementation of biochar application and the AWD irrigation method represents a strategic intervention to reduce GHG emissions from rice-based agricultural systems in Grobogan Regency. These two approaches target the most significant emission sources identified in the baseline inventory, namely N<sub>2</sub>O emissions from nitrogen fertilization and methane (CH<sub>4</sub>) emissions from flooded paddy fields.

#### *Biochar Application*

Biochar, a carbon-rich material produced through the pyrolysis of organic agricultural residues, functions as both a soil amendment and climate mitigation tool. In this study, biochar was assumed to be derived from rice husks and corncobs, with an application rate consistent with the agronomic recommendations. The incorporation of biochar into soil enhances microbial efficiency and nutrient retention, resulting in suppressed nitrification and denitrification processes that produce N<sub>2</sub>O. As reflected in the adjusted EFs (Table 4), direct N<sub>2</sub>O emissions from fertilization were reduced from 0.003 to 0.0021 kg N<sub>2</sub>O-N/kg N input, while indirect emissions from volatilization and leaching also proportionally decreased. Applying these revised factors to 2024 activity data yielded a reduction in total N<sub>2</sub>O-derived CO<sub>2</sub>-equivalent emissions from 484.69 to 339.28 tons CO<sub>2</sub>-eq. A meta-analysis showed that biochar application can reduce soil N<sub>2</sub>O emissions by an average of 38%, particularly in fertilized systems [28]. The mitigation effects in tropical soils with high nitrogen input conditions are characteristic of Grobogan's irrigated rice fields [29].

#### *Alternate Wetting and Drying (AWD)*

AWD is an irrigation strategy that interrupts continuous flooding by allowing the water table to drop intermittently below the soil surface, thereby suppressing anaerobic decomposition and reducing CH<sub>4</sub> emissions. In this study, the CH<sub>4</sub> EF for continuously flooded fields (1.61 kg CH<sub>4</sub>/ha/day) was adjusted to 1.127 kg CH<sub>4</sub>/ha/day, reflecting the mitigation potential of AWD as outlined in the 2019 IPCC Refinement Guidelines. When applied to the 35,899 hectares of irrigated rice fields in Grobogan, this reduction translated to a CH<sub>4</sub>-derived CO<sub>2</sub>-equivalent emission drop from 552.38 to 408.23 tons CO<sub>2</sub>-eq. Overall, the implementation of AWD achieved a

CH<sub>4</sub> emission reduction of approximately 26%. In Southeast Asia, CH<sub>4</sub> reductions of 20–48% in AWD-managed rice systems, depending on soil type, water regime, and organic matter content [30]. In Indonesia, comparable reductions were observed in West Java when AWD was introduced along with controlled fertilizer application [31]. Together, the adoption of biochar and AWD practices reduced Grobogan Regency's agricultural GHG emissions from 1,054.13 to 764.58 tons CO<sub>2</sub>-eq, representing a total reduction of 27.5%. This significant decline underscores the synergistic effect of integrated soil and water management on emission abatement. Moreover, the mitigation outcomes align with Indonesia's ENDC, which set a target of reducing agricultural GHG emissions by 30% by 2030.

### 3.3.2 Air pollutant reductions: Biosolar substitution

The research paper analyzed both GHG mitigation and air pollutant reduction strategies which focused on SO<sub>x</sub> and NO<sub>x</sub> emissions from agricultural machinery fuel combustion. Diesel-powered tractors that lead mechanized farming in the Grobogan Regency produce significant quantities of these emissions. This study created a hypothetical scenario to replace regular diesel with a biosolar biofuel obtained through the pyrolysis of agricultural biomass. The implementation of this substitution method depends on regional sustainable energy transition goals and Indonesia's agricultural low-emissions commitments. The emission reduction potential was evaluated using EFs adjusted based on contemporary biofuel combustion research. The EFs for diesel combustion started at 0.035 kg NO<sub>x</sub>/L and 0.002 kg SO<sub>x</sub>/L yet biosolar combustion results in 0.018 kg NO<sub>x</sub>/L and 0.0005 kg SO<sub>x</sub>/L emissions. A total of 125,705 liters of estimated diesel consumption in the regency for 2024 was used to generate projected NO<sub>x</sub> and SO<sub>x</sub> emissions under both fuel scenarios (Table 6).

**Table 6.** SO<sub>x</sub> and NO<sub>x</sub> reduction from biosolar

Pollutant	Fuel Type	Emission Factor (kg/L)	Total Emissions (tons/year)
SO <sub>x</sub>	Diesel (baseline)	0.002	269.39
	Biosolar (scenario)	0.0005	67.35
NO <sub>x</sub>	Diesel (baseline)	0.035	4,399.67
	Biosolar (scenario)	0.018	2,263.66

The results indicate a 75% reduction in SO<sub>x</sub> emissions and a 48.5% reduction in NO<sub>x</sub> emissions following the fuel switch. Biosolars derived from palm oil and biomass residues significantly lower particulate and gaseous emissions in off-road diesel engines [32, 33]. Furthermore, emission reductions in small-scale mechanized farms in Central Java highlight the co-benefits of biosolars in terms of both environmental performance and energy security [34]. Importantly, this strategy also aligns with the circular bioeconomy model, as biosolars are produced from locally available agricultural waste. This not only reduces emissions but also adds value to by-products and promotes rural energy autonomy. Despite these promising results, the feasibility of large-scale implementation remains contingent on infrastructure readiness, regulatory incentives, and farmer adoption rates [35]. Further field-based validation and life cycle assessment (LCA) studies are recommended to evaluate long-term

sustainability.

### 3.4 Synthesis: Effectiveness of integrated mitigation

This study implemented a comprehensive mitigation strategy that combined biochar soil treatment with AWD irrigation and switched from diesel to biosolar for significant reductions in agricultural GHG and conventional air pollutant emissions in the Grobogan Regency. The multi-pronged strategy combines different interventions that create mutual benefits for climate protection and air quality improvement, while preserving agricultural output [36]. The implementation of biochar and AWD led to a total GHG emission reduction from 1,054.13 tons of CO<sub>2</sub>-equivalent (CO<sub>2</sub>eq) to 764.58 tons CO<sub>2</sub>eq in 2024 which equals a 27.5% decrease or 289.55 tons CO<sub>2</sub>eq. The emission decreases occurred mainly from lower direct and indirect N<sub>2</sub>O emissions because biochar stabilized the soil while maintaining better nitrogen use efficiency, and the intermittent irrigation methods of AWD reduced CH<sub>4</sub> emissions. GHG mitigation achieved by combining AWD with biochar for East Asian rice fields demonstrated similar effectiveness in paddy field environments [8]. The soil retention of carbon and N<sub>2</sub>O flux reduction abilities of biochar are most effective in croplands that receive intensive fertilization [37, 38]. In parallel, the substitution of fossil-based diesel fuel with biosolar renewable fuel derived from biomass pyrolysis has yielded notable reductions in conventional air pollutants [39]. SO<sub>x</sub> emissions declined from 269.39 tons to 67.35 tons (a 75% reduction), while NO<sub>x</sub> emissions decreased from 4,399.67 tons to 2,263.66 tons (a 48.5% reduction). The reduction in off-road diesel engines operating on biodiesel blends further substantiates the biosolar's potential as a cleaner combustion alternative in mechanized agriculture [40]. Beyond quantitative reductions, the integrated strategy aligns with Indonesia's Enhanced ENDC, which target a 29–41% GHG reduction by 2030. It also supports multiple Sustainable Development Goals (SDGs), including SDG 13 (Climate Action), SDG 7 (Affordable and Clean Energy), and SDG 12 (Responsible Consumption and Production). Additionally, the approach is grounded in practical feasibility: biochar production can be decentralized using farm-scale pyrolysis units, AWD is compatible with the existing irrigation infrastructure, and biosolar adoption requires only minor engine adjustments.

Despite these technical advantages, the long-term effectiveness of the integrated mitigation strategy in Grobogan Regency is strongly influenced by local climatic conditions, agricultural structure, and enabling policy frameworks. The tropical monsoon climate and dominance of irrigated rice systems create favorable conditions for AWD adoption; however, seasonal water variability and irrigation governance capacity may affect consistent implementation. Biochar application, while technically effective, faces economic barriers related to initial production costs and labor requirements, particularly among smallholder farmers who dominate Grobogan's agricultural landscape. Similarly, the adoption of biosolar fuel depends on price competitiveness, supply chain availability, and government incentives supporting renewable energy use in agricultural machinery. These findings suggest that translating mitigation potential into sustained emission reductions requires complementary policy instruments, including targeted extension services, fertilizer and biochar incentives, irrigation management support, and renewable energy subsidies. Integrating technical

mitigation measures with institutional and economic mechanisms is therefore essential to ensure scalable and durable emission reduction outcomes at the regional level.

### 3.5 Policy and economic implications for mitigation implementation

The effectiveness of agricultural emission mitigation strategies in Grobogan Regency is not determined solely by their technical performance, but also by policy support, institutional capacity, and economic feasibility at the farm level. Although biochar application demonstrates strong potential for reducing N<sub>2</sub>O emissions and improving soil quality, its large-scale adoption is likely to be influenced by production costs, labor requirements, and access to processing facilities. In regions dominated by smallholder farmers such as Grobogan, policy instruments including organic fertilizer subsidies, integration of biochar production with agricultural waste management programs, and technical assistance through extension services are essential to lower adoption barriers and enhance economic viability. Similarly, the implementation of AWD irrigation is closely linked to local irrigation governance and farmer coordination. While Grobogan's extensive irrigated rice systems and tropical monsoon climate provide favorable conditions for AWD adoption, seasonal water variability and limited irrigation control during dry periods may result in partial or inconsistent implementation. Strengthening water user associations, improving irrigation scheduling, and expanding farmer training programs are therefore critical to ensuring the sustained effectiveness of AWD as a methane mitigation strategy.

The adoption of biosolar fuel substitution for agricultural machinery presents additional economic and policy considerations. Although biosolar offers substantial reductions in NO<sub>x</sub> and SO<sub>x</sub> emissions, its uptake depends on fuel price competitiveness, supply chain availability, and regulatory incentives supporting renewable energy use in the agricultural sector. For small-scale farmers, the economic attractiveness of biosolar is strongly influenced by fuel subsidies, distribution infrastructure, and compatibility with existing machinery. Government incentives for renewable fuels and rural energy transition programs could therefore play a decisive role in scaling up biosolar adoption and maximizing air quality co-benefits. These findings indicate that achieving sustained emission reductions in Grobogan Regency requires an integrated approach that combines technical mitigation measures with supportive policy frameworks and economic instruments. Aligning climate mitigation strategies with agricultural development policies, extension services, and energy incentives will be essential to translate mitigation potential into long-term, real-world emission reductions at the regional level.

## 4. CONCLUSION

Research shows that farming operations in the Grobogan Regency produce major GHG emissions, together with conventional air pollutants. The combined emission analysis showed that flooding rice fields and applying nitrogen fertilizers produce most GHG emissions and diesel machinery operation produces significant NO<sub>x</sub> and SO<sub>x</sub> emissions. The application of biochar amendment together with AWD and biosolar substitution resulted in substantial emission

reduction. The application of mitigation strategies led to a 27.5% reduction in GHG emissions and a 75% and 48.5% decrease in SO<sub>x</sub> and NO<sub>x</sub> emissions respectively. The data proves that using soil management together with water management and energy management creates effective environmental impact reduction while maintaining agricultural production levels.

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## APPENDIX

### A. Detailed emission calculation procedures

#### A.1 General emission calculation framework

GHG emissions in this study were calculated in accordance with the IPCC 2006 Guidelines and the 2019 Refinement using activity data and corresponding EFs. The general equation applied for all emission sources is:

$$E = AD \times EF$$

where,

E: emissions (kg gas or kg CO<sub>2</sub>-eq),

AD: activity data (e.g., cultivated area, fertilizer input, fuel consumption),

EF: emission factor associated with the activity.

All GHG emissions were converted to carbon dioxide equivalents (CO<sub>2</sub>-eq) using the 100-year GWP values from IPCC AR5:

CO<sub>2</sub> = 1, CH<sub>4</sub> = 28, and N<sub>2</sub>O = 265.

#### A.2 Methane (CH<sub>4</sub>) emissions from rice cultivation

Methane emissions from flooded rice fields were estimated

using the IPCC default daily emission factor for continuously flooded rice cultivation:

$$EF_{CH_4} = 1.61 \text{ kg CH}_4 \text{ ha}^{-1} \text{ day}^{-1}$$

Annual methane emissions were calculated using:

$$E_{CH_4} = EF_{CH_4} \times A \times D$$

where division by 1000 converts kilograms to tons.