

TECHNICAL NOTE

Fundamental Soil Science

Autoclaved lightweight aerated concrete suppressed N₂O and CO₂ emissions from paddy soil

Nagoda R. R. W. S. Rathnayake^{1,2} | Morihiro Maeda³  | Dewpura A. L. Leelamanie¹ | Atsushi Yatagai⁴

¹Department of Soil Science, Faculty of Agriculture, University of Ruhuna, Mapalana, Sri Lanka

²Department of Soil Science, Board of Study in Agriculture, Faculty of Graduate Studies, University of Ruhuna, Matara, Sri Lanka

³Graduate School of Environmental, Life, Natural Science and Technology, Okayama University, Kita-Ku, Japan

⁴Clion Co. Ltd, Isesaki, Japan

Correspondence

Morihiro Maeda, Graduate School of Environmental, Life, Natural Science and Technology, Okayama University, 3-1-1 Tsushima-Naka, Kita-Ku, Okayama 700-8530, Japan.

Email: mun@cc.okayama-u.ac.jp

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Abstract

Autoclaved lightweight aerated concrete (AAC), a construction waste that is utilized as a soil amendment, can influence terrestrial carbon dioxide (CO₂) emissions. Still, no evidence exists regarding its impact on the emission of nitrous oxide (N₂O), which has a higher global warming potential. This study examined effects of AAC on CO₂ and N₂O emissions from paddy soil under compacted and non-compacted conditions, under 60% and 100% water-holding capacity (WHC). Samples were incubated in glass vials (25°C) for 21 days. Emissions of CO₂ and N₂O were measured on days 0, 1, 3, 7, 14, and 21 using gas chromatography. The results revealed that AAC significantly ($p < 0.05$) lowered N₂O emission rate during the whole period of incubation, while it suppressed CO₂ emission rate only at the early stages (~7 days) of incubation. In compacted soil, the emissions of CO₂ were significantly lower, while N₂O was significantly higher than that in non-compacted soil, showing the influence of soil physical conditions. The emissions of CO₂ and N₂O were significantly lower at 100% WHC than those at 60% WHC. AAC suppressed both CO₂ and N₂O emissions under both compaction and WHC levels. The results confirm that AAC supports suppressing terrestrial emission of both CO₂ and N₂O, indicating that AAC has a potential as a sustainable soil amendment that enhances the climate change resilience.

1 | INTRODUCTION

Soil plays a significant role in the emissions of greenhouse gases (GHGs) such as CO₂, CH₄, and N₂O, which are produced through microbial activities, chemical processes, and soil fauna (Vargas & Le, 2023). Agricultural practices contribute notably to GHG emissions, particularly CO₂ and N₂O,

which are linked to global warming (Lynch et al., 2021). Among GHGs, CO₂ contributes to about 60% of global warming (Yoro & Daramola, 2020), while N₂O with a global warming potential 273 times that of CO₂ (IPCC, 2021) is primarily emitted due to fertilization and livestock grazing (Amadori et al., 2022).

Soil compaction may create conditions that restrict or alter microbial processes (Awe et al., 2023; Huang et al., 2022) by promoting denitrification when the oxygen consumption exceeds the supply (Bocking & Blyth, 2018) due to hampered soil gas diffusivity (Shah et al., 2024), potentially increasing

Abbreviations: AAC, autoclaved lightweight aerated concrete; CO₂, carbon dioxide; CS, compacted soil; N₂O, nitrous oxide; NCS, non-compacted soil; WFPS, water-filled pore space; WHC, water-holding capacity.

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GHG emissions (Das et al., 2024). Additionally, variations in soil moisture content significantly influence microbial processes that regulate GHG emissions (Loaiza et al., 2024). Amendments like autoclaved lightweight aerated concrete (AAC), a porous material made from calcium silicate, are used to improve soil properties (Ejaz et al., 2022; Zhan et al., 2023). AAC has been shown to improve soil pH, nutrient availability, and sequester CO₂ through mineral carbonation (Bashir et al., 2024; Morales-Flórez et al., 2014).

Despite the promising effects of AAC, its impact on N₂O emissions from paddy soil remains underexplored. Given that soil moisture and compaction affect microbial processes, we hypothesize that AAC may reduce both N₂O and CO₂ emissions in lowland paddy soil. Previous studies have focused on the use of AAC in agricultural systems, but little attention has been given to its role in mitigating GHG emissions in paddy fields, especially under varying moisture and compaction conditions. This knowledge gap justifies further investigation. This study aims to assess the potential effect of AAC as a sustainable soil amendment for mitigating CO₂ and N₂O emissions from compacted and uncompacted paddy soil at varying moisture levels. By understanding the potential of AAC to suppress GHG emissions, the research aims would contribute to sustainable agricultural practices that mitigate climate change.

2 | MATERIALS AND METHODS

2.1 | Soil sampling and preparation

Paddy soil was collected from 0- to 15-cm depth from a paddy field in Aioi, Hyogo, Japan (34°48'13.00"N, 134°28'5.02"E). The soil was classified as Fluvisol Hydragric Anthrosols, and the texture was identified as sandy loam. The soil was air-dried, sieved through 2 mm, and analyzed for total carbon (C) and nitrogen (N) by the dry combustion method using a CN analyzer (CN Corder MT-700; Yanaco). The initial properties of the soil are shown in Table 1.

2.2 | Preparation of soil for treatments

Sub-samples of air-dried soil (10 g) were placed in 100-mL glass vials. Samples were incubated at two moisture levels: 60% and 100% of water-holding capacity (WHC), which was determined by saturating and draining the soil (Verheijen et al., 2019). For compacted samples, first 2 mL of water was added, and the soil was compacted to 2.0 g cm⁻³ bulk density using a piston. Then, the excess 1 and 3 mL water were added to achieve 60% and 100% WHC, respectively. For non-compacted samples, 3 and 5 mL water was added to achieve 60% and 100% WHC, respectively. Commercially available

Core Ideas

- Autoclaved lightweight aerated concrete reduced N₂O and CO₂ emissions from lowland paddy soil.
- Compaction decreased CO₂ emission but increased N₂O emission.
- Both CO₂ and N₂O were significantly lower at higher WHC in autoclaved lightweight aerated concrete amended soil.

AAC was obtained (Clion Co. Ltd) for the experiment. Finely powdered AAC (50 g kg⁻¹) was applied as a thin surface layer to simulate a practical field-relevant application method, particularly in systems where surface broadcasting or minimal soil disturbance is preferred. This approach was chosen to limit mixing AAC with the soil to evaluate the direct surface-level interactions of AAC with soil gas exchange and moisture dynamics. The treatments included non-compacted soil without AAC (NCS), non-compacted soil with AAC (NCS-AAC), compacted soil without AAC (CS), and compacted soil with AAC (CS-AAC) in triplicate.

2.3 | Laboratory incubation

The vials with soil samples were incubated at 25°C for a period of 21 days, and the gas emissions were measured during this period. The emissions of N₂O and CO₂ were measured starting 2 h after the treatments were applied (day 0) and continued on days 1, 3, 7, 14, and 21. The vials were covered with a polyethylene film (0.02 mm thickness) to ensure minimal evaporation while maintaining air exchange during the experimental period. A separate set of samples were incubated under the same experimental conditions for the measurement of NH₄⁺-N and NO₃⁻-N contents, which were determined using a continuous flow analyzer (QuAAtro 2-HR; Bltec) following the 2 M KCl extraction (soil: KCl 1:10 w/w) on days 0, 7, 14, and 21 in parallel to the gas measurement.

2.4 | Determination of gas emission rates

Incubation vials were flushed with the fresh air at a rate of 3 L min⁻¹ with a mini pump (MP-2 N, Sibata, Japan) for 2 min, and kept sealed with rubber septa for 2 h before sampling. Gas samples were collected with a syringe and analyzed using a gas chromatograph (GC-8A; Shimadzu) with a thermal conductivity detector (for CO₂) and an electron capture detector (for N₂O). Gas emission rates were calculated using Equation (1), and the cumulative emissions were estimated by trapezoidal integration of the emission curves (Hoang & Maeda, 2018).

TABLE 1 The initial properties (mean $\pm$ standard deviation) of the soil.

Properties	Value
Total N (g N kg ⁻¹)	1.7 $\pm$ 0.1
Total C (g C kg ⁻¹)	15.8 $\pm$ 0.2
C/N ratio	9.7 $\pm$ 0.3
NH ₄ ⁺ -N (mg N kg ⁻¹)	35.1 $\pm$ 1.2
NO ₃ ⁻ -N (mg N kg ⁻¹)	1.2 $\pm$ 0.1
pH	5.9 $\pm$ 0.2
EC (μ S cm ⁻¹)	49.9 $\pm$ 2.1
WHC (g g ⁻¹ of air-dry soil)	0.50 $\pm$ 0.01
Sand (%)	55 $\pm$ 0.5
Silt (%)	26 $\pm$ 0.7
Clay (%)	19 $\pm$ 0.7
Texture	Sandy loam

Abbreviations: EC, electrical conductivity; NH₄⁺-N, ammonium nitrogen; NO₃⁻-N, nitrate nitrogen; WHC, water-holding capacity.

$$GE = \frac{\rho \times C \times 10^{-6} \times (V_g + (V_l \times \alpha)) \times 273}{(W \times (273 + T)) \times t}, \quad (1)$$

where GE is the gas (N₂O or CO₂) emissions (μ g N or C kg⁻¹ h⁻¹), ρ is the density (kg m⁻³) of N₂O (1.25) or CO₂ (0.5357), C is the concentration of N₂O or CO₂ (m³ m⁻³), V_g is the volume of the headspace (m³), V_l is the volume of the liquid phase (m³), α is the Bunsen absorption coefficients for N₂O (0.539) or CO₂ (0.614) at 25°C, W (kg) is the oven-dried weight of soil, T is the incubation temperature (25°C), and t is the period of time (h) from the incubation vial was closed with a rubber septum after flushing of the headspace until sampling.

2.5 | Statistical analysis

Two-way analysis of variance (ANOVA) was used to determine the significance of the effects of AAC on N₂O and CO₂ emissions at 5% significance. Mean separations were conducted at $p < 0.05$ using Tukey's HSD test separately at 60% and 100% WHC. All statistical analyses were performed using the R software.

3 | RESULTS AND DISCUSSION

3.1 | CO₂ and N₂O emissions rates

3.1.1 | CO₂ emission rate

Figure 1 presents the rates of CO₂ emissions from samples at 60% and 100% WHC levels. The rate of CO₂ emissions

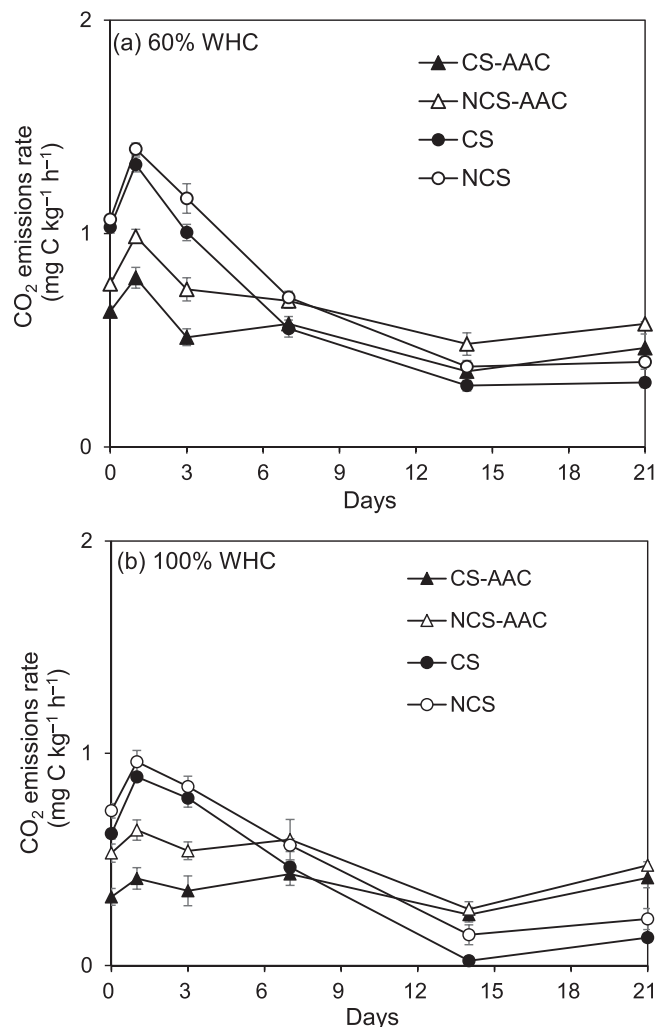


FIGURE 1 Emission rates of CO₂ from tested soils at (a) 60% and (b) 100% water-holding capacity (WHC). AAC, soil with AAC; C, compacted; NC, non-compacted; S, soil. Error bars indicate $\pm$ standard deviation.

from soils with AAC (NCS-AAC, CS-AAC) were significantly ($p < 0.05$) lower at both 60% and 100% WHC at the early period (0–7 days) than those without AAC. AAC reduced the rate of CO₂ emission (mg C kg⁻¹ soil h⁻¹) by 32%–53% in the first 3 days, with a smaller difference from day 7 to 21, especially under compacted conditions due to its reaction with calcium silicate. This effect was short-lived, as the reaction is irreversible (Haque et al., 2020). During the same period, NCS showed the highest rate of CO₂ emission, whereas CS-AAC showed the lowest at both 60% and 100% WHC levels. Compaction reduced the rate of CO₂ emission (15%–29%), which might be due to limiting aeration and microbial respiration (Liu et al., 2023).

Furthermore, the rate of CO₂ emission was remarkably higher at 60% WHC than at 100% WHC (Figure 1a,b), where the peak CO₂ emissions rate was approximately 40% higher at 60% WHC than that at 100% WHC. At 60% WHC, the

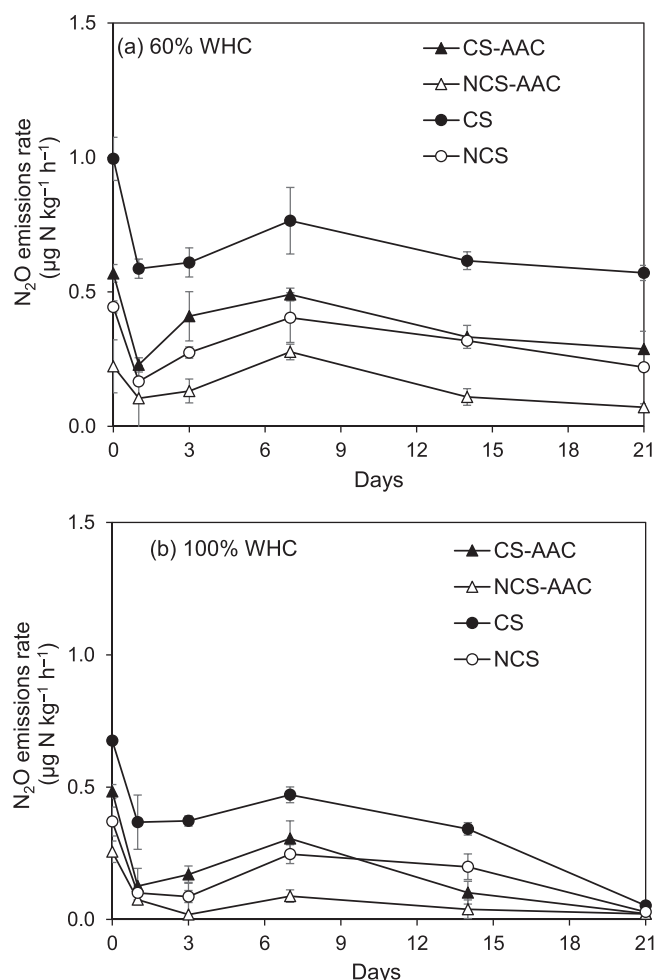


FIGURE 2 Emission rates of N_2O from tested soils at (a) 60% and (b) 100% water-holding capacity (WHC). AAC, soil with AAC; C, compacted; NC, non-compacted; S, soil. Error bars indicate $\pm$ standard deviation.

rate of CO_2 emissions was higher due to optimal aeration and microbial activity (Yan et al., 2019). At 100% WHC, reduced aeration inhibited these processes, lowering the rate of CO_2 emissions. The rate of CO_2 emission in all treatments peaked on day 1 and then decreased gradually toward day 14. The rate of CO_2 emission showed a slight increase again after day 14 in all treatments, although the difference was not significant ($p > 0.05$).

3.1.2 | N_2O emission rate

Figure 2 presents the N_2O emission rates from soil at 60% and 100% WHC. The peak of N_2O emission rate occurred on day 0. Although there were fluctuations in N_2O emission rates after day 1, the differences were mostly not statistically significant ($p > 0.05$). All treatments showed a similar pattern.

The emission rates of N_2O from soils with AAC (NCS-AAC, CS-AAC) were significantly lower ($p < 0.05$) than those without AAC at both 60% and 100% WHC levels (Figure 2a,b).

during the entire period. This reduction of the rates of N_2O emission with AAC was 44%–52% compared with those without AAC, likely due to increased soil pH facilitating nitrification and denitrification processes (Albina et al., 2019). These reductions highlight the potential of AAC to mitigate GHG emissions, especially N_2O , with its high global warming potential (Maier et al., 2022).

N_2O emission rates were higher in CS treatments generally by 52%–67% than in NCS treatments (Figure 2). NCS-AAC recorded the lowest N_2O emission rate, whereas the CS showed the highest at both 60% and 100% WHC. The higher rate of N_2O emission in CS treatments might be due to anaerobic conditions under the compaction that enhanced denitrification (Li et al., 2017). In addition, high initial NH_4^+ -N content can be associated with increased N_2O emission rates (Hoang & Maeda, 2018). Optimal aeration is also needed for complete nitrification that lower N_2O emissions (Guo et al., 2008). Another possible reason for the higher rate of N_2O emission in CS treatments would be the altered water-filled pore space (WFPS) due to compaction. High bulk density with compacted soil may lead to higher WFPS values. High WFPS values above 50% may favor denitrification and promote N_2O emission under anaerobic conditions (Ussiri et al., 2013). This might also have contributed to the increased emission rate of N_2O under compacted conditions.

Similar to the rate of CO_2 emission, the emission rate of N_2O was also significantly higher at 60% WHC compared with the 100% WHC ($p < 0.05$). At 60% WHC, the rates of N_2O emission were higher, probably due to optimal aeration and microbial activity for N_2O production in the nitrification process (Khalil et al., 2004). In addition, complete denitrification can be a reason for the lower emissions rates of N_2O at 100% WHC.

Changes in soil NH_4^+ -N and NO_3^- -N contents are presented in Table 2. The NH_4^+ -N content gradually decreased, while the NO_3^- -N content gradually increased irrespective of moisture contents, presence or absence of AAC, or compaction conditions. This trend of NH_4^+ -N and NO_3^- -N contents indicates that the major process in this experiment was nitrification (Zhang et al., 2016). While the decrease in NH_4^+ -N contents in both compacted and non-compacted soils was comparable, the increases in NO_3^- -N contents in compacted soils were significantly lower ($p < 0.05$) than those in non-compacted soils. Probably, simultaneous occurrence of denitrification and nitrification in compacted soils would have increased N_2O emissions as reported by Khalil et al. (2004) and Kool et al. (2010).

3.2 | Cumulative emission of CO_2 and N_2O

Figure 3 shows the cumulative CO_2 emissions from all soils at 60% and 100% WHC during the incubation period. At 60% WHC, the treatments with AAC showed approximately

TABLE 2 Temporal variations of NH₄⁺-N and NO₃⁻-N throughout the experimental period.

NH ₄ ⁺ -N/(mg kg ⁻¹)						
	60% WHC			100% WHC		
	7 days	14 days	21 days	7 days	14 days	21 days
CS	9.6 ± 0.4	5.6 ± 0.2	3.5 ± 0.2	14.3 ± 0.2	4.9 ± 0.2	2.6 ± 0.5
CS-AAC	6.5 ± 0.5	5.4 ± 0.3	4.2 ± 0.3	6.5 ± 0.5	5.0 ± 0.3	3.8 ± 0.3
NCS	4.2 ± 0.3	4.9 ± 0.3	3.3 ± 0.3	4.2 ± 0.3	5.2 ± 0.2	3.6 ± 0.6
NCS-AAC	0.8 ± 0.3	5.1 ± 0.4	3.7 ± 0.5	0.8 ± 0.3	4.7 ± 0.2	3.3 ± 0.4
NO ₃ ⁻ -N/(mg kg ⁻¹)						
CS	4.8 ± 0.6	21.4 ± 0.6	25.0 ± 0.4	10.1 ± 0.3	26.4 ± 0.3	28.9 ± 0.3
CS-AAC	6.4 ± 0.5	26.7 ± 0.5	30.6 ± 0.3	10.2 ± 0.3	30.8 ± 0.6	34.3 ± 0.4
NCS	13.7 ± 0.4	37.1 ± 0.5	48.7 ± 0.3	18.4 ± 0.5	38.9 ± 0.3	48.8 ± 0.4
NCS-AAC	15.1 ± 0.4	39.8 ± 0.4	51.3 ± 0.4	20.6 ± 0.4	44.0 ± 0.3	51.7 ± 0.5

Abbreviations: AAC, soil with AAC; C, compacted; NC, non-compacted; WHC, water-holding capacity.

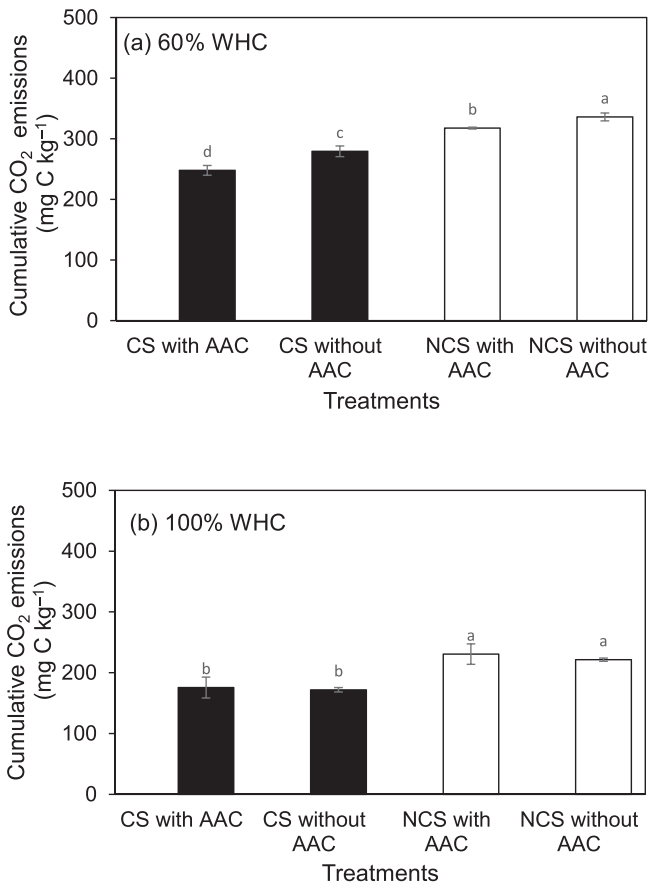


FIGURE 3 Cumulative emissions of CO₂ from tested soils at (a) 60% and (b) 100% water-holding capacity (WHC). AAC, soil with AAC; C, compacted; NC, non-compacted; S, soil. Error bars indicate ± standard deviation. The same lowercase letters are not significantly different at $p > 0.05$.

11% and 6% decrease (significant at $p < 0.05$) in cumulative CO₂ emissions in compacted and non-compacted soils, respectively, compared with soils without AAC. On the other hand, at 100% WHC, cumulative CO₂ emissions from soils

with AAC in both compacted and non-compacted soils did not show any statistically significant differences ($p > 0.05$) compared with soils without AAC. Non-compacted soils with and without AAC showed significantly higher cumulative CO₂ emissions than the compacted samples at both 60% and 100% WHC ($p < 0.05$). The cumulative CO₂ emissions in all samples were significantly higher at 60% WHC compared with those at 100% WHC ($p < 0.05$).

Figure 4 presents cumulative N₂O emissions from soils at 60% and 100% WHC during the incubation period. Cumulative N₂O emissions of samples with AAC were approximately 43% and 51% lower in compacted and non-compacted soils, respectively, compared with soils without AAC at 60% WHC. Similarly, at 100% WHC, cumulative N₂O emissions of samples with AAC in compacted and non-compacted soils, respectively, showed 52% and 67% decline (significant at $p < 0.05$), compared with samples without AAC.

In contrast to cumulative CO₂ emissions, cumulative N₂O emissions were significantly higher under compacted conditions than that under non-compacted conditions in soils irrespective of AAC or WHC ($p < 0.05$). Cumulative N₂O emissions in all samples were significantly higher at 60% WHC compared with those at 100% WHC ($p < 0.05$).

4 | CONCLUSIONS

This study investigated the effects of AAC on N₂O and CO₂ emissions from Japanese lowland paddy soil under compacted and non-compacted conditions at two moisture levels. AAC significantly reduced N₂O and CO₂ emissions from soil, with a more lasting effect on N₂O. The CO₂ reduction was short-lived due to the irreversible nature of the AAC-CO₂ reaction. While higher AAC amounts might improve CO₂ capture, cost-effectiveness must be considered. Our study suggested implementing the precise dosage (50 g kg⁻¹) of AAC

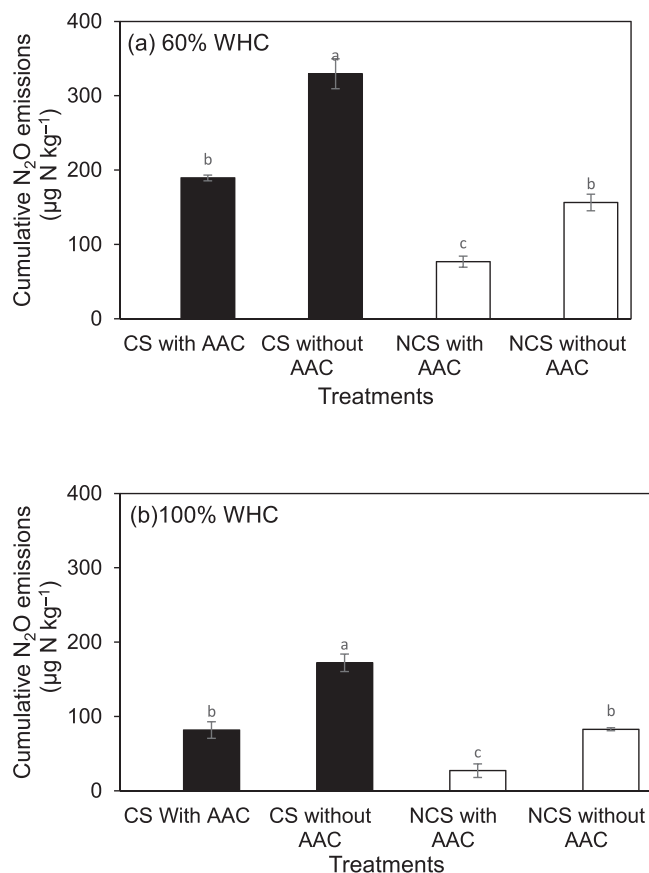


FIGURE 4 Cumulative emissions of N₂O from tested soils at (a) 60% and (b) 100% water-holding capacity (WHC). AAC, soil with AAC; CS, compacted soil; NCS, non-compacted soil; Error bars indicate $\pm$ standard deviation. The same lowercase letters are not significantly different at $p > 0.05$.

significantly contributes to the suppression of N₂O and CO₂ emissions from paddy soil under laboratory aerobic conditions, which was more effective at 100% WHC. To properly interpret the observed phenomena, microbial analysis is necessary. Data on microbial communities or activities would enhance the understanding of the mechanisms behind N₂O emissions and their response to soil compaction and AAC application.

AUTHOR CONTRIBUTIONS

Nagoda R. R. W. S. Rathnayake: Data curation; formal analysis; investigation; methodology; validation; visualization; writing—original draft. **Morihiro Maeda:** Conceptualization; data curation; funding acquisition; investigation; methodology; project administration; resources; software; supervision; validation; visualization; writing—review and editing. **Dewapura A. L. Leelamanie:** Conceptualization; methodology; resources; supervision; validation; visualization; writing—review and editing. **Atsushi Yatagai:** Conceptualization; resources; visualization.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

ORCID

Morihiro Maeda  <https://orcid.org/0009-0009-4396-4874>

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