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Field evaluation of activated carbon-based soil amendment and greenhouse gas monitoring for sustainable jasmine rice cultivation in central Thailand

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Abstract: Sustainable rice cultivation requires field-based strategies that reduce environmental impacts while maintaining crop productivity. This study presents an exploratory field evaluation of activated carbon-based soil amendment formulations combined with greenhouse gas monitoring in jasmine rice cultivation in Nakhon Luang District, Phra Nakhon Si Ayutthaya Province, Thailand. Six treatment-level field plots were evaluated using Khao Dawk Mali 105 rice, including a no-amendment control, urea fertilizer 46-0-0, and activated carbon-based amendments containing 2%, 4%, 6%, and 8% activated carbon. Four 2 m × 2 m subplots within each treatment plot were used as within-plot sampling locations and were not treated as independent field replicates. Greenhouse gases were monitored using a closed chamber method coupled with a GASERA ONE gas analyzer, while heavy metals in soil and white rice grain were analyzed using atomic absorption spectrophotometry. The AC-based amendment 6% treatment showed the lowest observed CH_4 response, whereas the AC-based amendment 4% treatment showed the lowest observed N_2O response and lower Pb and Cr concentrations in white rice grain. The AC-based amendment 8% treatment produced the highest yield at 1,582.53 kg ha^{-1}. These findings provide preliminary field evidence and require confirmation through fully replicated field trials.

Keywords: *Activated carbon, Greenhouse gas monitoring, Heavy metals, Jasmine rice, Soil amendment, Sustainable agriculture.*

1. Introduction and Problem Statement

Rice cultivation is one of the most important agricultural activities for food security and rural livelihoods, particularly in Asia, where rice remains a major staple crop [1]. However, conventional flooded rice cultivation is also associated with environmental concerns, especially greenhouse-gas emissions. Methane (CH_4) is mainly produced through the anaerobic decomposition of organic matter in submerged paddy soils, where methanogenic microorganisms become active under oxygen-limited conditions [2, 3]. Nitrous oxide (N_2O) may also be released through nitrification and denitrification processes under changing soil moisture and aeration conditions. In addition, nitrogen-fertilizer application, including urea fertilizer, can influence soil-nitrogen transformation and contribute to greenhouse-gas emissions from managed agricultural soils [4]. Therefore, improving soil-management practices and optimizing agricultural inputs are important strategies for reducing the environmental impacts of rice cultivation while maintaining crop productivity.

Greenhouse gas emissions from rice fields are influenced by several interacting factors, including water management, organic matter availability, nitrogen fertilizer application, soil properties, and crop growth stage [5]. Fertilizer management is particularly important because nitrogen input can affect both crop productivity and N_2O emissions, while flooded soil conditions strongly influence CH_4 generation [6, 7]. These relationships indicate that field-specific evaluation is necessary, especially under local agricultural conditions where soil characteristics, irrigation practices, and fertilizer use may differ among production areas. Practical mitigation strategies for rice cultivation should therefore

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consider not only greenhouse gas reduction but also soil quality, yield performance, and field applicability [8].

Soil amendments have been widely investigated as practical approaches to improve soil properties, enhance nutrient retention, and reduce environmental risks in agricultural systems. Carbon-based amendments, such as biochar and activated carbon, are of particular interest because of their porous structures, high surface areas, and potential ability to influence nutrient availability, microbial activity, soil physicochemical properties, and contaminant immobilization [9, 10]. Previous studies have reported that biochar application can affect soil greenhouse gas fluxes, including CO_2, CH_4, and N_2O, although the direction and magnitude of these effects depend on feedstock type, amendment properties, application rate, soil conditions, and water-management practices [11, 12]. Biochar has also been reported to influence methane emissions from flooded or paddy soils, but its effectiveness can vary substantially depending on field conditions [10].

Field studies in rice systems have shown that carbon-based amendments can influence greenhouse gas emissions and rice productivity. For example, biochar amendment in rice paddies has been reported to affect rice yield and CH_4 and N_2O emissions, although responses may differ depending on soil and amendment conditions [13]. A regional meta-analysis of East Asian paddy fields reported that biochar application can reduce methane emissions and improve crop yield under certain conditions [14]. In tropical paddy soil, rice straw-derived biochar has also been reported to mitigate methane emissions and global warming potential while improving rice productivity [15, 16]. These findings suggest that carbon-based soil amendments have potential for sustainable rice cultivation, but their effectiveness remains highly dependent on site-specific conditions and application rates.

In addition to greenhouse gas mitigation, carbon-based soil amendments may support safer rice production by reducing the mobility and bioavailability of certain heavy metals in paddy soils. Biochar has been reviewed as a promising material for contaminant management in soil and water because of its adsorption capacity and effects on soil chemical properties [17, 18]. In paddy systems, recent field research has shown that biochar- and activated carbon-based amendments can reduce bioavailable cadmium in soil and decrease cadmium accumulation in rice grains through changes in soil pH, organic carbon, cation-exchange capacity, and metal fraction transformation [19]. However, activated carbon may perform differently from conventional biochar depending on its source, structure, application rate, and interaction with other soil-conditioning components. Therefore, field-based evaluation is needed before activated carbon-based soil amendment can be recommended as a practical soil management approach for rice cultivation.

Environmental gas monitoring is another important component in assessing the sustainability of rice cultivation systems. Field-based gas measurement allows researchers to observe greenhouse gas behavior under actual cultivation conditions and to link soil management practices with gas emissions from the soil–plant system. Photoacoustic gas analyzers such as the GASERA ONE platform can support high-sensitivity monitoring of greenhouse gases, including methane and nitrous oxide, and are suitable for environmental gas assessment [20]. Integrating soil-amendment application with greenhouse-gas monitoring can, therefore, provide a more comprehensive understanding of sustainable rice-field management.

Although previous studies have examined soil amendments, biochar application, heavy metal immobilization, and greenhouse gas emissions in rice cultivation, limited research has integrated activated-carbon-based mixed soil amendment with closed-chamber greenhouse gas monitoring in actual jasmine rice cultivation fields in Thailand. In particular, there is still insufficient field evidence comparing different activated-carbon proportions in a soil amendment formulation with a no-amendment control and a conventional urea-fertilizer treatment. This research gap limits the development of practical soil-amendment strategies for low-carbon and environmentally responsible rice production.

The novelty of this study lies in its integrated field-based approach combining activated carbon-based soil amendment formulation and greenhouse gas monitoring under actual rice cultivation conditions in Nakhon Luang District, Phra Nakhon Si Ayutthaya Province, Thailand. A six-treatment field experiment was designed to compare a no-amendment control, a urea fertilizer treatment, and activated carbon-based soil amendment formulations containing 2%, 4%, 6%, and 8% activated carbon. Greenhouse gases, including CO_2, CH_4, and N_2O, were monitored using a closed-chamber method coupled with a GASERA ONE gas analyzer. This design allows the effects of activated carbon proportion on greenhouse gas behavior, soil properties, heavy metal accumulation, and rice yield to be assessed under real agricultural conditions.

Therefore, this study aims to evaluate the effects of activated-carbon-based soil-amendment formulation combined with greenhouse-gas monitoring on sustainable jasmine-rice cultivation. The experiment compares rice plots without amendment, plots treated with urea fertilizer, and plots treated with different activated-carbon proportions in the soil-amendment formulation. The findings are expected to provide useful information for developing appropriate soil-amendment strategies, reducing environmental impacts, and supporting sustainable rice production in Thailand.

2. Materials and Methods

2.1. Study Area and Experimental Site

The field experiment was conducted in actual rice cultivation fields located in Nakhon Luang District, Phra Nakhon Si Ayutthaya Province, Thailand. The study area represents a typical lowland rice cultivation system in central Thailand, where rice is commonly cultivated under flooded or semi-flooded field conditions. The experiment was carried out from October 2025 to February 2026, covering the rice-growing period from planting to harvesting. The location of the study area and the experimental field layout are shown in Figure 1. Six treatment plots were established in the field, corresponding to the no-amendment control, urea fertilizer treatment, and activated carbon-based soil amendment treatments with different activated carbon proportions.

Figure 1.
(a) Location of the study area in Thailand, (b) Location of the experimental site in Phra Nakhon Si Ayutthaya Province, and (c) satellite image of the rice experimental field in Nakhon Luang District showing the six treatment plots.
***Source:** Adapted from Google Maps/Google Earth satellite imagery.

2.2. Rice Variety and Cultivation Period

The rice variety used in this study was Khao Dawk Mali 105 (KDML105), a Thai jasmine rice cultivar of *Oryza sativa* L. This variety is widely recognized for its aromatic grain quality and is commonly cultivated in Thailand. Rice planting was conducted in October 2025, and harvesting was completed in February 2026. All experimental plots were managed under similar field conditions, including irrigation, planting practice, weed control, and general crop management, except for the assigned soil amendment and fertilizer treatments.

2.3. Experimental Design and Treatments

This study was designed as an exploratory field evaluation rather than a fully replicated randomized field experiment. Six treatment-level field plots were established to compare the field responses of a no-amendment control, a conventional urea fertilizer treatment, and activated carbon-based soil amendment formulations with different activated carbon proportions [21].

Each treatment was established within a 10 m × 10 m field plot. Within each treatment plot, four 2 m × 2 m subplots were prepared for rice cultivation, greenhouse gas monitoring, soil sampling, heavy metal assessment, and crop data collection. These subplots were used as within-plot sampling locations to describe spatial variation within each treatment plot. They were not considered independent experimental replicates because they were located within the same treatment plot and shared the same field environment. The surrounding area of each treatment plot served as a buffer zone to reduce cross-treatment interference from water movement, soil disturbance, fertilizer movement, and field management activities. A schematic diagram of the exploratory field layout is shown in Figure 2. Because each treatment was represented by one treatment-level field plot, the results were interpreted descriptively as preliminary field evidence. Further replicated field trials are required to confirm treatment effects statistically [22].

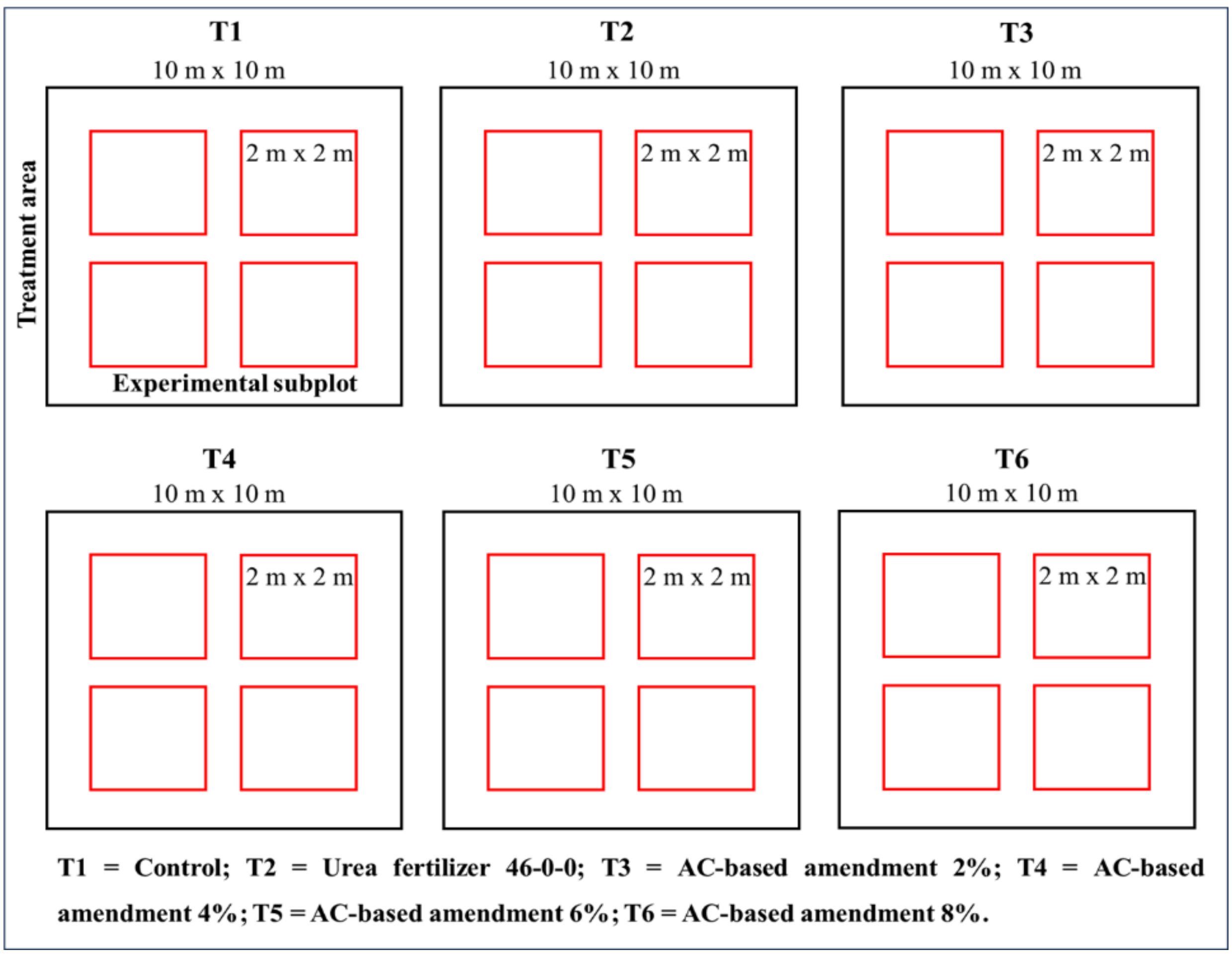

Figure 2.
Schematic diagram of the exploratory field evaluation layout. Each treatment was established within a 10 m × 10 m treatment-level field plot containing four 2 m × 2 m within-plot sampling subplots. The subplots were used for gas monitoring, soil sampling, heavy metal assessment, and yield observation, but were not treated as independent field replicates.

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Table 1.
Experimental treatments and application details.

Treatment	Description	Application detail
T1	Control	No soil amendment and no urea fertilizer
T2	Urea fertilizer 46-0-0	62.5 kg ha^{-1}
T3	AC-based amendment 2%	2,500 kg ha^{-1}
T4	AC-based amendment 4%	2,500 kg ha^{-1}
T5	AC-based amendment 6%	2,500 kg ha^{-1}
T6	AC-based amendment 8%	2,500 kg ha^{-1}

The soil amendment application rate was 2,500 kg ha^{-1}, equivalent to 0.25 kg m^{-2}. Therefore, each 2 m × 2 m experimental subplot received approximately 1.0 kg of soil amendment. The urea fertilizer application rate was 62.5 kg/ha, equivalent to 6.25 g m^{-2} or approximately 25 g per 2 m × 2 m subplot. The activated carbon percentages refer to the proportion of activated carbon by weight in the total soil amendment formulation.

2.4. Soil Amendment Formulation

The soil amendment used in this study was an activated carbon-based mixed formulation. The formulation consisted of leonardite, gypsum, horse manure, rice-husk charcoal, ash, and activated carbon. These components were selected to provide organic matter, mineral amendment, porous carbon material, and adsorptive functional material for improving soil conditions in rice cultivation. Carbon-based amendments and organic-mineral materials have been widely used to improve soil properties, increase adsorption capacity, and reduce contaminant mobility in agricultural soils [19, 23, 24].

Activated carbon was used as the main variable component in the formulation. Four activated carbon-based soil amendment treatments were prepared by varying the activated carbon proportion at 2%, 4%, 6%, and 8% by weight of the total amendment mixture. The remaining components were maintained as the base formulation. This design was used to evaluate the effect of increasing activated carbon content in the soil amendment formulation on greenhouse gas behavior, soil properties, heavy metal accumulation, and rice cultivation performance.

2.5. Field Plot Preparation and Crop Management

Each treatment area was prepared under similar field conditions. The activated carbon-based soil amendment formulation was applied according to the assigned treatment and incorporated into the surface soil layer during field preparation. The urea fertilizer treatment was applied at 62.5 kg ha^{-1} to represent conventional nitrogen fertilizer management. Rice cultivation was conducted using standard local farming practices suitable for KDML105 jasmine rice. Water management, field maintenance, weed control, and other agronomic practices were applied consistently across all treatments as much as possible to reduce non-treatment variation.

2.6. Greenhouse Gas Monitoring Using the Closed Chamber Method

Greenhouse gas monitoring was conducted using a closed-chamber method combined with a GASERA ONE gas analyzer. The closed-chamber method has been widely used for measuring greenhouse gas emissions from agricultural soils and rice fields because it allows gas accumulation from the soil–plant system to be monitored over a defined closure period [25, 26]. A rectangular chamber with dimensions of 40 cm × 40 cm × 140 cm was used to cover the rice plants and soil surface during gas measurement. During each measurement, the chamber was inserted approximately 5 cm into the soil to minimize gas leakage and allow gas accumulation from the soil–plant system. The effective chamber height above the soil surface was approximately 135 cm, with a ground coverage area of 0.16 m^2 and an approximate effective chamber volume of 0.216 m^3.

Gas measurements were conducted every 10 days throughout the rice cultivation period. For each measurement, gas concentrations inside the closed chamber were recorded at 0, 10, 20, and 30 min after chamber closure. The monitored greenhouse gases were carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), according to the instrument configuration. The same chamber size, closure duration, and measurement procedure were applied to all treatments.

Measurements were performed under comparable field conditions and, preferably, at similar times of the day to reduce the influence of diurnal variation in temperature and humidity. The gas-concentration data obtained from 0 to 30 min were used to evaluate gas accumulation behavior inside the chamber and to compare greenhouse-gas responses among the no-amendment control, urea-fertilizer treatment, and activated-carbon-based soil-amendment treatments.

The rate of gas concentration change was estimated from the linear slope of gas concentration against chamber closure time. Where gas flux was calculated, the chamber volume, chamber ground area, molecular weight of each gas, chamber air temperature, and pressure correction were considered according to standard closed-chamber calculation principles [26].

2.7. Soil Sampling and Analysis

Soil samples were collected before planting and after rice cultivation to evaluate changes in soil properties and heavy metal concentrations. Soil samples were collected from the surface-soil layer at a depth of 0–15 cm. Samples from each subplot were collected, air-dried, homogenized, and prepared for laboratory analysis. Soil sampling from the surface layer is commonly used in agricultural studies to evaluate management-induced changes in soil properties and contaminant behavior [1].

The analyzed soil parameters included soil pH and selected soil quality indicators, depending on available analytical data. Soil samples were also analyzed for selected heavy metals to assess the effect of the activated-carbon-based soil amendment formulation on heavy-metal behavior in paddy soil.

2.8. Heavy Metal Analysis in Soil and White Rice Grain

Heavy metal analysis was conducted on soil samples collected before planting and after harvesting, as well as on white rice grain samples obtained after harvest. The selected heavy metals included arsenic (As), cadmium (Cd), lead (Pb), chromium (Cr), and mercury (Hg), depending on the analytical scope of the study [27].

The samples were prepared using appropriate acid-digestion procedures and analyzed using atomic-absorption spectrophotometry (AAS). Acid digestion is commonly applied for preparing soil and sediment samples before metal analysis, and atomic-absorption spectrophotometry is widely used for determining metal concentrations in environmental samples [28, 29]. The results were used to evaluate changes in heavy-metal concentrations in soil and the accumulation of heavy metals in white rice grains under different treatment conditions.

2.9. Rice Growth and Yield Measurement

Rice growth and yield-related data were collected during the cultivation period and at harvest. Growth parameters included plant height and other observable growth characteristics. At harvest, grain yield was collected from the 2 m × 2 m experimental subplots and converted to a hectare basis. The final rice yield was reported as kg/ha to allow comparison with international agricultural studies. Crop yield measurement was used for descriptive treatment-level comparison because this study was conducted as an exploratory field evaluation [16].

The crop data were used to evaluate whether the activated-carbon-based soil-amendment formulation influenced rice growth and productivity compared with the no-amendment control and the urea-fertilizer treatment.

2.10. Data Treatment and Interpretation

Because this study was conducted as an exploratory field evaluation with one treatment-level field plot per treatment, the four 2 m × 2 m subplots within each treatment plot were treated as within-plot sampling locations rather than independent experimental replicates. Therefore, the data were

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summarized using descriptive statistics, including mean, standard deviation, percentage change relative to the control, and treatment-level comparison.

No inferential statistical test, such as one-way ANOVA or Tukey's post hoc test, was used to claim statistically significant differences among treatments unless independent, replicated field plots were available. The greenhouse-gas results were interpreted as preliminary chamber-based responses. The CH_4 and N_2O results were interpreted as preliminary chamber-based treatment responses and were used primarily for descriptive comparison among treatments rather than for establishing definitive emission factors. CO_2 was interpreted as a net chamber concentration-change rate because the chamber covered both rice plants and soil, allowing photosynthetic uptake and soil–plant respiration to occur simultaneously. For heavy-metal analysis, the reported values were interpreted based on available laboratory results. Quality-assurance and quality-control information, including detection limits, calibration performance, recovery, certified reference materials, and sample replication, should be reported if available from the analytical laboratory.

3. Results and Discussion

3.1. Greenhouse Gas Fluxes under Different Soil Amendment Treatments

As this study was conducted as an exploratory field evaluation, greenhouse gas data were interpreted descriptively at the treatment-plot level. The seasonal mean greenhouse gas fluxes varied among the six treatments. The treatment codes from the original data file were converted to the manuscript treatment codes as follows: Treatment 1 = T1, Treatment 2 = T2, Treatment 4 = T3, Treatment 5 = T4, Treatment 6 = T5, and Treatment 7 = T6. The six treatments were defined as T1: no-amendment control, T2: urea fertilizer 46-0-0, T3: AC-based amendment 2%, T4: AC-based amendment 4%, T5: AC-based amendment 6%, and T6: AC-based amendment 8%.

The average CH_4 flux ranged from 1,007.06 to 2,233.77 mg m^{-2} h^{-1} among the six treatments. The control treatment (T1) showed an average CH_4 flux of 1,646.06 mg m^{-2} h^{-1}, while the urea fertilizer treatment (T2) showed a lower value of 1,168.92 mg m^{-2} h^{-1}. Among the activated carbon-based soil amendment treatments, T5 (AC-based amendment 6%) showed the lowest average CH_4 flux at 1,007.06 mg m^{-2} h^{-1}, corresponding to a 38.82% reduction compared with the control and a 13.85% reduction compared with the urea fertilizer treatment. In contrast, T4 (AC-based amendment 4%) and T6 (AC-based amendment 8%) showed higher CH_4 fluxes of 2,233.77 and 2,006.43 mg m^{-2} h^{-1}, respectively.

The N_2O flux also showed treatment-dependent variation. The control treatment (T1) showed an average N_2O flux of 48.30 mg m^{-2} h^{-1}, while the urea fertilizer treatment (T2) showed 39.68 mg m^{-2} h^{-1}. The lowest N_2O flux was observed in T4 (AC-based amendment 4%), with a value of 38.74 mg m^{-2} h^{-1}, representing a 19.80% reduction compared with the control and a 2.38% reduction compared with the urea fertilizer treatment. In contrast, T5 (AC-based amendment 6%) and T6 (AC-based amendment 8%) showed higher N_2O fluxes of 115.23 and 89.20 mg m^{-2} h^{-1}, respectively.

CO_2 concentration changes inside the closed chamber also varied among treatments. Unlike CH_4 and N_2O, CO_2 was interpreted as a net concentration change rate because the chamber covered both soil and rice plants, allowing the observed CO_2 response to reflect the combined effects of soil respiration, root respiration, microbial activity, and plant photosynthetic uptake during daytime measurement. The mean net CO_2 change rate was −2.22 ± 1.09 ppm/min in the control treatment, −0.64 ± 0.47 ppm/min in the urea fertilizer treatment, −0.54 ± 0.85 ppm/min in T3, −0.58 ± 2.01 ppm/min in T4, −0.31 ± 0.69 ppm/min in T5, and −2.30 ± 1.50 ppm/min in T6. The negative values indicate that CO_2 concentration inside the chamber generally decreased during the measurement period, suggesting that photosynthetic CO_2 uptake by rice plants may have exceeded CO_2 release from soil and plant respiration under the measurement conditions. Therefore, CO_2 results should be interpreted as net chamber CO_2 dynamics rather than direct soil CO_2 emission alone.

Table 2.
Greenhouse gas responses under different treatments.

Treatment	CH_4 flux (mg m^{-2} h^{-1})	N_2O flux (mg m^{-2} h^{-1})	Net CO_2 change rate (ppm min^{-1})
T1 Control	1,646.06	48.30	−2.22 ± 1.09
T2 Urea fertilizer 46-0-0	1,168.92	39.68	−0.64 ± 0.47
T3 AC-based amendment 2%	1,382.99	53.59	−0.54 ± 0.85
T4 AC-based amendment 4%	2,233.77	38.74	−0.58 ± 2.01
T5 AC-based amendment 6%	1,007.06	115.23	−0.31 ± 0.69
T6 AC-based amendment 8%	2,006.43	89.20	−2.30 ± 1.50

Overall, Table 2 shows that the greenhouse gas response differed among treatments and gases. The AC-based amendment 6% treatment showed the lowest CH_4 flux, whereas the AC-based amendment 4% treatment showed the lowest N_2O flux. In contrast, CO_2 showed negative net concentration change rates across all treatments, indicating that daytime chamber CO_2 dynamics were influenced by plant photosynthetic uptake as well as soil–plant respiration. These findings indicate that the activated carbon proportion in the mixed soil amendment formulation influenced greenhouse gas behavior, but the response was not linear. Increasing the activated carbon proportion did not consistently reduce all greenhouse gas indicators. The contrasting CH_4 and N_2O responses are reasonable because CH_4 is mainly associated with anaerobic decomposition under flooded conditions, whereas N_2O is related to nitrification and denitrification processes under fluctuating oxygen and nitrogen conditions.

3.2. Heavy Metal Concentrations in Soil Before Planting and After Harvesting

Heavy metal concentrations in soil were analyzed before planting and after rice cultivation to evaluate changes in soil metal status under different treatments. The analyzed metals included Pb, Cd, Cr, As, and Hg. The results are summarized in Table 3. Overall, the concentrations of most metals changed after rice cultivation, but the magnitude and direction of change differed among treatments and metals.

For Pb, soil concentrations generally decreased after cultivation in T1–T5, with the largest reduction observed in T3, decreasing from 18.409 to 17.231 mg/kg. However, T6 showed a slight increase in Pb concentration from 19.389 to 19.9416 mg kg^{-1}. For Cd, all treatments showed lower concentrations after cultivation, suggesting a general decrease in extractable or measurable Cd in the surface soil layer. The largest Cd reduction was observed in T3, decreasing from 0.149 to 0.105 mg kg^{-1}. For Cr, most treatments showed decreased concentrations after cultivation, except T2, which showed a slight increase from 50.753 to 52.263 mg kg^{-1}. As concentrations decreased in all treatments after cultivation, the greatest reduction was observed in T6, decreasing from 1.4619 to 1.0174 mg kg^{-1}. Hg concentrations remained low across all treatments and showed only small changes after cultivation.

These results indicate that the activated carbon-based amendment influenced soil heavy metal behavior, but the response was metal-specific and not directly proportional to activated carbon content. The decrease in Cd and As in several treatments may be related to adsorption, complexation, changes in soil chemical conditions, and interactions between activated carbon and other amendment components. However, the relationship between soil metal concentrations and metal accumulation in rice grain was not always direct. This suggests that heavy metal uptake by rice is controlled not only by total soil concentration but also by metal bioavailability, soil redox conditions, pH, organic matter, and plant uptake mechanisms.

Table 3.
Heavy metal concentrations in soil before planting and after rice cultivation.

Treatment	Sampling period	Pb	Cd	Cr	As	Hg
T1 Control	Before planting	17.902	0.157	52.398	1.4274	0.0164
T1 Control	After cultivation	17.314	0.129	47.201	1.2115	0.0161
T2 Urea fertilizer 46-0-0	Before planting	17.853	0.167	50.753	1.4356	0.0165
T2 Urea fertilizer 46-0-0	After cultivation	17.455	0.124	52.263	1.1948	0.0170
T3 AC-based amendment 2%	Before planting	18.409	0.149	51.724	1.2506	0.0170
T3 AC-based amendment 2%	After cultivation	17.231	0.105	45.683	1.2334	0.0167
T4 AC-based amendment 4%	Before planting	18.368	0.143	55.018	1.2287	0.0188
T4 AC-based amendment 4%	After cultivation	17.587	0.115	52.414	1.1130	0.0169
T5 AC-based amendment 6%	Before planting	17.624	0.136	48.407	1.2617	0.0182
T5 AC-based amendment 6%	After cultivation	17.204	0.119	46.628	1.0259	0.0197
T6 AC-based amendment 8%	Before planting	19.389	0.135	49.904	1.4619	0.0171
T6 AC-based amendment 8%	After cultivation	19.942	0.114	45.856	1.0174	0.0181

Note: Unit: mg kg^{-1}.

3.3. Heavy Metal Concentrations in White Rice Grain

Heavy metal concentrations in white rice grain were evaluated for Pb, Cd, Cr, As, and Hg. The results are summarized in Table 4. The concentrations were expressed as mg kg^{-1}. The data showed that heavy-metal accumulation in white rice grain varied among treatments and depended on both the activated-carbon proportion and the specific metal.

For Pb, the concentration in the control treatment (T1) was 0.0716 mg kg^{-1}. The lowest Pb concentration was observed in T4 (AC-based amendment 4%), with a value of 0.0484 mg kg^{-1}, representing a reduction of approximately 32.40% compared with the control. For Cd, the control treatment showed 0.0097 mg kg^{-1}, while the lowest Cd concentration was found in T3 (AC-based amendment 2%), with a value of 0.0068 mg kg^{-1}, corresponding to a 29.90% reduction compared with the control. For Cr, the lowest concentration was again observed in T4, with a value of 0.2998 mg kg^{-1}, which was slightly lower than the control value of 0.3162 mg kg^{-1}. For As, T3 showed the lowest concentration at 0.0102 mg kg^{-1}, representing a 33.33% reduction compared with the control value of 0.0153 mg/kg. Hg was not detected in T4 and T5, while very low concentrations were detected in the other treatments.

Overall, the AC 2% formulation showed favorable performance for reducing Cd and As accumulation in white rice grain, while the AC 4% formulation showed favorable performance for reducing Pb and Cr. However, higher activated carbon proportions did not consistently reduce heavy metal accumulation. For example, T6 (AC-based amendment 8%) showed the highest concentrations of Pb, Cr, and As among the selected treatments. This result suggests that the effect of activated carbon-based soil amendment on heavy metal accumulation was metal-specific and formulation-dependent rather than directly proportional to activated carbon content. Similar findings have been reported for biochar-based amendments, where the reduction of metal uptake in rice depends on amendment properties, application rate, soil chemistry, and metal bioavailability [30].

The observed reduction in selected heavy metals may be associated with adsorption, complexation, pH-related changes, and the interaction of activated carbon with other amendment components such as leonardite, gypsum, horse manure, rice husk charcoal, and ash. These components may affect soil chemical conditions and metal bioavailability. Nevertheless, the variation among treatments indicates that the optimum formulation should be identified based on the combined response of individual metals, greenhouse gas behavior, and rice yield rather than relying on activated-carbon percentage alone. Because rice is an important dietary pathway for exposure to toxic elements, future work should also include complete QA/QC reporting and food-safety comparison based on relevant standards [31].

Table 4.
Heavy metal concentrations in white rice grain under different treatments.

Treatment	Pb	Cd	Cr	As	Hg
T1 Control	0.0716	0.0097	0.3162	0.0153	0.0000
T2 Urea fertilizer 46-0-0	0.0565	0.0098	0.3053	0.0108	0.0001
T3 AC-based amendment 2%	0.0713	0.0068	0.4062	0.0102	0.0003
T4 AC-based amendment 4%	0.0484	0.0149	0.2998	0.0123	ND
T5 AC-based amendment 6%	0.0735	0.0200	0.3865	0.0146	ND
T6 AC-based amendment 8%	0.0786	0.0094	0.5503	0.0175	0.0002

Note: Unit: mg kg^{-1}; ND = not detected.

3.4. Rice Yield Response

Rice yield differed among treatments, indicating that the activated carbon-based amendment formulation influenced crop performance. The results are summarized in Table 5. The control treatment (T1) produced a yield of 1,260.66 kg ha^{-1}, while the urea fertilizer treatment (T2) produced 1,337.33 kg ha^{-1}. The urea-fertilizer treatment increased yield by approximately 6.08% compared with the control, reflecting the expected benefit of nitrogen input on rice productivity.

Among the activated carbon-based treatments, T6 (AC-based amendment 8%) produced the highest rice yield at 1,582.53 kg ha^{-1}. This represented an increase of approximately 25.53% compared with the control and 18.33% compared with the urea fertilizer treatment. T4 (AC-based amendment 4%) produced 1,047.65 kg ha^{-1}, while T3 (AC-based amendment 2%) and T5 (AC-based amendment 6%) produced lower yields of 648.60 and 569.92 kg ha^{-1}, respectively. Recent studies have shown that biochar and carbon-based amendments can improve or maintain rice yield under certain field conditions, particularly when combined with appropriate fertilizer or soil management practices [32, 33].

These results indicate that the effect of the amendment formulation on rice yield was not directly proportional to its greenhouse-gas mitigation performance. Although T5 showed the lowest CH_4 flux, it also produced the lowest yield. Conversely, T6 produced the highest yield but did not show the lowest greenhouse-gas fluxes or the lowest heavy-metal accumulation. This trade-off suggests that yield performance and environmental mitigation should be evaluated together when selecting the most appropriate amendment formulation. These findings should not be interpreted as definitive treatment effects because each treatment was represented by one treatment-level field plot. The results provide preliminary evidence for selecting promising amendment formulations for future replicated trials.

The relatively higher yield in T6 may be related to improved soil condition, better nutrient retention, and the combined contribution of organic, mineral, and carbon-based components in the amendment formulation [34]. However, the increase in CH_4 and N_2O under T6 suggests that improved plant growth or increased organic and nutrient availability may also enhance biological activity and gas production. Therefore, the best amendment formulation should not be selected based only on yield, but should also consider greenhouse-gas response and food-safety indicators.

Table 5.
Rice yield under different treatments.

Treatment	Rice yield (kg ha^{-1})	Change compared with control (%)
T1 Control	1,260.66	0.00
T2 Urea fertilizer 46-0-0	1,337.33	+6.08
T3 AC-based amendment 2%	648.60	−48.55
T4 AC-based amendment 4%	1,047.65	−16.90
T5 AC-based amendment 6%	569.92	−54.79
T6 AC-based amendment 8%	1,582.53	+25.53

3.5. Integrated Evaluation of Greenhouse Gas, Heavy Metal, and Yield Performance

The integrated results showed that each activated carbon-based amendment formulation had different strengths. T3 (AC-based amendment 2%) was favorable for reducing Cd and As accumulation in white rice grain. T4 (AC-based amendment 4%) showed the lowest N_2O flux and the lowest Pb and Cr concentrations. T5 (AC-based amendment 6%) showed the lowest CH_4 flux, but its yield was the lowest among the six treatments. T6 (AC-based amendment 8%) produced the highest rice yield, but it did not provide the best performance in terms of greenhouse-gas reduction or heavy-metal accumulation.

These findings indicate that activated carbon-based soil amendment should be optimized according to the intended management objective. If the main target is methane mitigation, the AC 6% formulation may be useful. If the main target is N_2O reduction and lower Pb and Cr accumulation, the AC 4% formulation appears more appropriate. If the main target is yield improvement, the AC 8% formulation provided the best performance. However, for sustainable rice cultivation, the most appropriate treatment should balance greenhouse gas mitigation, heavy metal reduction, and rice yield rather than relying on a single performance indicator [8, 23].

Considering all indicators together, the AC 4% formulation can be considered a balanced treatment because it produced the lowest N_2O flux, the lowest Pb and Cr concentrations, and a moderate rice yield. The AC 8% formulation showed strong agronomic potential due to the highest yield, but its higher CH_4, N_2O, Pb, Cr, and As values suggest that it may not be the best option from an environmental and food safety perspective. Therefore, an intermediate activated carbon proportion may be more suitable for sustainable rice field management than the highest activated carbon proportion [24, 27].

Overall, the study demonstrates that activated carbon-based mixed soil amendment, when combined with field greenhouse gas monitoring, can provide useful information for improving rice cultivation management. The results support the need for integrated evaluation rather than single-parameter assessment. Field-based evidence from Nakhon Luang District, Phra Nakhon Si Ayutthaya Province, Thailand, suggests that soil amendment formulation can affect greenhouse gas behavior, heavy metal accumulation, and yield in different ways. Future studies should include multi-season trials, replicated field locations, and more detailed soil chemical and microbial analyses to confirm the mechanisms and optimize the formulation for practical use [35-37].

3.6. Methodological Considerations and Limitations

This study should be interpreted as an exploratory field evaluation. Each treatment was represented by one treatment-level field plot, and the four subplots within each plot were used only as within-plot sampling locations. Further studies should apply fully replicated field plots and standardized flux validation procedures to confirm absolute emission estimates. In addition, the exact proportions of all amendment components should be reported, if available, including leonardite, gypsum, horse manure, rice husk charcoal, ash, and activated carbon. Heavy-metal QA/QC information, including detection limits, recovery, calibration, certified reference materials, and number of analytical samples, should also be included when available. Future studies should use fully replicated and randomized field plots across seasons or locations to confirm the treatment effects.

4. Conclusion

This exploratory field evaluation assessed the preliminary responses of activated carbon-based soil amendment formulations on greenhouse gas behavior, heavy metal dynamics, and yield in jasmine rice cultivation under field conditions in central Thailand. The results showed that the responses of CH_4, N_2O, heavy metals, and rice yield differed among activated carbon proportions. Soil heavy metal results showed that Cd and As generally decreased after rice cultivation, while Pb, Cr, and Hg responses varied among treatments, indicating that soil metal behavior was influenced by both amendment formulation and field conditions. The AC-based amendment 6% treatment showed the lowest CH_4 flux, with a 38.82% reduction compared with the control, while the AC-based amendment 4% treatment showed the lowest N_2O flux and the lowest Pb and Cr concentrations in white rice grain. The AC-based amendment 2% treatment was most effective in reducing Cd and as concentrations. In contrast, the AC-based amendment 8% treatment produced the highest rice yield, increasing yield by 25.53% compared with the control, but it did not provide the best performance for greenhouse gas reduction or heavy metal accumulation.

The findings indicate that increasing the activated carbon proportion does not necessarily result in proportional environmental benefits. Instead, the optimum formulation depends on the balance between greenhouse gas mitigation, heavy metal reduction, and rice productivity. Overall, the AC-based amendment 4% treatment appeared to provide the most balanced environmental performance, while the AC-based amendment 8% treatment showed the greatest yield potential. This study provides field-based evidence that activated carbon-based mixed soil amendments, combined with greenhouse gas monitoring, can support sustainable rice cultivation. Further multi-season and multi-site studies are recommended to confirm the long-term effectiveness of the amendment formulation and to refine its practical application for low-carbon and safer rice production. Because the study used one treatment-level field plot per treatment, the findings should be considered preliminary and descriptive. Fully replicated field trials are required before making definitive recommendations for field-scale application.

Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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