International Journal of Agricultural Technology 2026 Vol. 22(1):259-274
DOI: https://doi.org/10.63369/ijat.2026.22.1.259-274
Available online http://www.ijat-aatsea.com
ISSN 2630-0192 (Online)

A comparative analysis of carbon dioxide emissions across land uses in Bengkulu city, Indonesia

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Muktamar, Z., Wiryono, W., Kencana, N. P. and Marpaung, M. T. (2026). A comparative analysis of carbon dioxide emissions across land uses in Bengkulu city, Indonesia. International Journal of Agricultural Technology 22(1):259-274.

Abstract The study found that CO_2 emissions varied across different land uses over six observation periods, with the most pronounced fluctuations occurring in agricultural areas. Forest soils released the highest levels of CO_2 but also supported the greatest accumulation of carbon through higher dry litter biomass, dry bottom plant biomass, and soil organic carbon. Specifically, dry litter biomass in forested areas was 250% and 167% higher than in home yards and palm oil plantations, respectively. Additionally, forest soils exhibited superior quality, contributing the highest soil total nitrogen (N), available phosphorus (P), exchangeable potassium (K), cation exchange capacity (CEC), and pH, while maintaining the lowest bulk density. As comparison to palm oil plantations, forest soils had 49.1% more organic carbon, 258.4% more available P, and 36.4% more exchangeable K. However, total soil nitrogen did not significantly differ between forests and palm oil plantations. Microbial populations were also relatively consistent across all land use types. Further research is needed to assess the carbon balance of each land use type to better understand their potential as carbon sinks or sources.

Keywords: Carbon flux, Forest floor, Soil quality, Soil organic carbon

Introduction

For over three decades, carbon emissions have drawn significant attention due to their major role in the rise of greenhouse gases. Anthropogenic activities are a key driver of this increase, particularly through CO_2 emission (Phiri *et al.* 2021). Land use and land use changes are the major contributors to carbon emission (Zhu *et al*., 2022; Huang *et al*., 2021; Zue *et al*., 2019). According to the Intergovernmental Panel on Climate Change, carbon dioxide contributed 75% of total greenhouse gas emission in 2019, equivalent to 44.25 Gt CO_2 eq y^{-1}. Of this, 64% originated from fossil fuels and industrial processes, while 11% was attributed to land use, land use change, and forestry. Notably, emissions from land use have increased by 133% since 1990 (IPCC, 2022).

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The agriculture sector plays a significant role in rising CO_2 emissions. In 2018, emissions from agriculture and associated land use reached 9.3 Gt CO_2 eq y^{-1} with 57% originating from crop and livestock production, and the remainder from land use and land use change activities. Indonesia contributes the highest emission from agricultural land use and is among the three countries that contribute 30% of global agriculture emissions (FAO, 2018). Soil characteristics, farming practices, and crop commodities significantly influence CO_2 emission from the respective land. For example, Bilandžija *et al*. (2016) reported that average monthly CO_2 emissions during the growing season ranged from 6.2 to 33.6 kg ha^{-1} day^{-1} for corn, and from 22.1 to 36.2 kg ha^{-1} day^{-1} for winter wheat. Soil disturbance has been shown to significantly increase CO_2 emissions in soybean–corn rotation systems (Utomo *et al*., 2012) and in organic sweet corn farming (Muktamar *et al*., 2019). In peatland agriculture, Barchia (2016) found that greater peat thickness and lower water tables led to higher CO_2 emissions.

Agricultural plantations also contribute significantly to CO_2 emissions from the land, with oil palm being one of the key annual crops of concern. Widely cultivated across various soil types in Southeast Asia—particularly in Malaysia and Indonesia—oil palm plantations are notable sources of carbon emissions. Sakata *et al*. (2015) reported that CO_2 emissions from Ultisols in the Tunggal Oil Palm Plantation, Riau Province, Indonesia, ranged from 45.5 to 56.8 mg m^{-2} h^{-1} during the wet season and 56.4 to 95.5 mg m^{-2} h^{-1} in the dry season. In contrast, emissions from the Simunjan Plantation in Sarawak, Malaysia, ranged from 72.1 to 114.0 mg m^{-2} h^{-1} during the wet season and 104.0 to 134.0 mg m^{-2} h^{-1} in the dry season. Another study by Putra *et al*. (2020) found that land in an oil palm plantation in South Bengkulu, Indonesia, emitted between 4.45 and 5.25 kg ha^{-1} day^{-1} of CO_2. Additionally, Manning *et al*. (2019) reported that average CO_2 emissions from oil palm plantations on peat soil reached as high as 830 mg m^{-2} h^{-1}.

In addition to sequestering carbon, forest lands also emit CO_2 into the atmosphere through processes such as soil respiration and the decomposition of organic matter. In tropical forests of Thailand, soil respiration has been observed to range from 0.94×10^{-7} to 6.2×10^{-7} kg m^{-2} s^{-1}, with fluctuations influenced by seasonal changes—particularly between the rainy and dry seasons (Hashimoto *et al*., 2004)—as well as tree maturity (Rodtassana *et al*., 2021). Zhao *et al*. (2021) further confirmed that soil respiration rates are closely tied to seasonal temperature variations.

To better understand the role of different land uses in contributing to greenhouse gas emissions, comparative analysis of carbon emissions across land types is essential. Therefore, this study aimed to determine CO_2 emissions from various land uses in Bengkulu City, Indonesia.

Materials and methods

The study was conducted in four land uses in the City of Bengkulu and Central Bengkulu District. The first location was the University of Bengkulu campus forest at 15 m above sea level (asl). The second location was agricultural land at the Faculty of Agriculture Experiment Station, Medan Baru Hamlet, Kandang Limun Village at 14 m asl. The third location was residential yards in Surabaya Village at 7 m asl, in Bengkulu City. The fourth location was oil palm plantation on mineral soil in Talang Pauh Village at 26 m asl in Central Bengkulu District. All locations were purposely selected to represent the most dominant land uses in and around the City of Bengkulu. The study locations are illustrated in Figure 1.

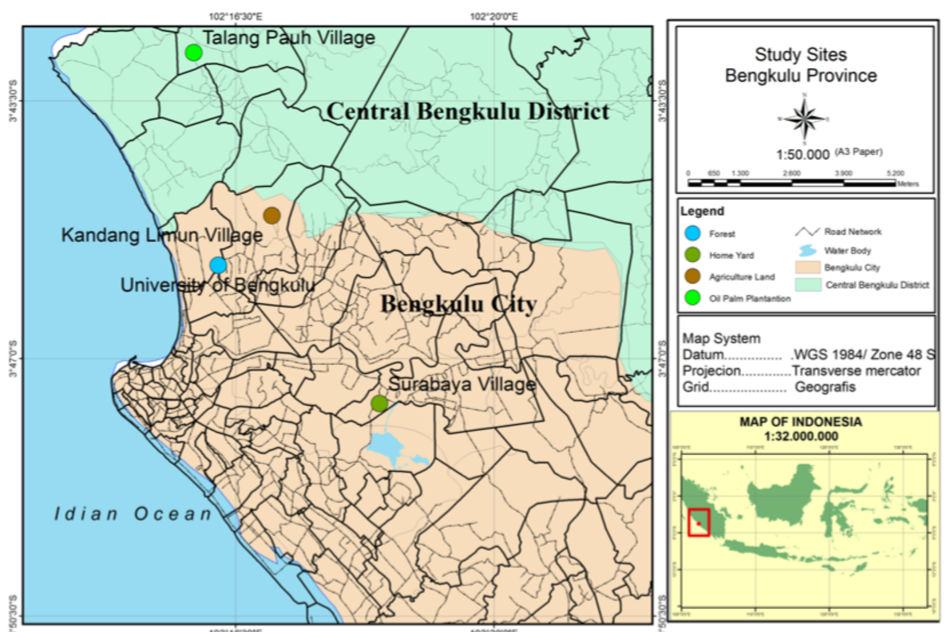

Figure 1. Study sites

Four sampling sites (replicates) were randomly selected within each land use type for CO_2 emission measurements and soil sampling. The forest area was characterized by dense tree cover and abundant litter, including leaves, stems, and other organic matter. The agricultural land was planted with corn at sites 1 and 3, sweet potato at site 2, and chili pepper at site 4. The home yards featured a mix of fruit trees—such as cacao, jackfruit, and banana—along with grass cover. The plantation area was dominated by oil palm trees.

Carbon emission and soil sampling

Prior to measuring CO_2 emissions, a 5 × 5 m plot was established at each site. Emissions were then recorded at five sampling points within each plot—one at each corner and one at the center—as illustrated in Figure 2. Measurements across the four land use types were conducted simultaneously to maintain similar environmental conditions. CO_2 emissions were recorded weekly over a six-week period using the method developed by Anderson (1982), with measurements taken between plants within the designated plots. Each measurement session lasted for 24 hours, beginning at 9 a.m. and concluding at the same time the following day.

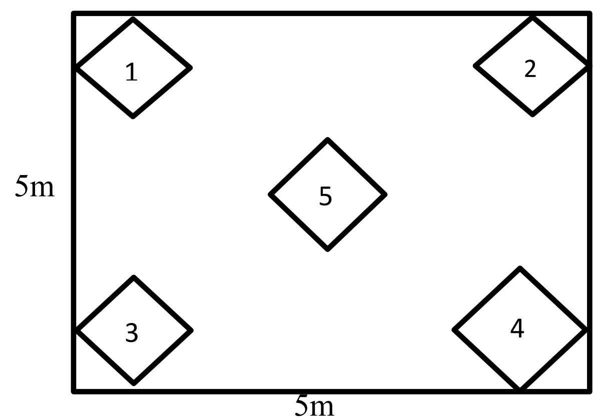

Figure 2. Plot design for sampling measurement

Soil samples from a depth of 0–10 cm were collected from the same spots used for CO_2 measurements within each constructed plot. These samples were then composited, air-dried, ground, and sieved using a 0.5 mm screen before being analyzed for their physical and chemical properties. Fresh soil samples were also taken for microbial analysis. Additionally, undisturbed soil samples were collected using a ring sample to determine bulk density and field capacity moisture content.

Soil texture, including clay, silt, and sand content, was determined using the hydrometer method. Bulk density and field capacity moisture content were measured using the pressure plate method. Organic carbon content was analyzed using the Walkley and Black method, while total nitrogen was measured using the Kjeldahl method. Available phosphorus was determined with the Bray-I method, and exchangeable potassium was measured using a flame photometer following extraction with 1N NH_4OAc. Exchangeable Ca was analyzed using EDTA method. Cation exchange capacity (CEC) was measured with a spectrophotometer after extraction with 1N NH_4OAc. Soil pH was measured using a pH meter in a soil-to-distilled water ratio of 1:2.5.

Litter and biomass sampling

The biomass of understory vegetation and litter beneath the main crops or trees was collected to estimate total biomass. Sampling was conducted within each plot using randomly selected 1 × 1 m subplots, with fresh weights recorded separately for understory plants and litter. All ground cover vegetation—including herbs, grasses, and plants with stem diameters less than 2 cm—was harvested by cutting at the base. Litter present within the subplots was also collected. Both ground cover and litter were weighed to determine fresh biomass. From each fresh sample, 300 g were taken, oven-dried at 65–70°C for 24 hours and then weighed to obtain dry biomass.

Data analysis

Data were subjected to Analysis of Variance (ANOVA) at 5% level using SAS for Academics and variable means among land uses were compared using LSD at 5% level.

Results

Litter and ground cover biomass

Dry litter biomass varied across sites and land use types, as shown in Table 1. On average, the forest recorded the highest dry litter biomass, while the other land uses showed relatively similar values. The forest floor contained 2.5 times and 1.67 times more dry litter biomass than the home yard and oil palm plantation, respectively, due to a greater number of trees shedding mature leaves. In contrast, a different pattern emerged for ground cover biomass. Agricultural land exhibited the highest ground cover biomass, while the remaining land uses showed comparable amounts. On average, ground cover biomass in agricultural areas was more than 18 times greater than in the forest, primarily because the dense forest canopy restricted sunlight from reaching the forest floor, thereby limiting understory plant growth.

Table 1. Dry litter and ground cover biomass across land uses

Land use	Site				
	1	2	3	4	Average
			Dry litter biomass (g m^{-2})		
Agricultural land	110.4	102.9	252.4	67.3	133.2 a
Home yard	47.2	91.8	110.7	67.5	79.3 a
Palm oil plantation	66.5	93.0	104.6	154.9	104.8 a
Forest	322.6	289.6	222.5	282.2	279.9 b
			Dry ground cover biomass (g m^{-2})		
Agricultural land	127.6	313.4	97.9	90.0	157.3 a
Home yard	20.8	67.9	10.5	64.5	41.4 b
Palm oil plantation	16.8	60.9	24.9	73.9	44.1 b
Forest	4.6	12.5	0	15.7	8.2 b

Note: the number in a column with the same letter is not significantly different

Weekly carbon emission

Carbon emission from each agricultural land site fluctuated over the six-week measurement period (Figure 3). Emissions increased notably during weeks 3, 4, and 6. At site 1, carbon emissions ranged from 340 to 1346 mg m^{-2} d^{-1}; at site 2, from 457 to 1517 mg m^{-2} d^{-1}; at site 3, from 448 to 1345 mg m^{-2} d^{-1}; and at site 4, from 394 to 1426 mg m^{-2} d^{-1}. On average, the highest carbon emission was observed at site 2 and the lowest at site 3, although the differences among sites were not statistically significant.

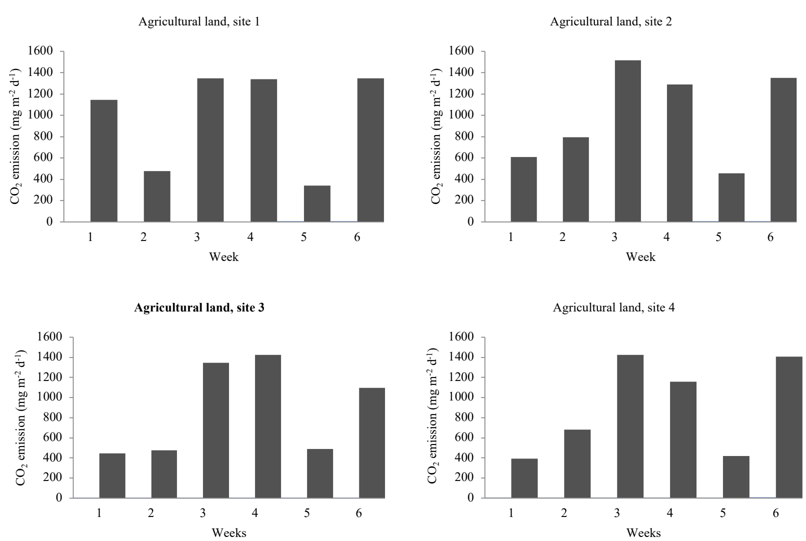

Figure 3. Carbon emission under the agricultural land

Fluctuation of carbon emission is also observed in the home yard (Figure 4). The carbon emission in site 1 ranged from 552 to 1313 mg m^2 d^{-1}, ranging from 465 to 1106 mg m^2 d^{-1} in site 2, ranging from 560 to 1150 mg m^2 d^{-1} in site 3 and from 503 to 1283 mg m^2 d^{-1} in site 4. Similar to carbon emission in agriculture land, the average emission among sites was not significantly different even though site 1 tended to exhibit the highest emission.

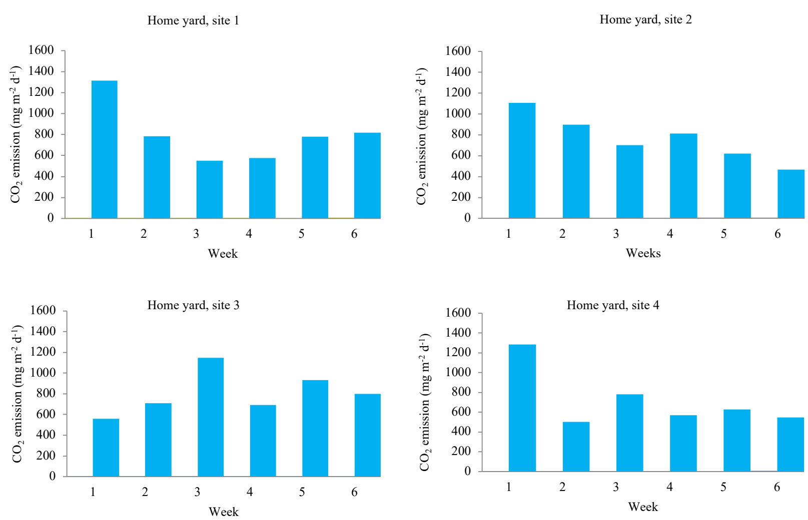

Figure 4. Carbon emission in the home yard

Carbon emissions in the home yard sites also showed fluctuations over the measurement period (Figure 4). Emissions at site 1 ranged from 552 to 1,313 mg m^{-2} d^{-1}; at site 2, from 465 to 1,106 mg m^{-2} d^{-1}; at site 3, from 560 to 1,150 mg m^{-2} d^{-1}; and at site 4, from 503 to 1,283 mg m^{-2} d^{-1}. As with the agricultural land, average carbon emissions among the home yard sites did not differ significantly, although site 1 generally showed the highest emission levels.

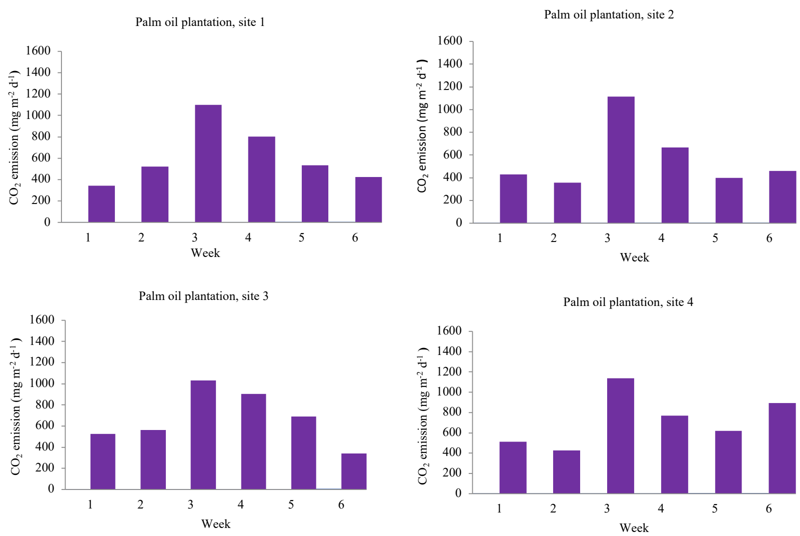

Figure 5. Carbon emission in palm oil plantation

Carbon emissions on the forest floor also fluctuated over the six-week observation period (Figure 6), although the variations were less pronounced compared to other land uses. Generally, carbon emissions increased in the second week and then remained relatively stable. At site 1, emissions ranged from 735 to 1264 mg m^{-2} d^{-1}; at site 2, from 778 to 1383 mg m^{-2} d^{-1}; at site 3, from 470 to 1319 mg m^{-2} d^{-1}; and at site 4, from 718 to 1474 mg m^{-2} d^{-1}. On average, carbon emissions were relatively consistent across all forest sites.

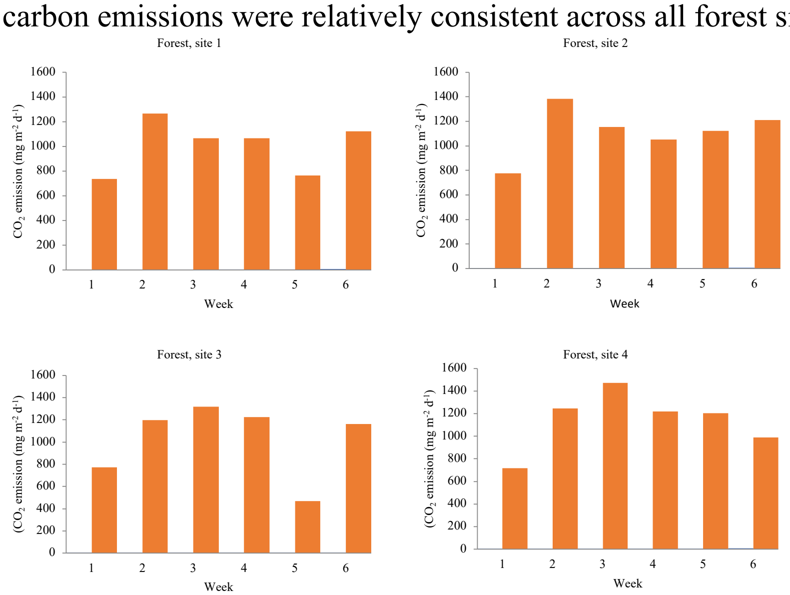

Figure 6. Carbon emission on the forest floor

Carbon emission and soil properties

A comparison of carbon emissions across different land uses is presented in Table 2. Unexpectedly, the forest floor recorded the highest CO_2 emissions, approximately 13% and 56% higher than those from agricultural land and the oil palm plantation, respectively. Agricultural land had the second highest CO_2 emissions, followed by the home yard. Interestingly, the oil palm plantation had the lowest CO_2 emissions among all land uses. It indicated that organic carbon content varied significantly among land uses (Table 2). The forest had the highest organic carbon content, followed by agricultural land and the oil palm plantation, with the lowest levels observed in the home yard.

Table 2. Carbon emission and soil properties in different land uses

Land use	CO_2 Emission (mg m^{-2} d^{-1})	Organic-C (%)	Microbial pop (10^6 CFU g^{-1})	Total-N (%)	Available P (mg kg^{-1})	Exch K (cmol kg^{-1})
Agricultural Land	949 a	4.83 a	288.1	0.21 a	3.24 a	0.33 a
Home yard	774 b	2.05 b	299.9	0.26 ab	5.58 b	0.27 a
Oil Palm Plantation	648 c	3.75 c	262.7	0.30 ab	3.08 a	0.33 a
Forest	1072 d	5.59 d	383.7	0.38 b	11.04 c	0.45 b

Note: the number in a column with the same letter is not significantly different

Total soil nitrogen was greatest in the forest, though not significantly different from the levels found in the oil palm plantation and home yard, while the lowest levels were observed in agricultural land (Table 2). A similar pattern was seen for available soil phosphorus, with the forest showing the highest levels, followed by the home yard and oil palm plantation, both of which were not significantly different from agricultural land. Exchangeable potassium also followed this trend, with the forest having the highest content, while the agricultural land, home yard, and oil palm plantation had comparable levels. The microbial populations were generally similar across all land uses as indicared in Table 2.

The study also revealed significant differences in soil pH among the various land uses, with the forest showing the highest pH, followed by the home yard, oil palm plantation, and agricultural land. Soil pH in the forest was over 19% higher than in agricultural land. Additionally, bulk density was lowest in the home yard, which was not significantly different from that in the forest, while the highest bulk density was observed in the oil palm plantation (Table 3).

Table 3. Selected chemical and physical properties of soils from different land uses.

Land use	pH	Exch Ca (cmol kg^{-1})	CEC (cmol kg^{-1})	BD (g cm^{-3})	Field Capacity (%)	Sand (%)	Silt (%)	Clay (%)
Agricultural Land	4.66 a	1.24 a	22.86 a	1.09 ab	40.5	48.0 a	25.6 a	26.4 a
Home yard	5.19 b	2.06 b	13.51 b	1.04 a	39.25	44.0 a	37.0 b	19.0 ab
Oil Palm Plantation	4.75 a	0.90 a	15.90 b	1.18 b	38.25	75.2 b	12.3 c	12.5 b
Forest	5.55 b	0.79 a	24.35 a	1.07 a	46.2	51.5 a	16.6 c	31.9 a

Note: the number in a column with the same letter is not significantly different

Discussion

The study shows that dry litter is highest in the forest, as indicated in Table 1. This finding is associated with the accumulation of litter on the forest floor. Previous research also suggests that forests produce a substantial amount of above-ground litter, influenced by factors such as soil properties, seasonality, age, and altitude (Junior *et al*., 2022; Ahirwal *et al*., 2021; Sukardjo *et al*., 2013; Lawrence, 2005). Conversely, the greater ground cover biomass observed in agricultural land, which reflects higher understory plant growth, may be due to an abundance of weeds. In this land use, adequate light penetration beneath the crops creates favorable conditions for weed proliferation. Weeds can compete with the main crops for light and nutrients, affecting their development (Savic *et al*., 2025; Korav *et al*., 2018). These variations in litter content may contribute to differences in above-ground carbon emissions.

Carbon emissions over the six-week measurement period varied among different land uses. Within the agricultural land sites, emissions fluctuated throughout the six weeks. Similar patterns have been reported by other researchers studying crops. For example, Neogi *et al*. (2014) observed that carbon emissions in a rice-corn-cowpea rotation system varied throughout the season, linked to the crops' growth stages and the release of CO_2 trapped in soil pores following physical disturbance. Likewise, Muktamar *et al*. (2019) noted that carbon emission fluctuations in organically grown sweet corn were influenced by both crop growth stages and soil disturbance.

In contrast to agricultural land, carbon emission patterns in the home yard varied between sites. This variation may be related to the diversity of plant species present at each site. Site 1 had minimal litter and was mainly covered by broadleaf weeds; site 2 was cultivated with cassava and also dominated by broadleaf weeds; site 3 featured trees such as jackfruit, oil palm, cacao, and papaya, with the home yard being regularly maintained; and site 4 was dominated by *Ageratum conyzoides*, banana trees, and had high soil moisture content. Differences in plant species and litter production likely influenced the variations in carbon emissions observed.

Additionally, carbon emissions in the oil palm plantation were consistent across different sites, likely due to the uniformity of the vegetation. Jamili *et al*. (2021) conducted a related study in peatlands and found that carbon emissions from palm oil plantations fluctuated over a four-month period but were not influenced by soil temperature. Additionally, Uning *et al*. (2020) reported high spatial variability in carbon emissions within oil palm plantations on peatlands.

The study also indicates that carbon emissions on the forest floor fluctuated over the six-week observation period, even though these fluctuations were less pronounced compared to other land uses. This pattern may be attributed to the dominance of trees in the area. Similarly, Forest Research (2022) reported fluctuating emissions from a mature spruce forest on organo-mineral soil over a four-year monitoring period. Additionally, Makita *et al*. (2018) observed seasonal and diurnal variations in soil respiration during their six-year study of a coniferous forest.

A comparison of carbon emissions among land uses is presented in Table 2. Unexpectedly, the forest floor emitted the highest amount of CO_2, approximately 13% and 56% more than agricultural land and oil palm plantation, respectively. Result revealed that the forest produced the greatest amount of floor litter and soil organic carbon. In addition to soil respiration, the accumulation of litter biomass promotes the decomposition of organic matter—likely driven by a higher microbial population which is released CO_2 during this process. Nevertheless, the elevated soil organic matter in the forest suggested that this land use stores carbon in the soil as well as in the trees. Therefore, assessing the carbon balance in the forest and other land uses is essential to better understand the net carbon dynamics as both a sink and source of this element.

Agricultural land had the second highest CO_2 emissions. Practices such as tillage and fertilization, particularly with nitrogen fertilizer, stimulate CO_2 release. Tillage enhances oxygen availability in the soil, which boosts microbial respiration and organic matter decomposition, resulting in increased CO_2 emissions. Similarly, nitrogen fertilization enhances nitrogen availability, supporting microbial activity. Agricultural land also produced the second highest amount of litter biomass, and the greater ground cover biomass contributed to increased respiration. Supporting this, Lu and Liao (2017) found that conventionally tilled soils released more CO_2 than those under minimum or no-tillage systems. Additionally, nitrogen fertilization has been shown to elevate soil CO_2 emissions (Utomo *et al*., 2012).

Surprisingly, the oil palm plantation floor emitted the lowest amount of CO_2 compared to the other land uses. This low emission may be attributed to the minimal litter biomass and ground cover present. Most of the emissions likely originated from root oil palm respiration and the decomposition of soil organic matter. These findings suggested that the quantity of litter and ground cover plays a significant role in CO_2 emissions. Additionally, it implies that land clearing during the establishment of oil palm plantations significantly contributes to increased CO_2 emissions, as noted by Jafaar *et al*. (2020).

Total soil nitrogen, available phosphorus, exchangeable potassium, cation exchange capacity (CEC), and soil pH were highest in the forest compared to other land uses. This result is closely linked to the soil organic carbon content. The decomposition of organic matter by microbial activity releases nitrogen, phosphorus, and potassium into the soil, contributing to their increased levels. In addition to nutrient release, organic matter decomposition produces stable carbon compounds such as humic and fulvic acids, which are rich in functional groups (Spark, 2003). These functional groups contribute negative charges that enhance CEC. They also bind aluminum to form organo-metal complexes, preventing aluminum hydrolysis and reducing proton production in the soil, which in turn raises soil pH (Muktamar *et al*., 2018).

The study also found that while home yard had the lowest bulk density which is not significantly different from forest. On the other hand, forest exhibited the highest field capacity moisture content. Functional groups produced during organic matter decomposition can act as binding agents for soil particles, promoting the formation of soil aggregates. This aggregation improves soil structure and reduces bulk density. Athira *et al*. (2019) demonstrated a linear relationship between soil organic matter and bulk density, showing that an increase in organic matter leads to a decrease in bulk density.

In summary, carbon emissions across different land uses fluctuated throughout the six-week observation period, with the most pronounced variations occurring in agricultural land. Although the forest floor emitted the highest levels of CO_2, it also contained the greatest amount of soil organic carbon, indicating a strong capacity for carbon sequestration. The abundant litter on the forest floor contributed to increased soil organic carbon, which in turn led to higher total nitrogen, available phosphorus, exchangeable potassium, cation exchange capacity (CEC), and soil pH. The study suggested that forests play a significant role in enhancing soil quality despite releasing substantial amounts of CO_2. Further research on the carbon balance within these land uses is essential to clarify their roles as carbon sinks or sources.

Acknowledgments

Sincerely appreciation goes to the Institute of Research and Community Services, the University of Bengkulu, for financial support. The authors also thank Yohan, Paka, Oki, and Andreas for assisting with the field works, and Zainal Arifin for the laboratory analysis.

Conflicts of interest

The authors declare no conflict of interest.

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(Received: 29 May 2025, Revised: 25 December 2025, Accepted: 1 January 2026)