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*Full Length Research*

# High frequency monitoring of carbon (iv) oxide evolution from a tropical soil amended with organomineral fertilizer in a screenhouse Ile-Ife, Nigeria

**Tijani, F. O.*, Okunkenu, A. S., Afolabi, F., Akinde, B. P. and Oyedele, D. J.**

Department of Soil Science and Land Resources Management, Obafemi Awolowo University, Ile-Ife, Osun State, Nigeria.

*Corresponding author: Email: dftijani@oauife.edu.ng



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**ABSTRACT:** The study compared responses of carbon (iv) oxide evolved from an Ultisol sampled at different time scales and the soil properties when amended with organomineral fertilizer (OMF); thus tracking the carbon footprint of the amendment in ambient air. The carbon (iv) oxide efflux was measured titrimetrically in a static chamber set up in a screenhouse at sub-daily, daily and weekly time scales. At the same time, the antecedent soil properties were determined using standard methods. The treatments involved OMF addition at three rates (0 kg OMF, 40 kg Urea-N + 2.5 tons/ha organic fertilizer and 40 kg Urea-N + 5 tons/ha organic fertilizer) based on some Nigerian indigenous vegetable nutrient requirements. The result showed that a more detailed and accurate understanding of $CO_2$ evolution processes was revealed at daily sampling resolution while sub-daily variation occurred in response to sub-daily variation in ambient temperature. Organomineral fertilizer at 40 kg/ha Urea + 2.5 tons/ha OF rate was comparatively safer in C management through the reduction in the $CO_2$ released thus constituting a better alternative in terms of the greenhouse effect. Thus, the study recommends at least daily monitoring for a detailed understanding of $CO_2$ evolution dynamics and management and identifies OMF rate with less $CO_2$ release as a comparatively better alternative in the production of those vegetables in the environmental context.

**Keywords**: Carbon (iv) oxide release, environment, organomineral fertilizers, sampling frequency, soil.

**Abbreviations: OF**, Organic fertilizer, **OMF,** Organomineral fertilizer; **CO2,** Carbon (iv) Oxide, **SOM,** Soil organic matter, **GHG,** Greenhouse gas

## INTRODUCTION

To meet the need for food by the global teeming population, agriculture has relied on the use of mineral fertilizers to sustain crop output and this is not without environmental implications (Rahman and Zhang, 2018; Ilahi *et al.,* 2020). One of such impacts is global warming. The reality, importance and impact of global warming in the world cannot be ignored. Greenhouse gases, which include carbon dioxide ($CO_2$), methane ($CH_4$) and nitrous oxides are major contributors to greenhouse gas emissions (GHGs) (Shi *et al*., 2006; Bréchet *et al.,* 2021; Mohammed *et al.,* 2021). Notably, $CO_2$ efflux from soil to the atmosphere is a major component of GHGs, and it is a crucial pathway of the carbon (C) cycle (Shi *et al*., 2006; Liu *et al.*, 2011; Mohammed *et al.,* 2021). The soil $CO_2$ efflux that gets to the atmosphere is produced by heterotrophic (decomposer organisms) and autotrophic (living roots and mycorrhizae) activities which depend on the substrate quality and the environmental conditions Subke *et al*., 2003; Kim *et al*., 2010; Lopez-Canfin *et al.,* 2018). It makes up about 20-40% of the total annual input of $CO_2$ into the atmosphere (Subke *et al*., 2003; Kim *et al*., 2010; Carlson *et al.,* 2016). Lorenz and Lal (2014) reported that $CO_2$ contributes about 60% to greenhouse gas emissions (GHG) and that any activity that results in C sequestration could be an effective mitigation strategy for global climate change. Soil temperature and moisture are among the most important factors controlling soil $CO_2$ efflux (Berglund *et al.,* 2010; Oyedele and Tijani, 2010; Gomes *et al.,* 2016; Yang *et al.,* 2017). Previous studies indicated that soil temperature is the major environmental driving factor influencing $CO_2$ efflux (Shi *et al.,* 2006; Hursh *et al.,* 2016; Kuzyakov *et al.,* 2019; Gołasa *et al.,* 2021). A number of organic materials could be incorporated into the soil to increase C sequestration in agricultural lands. This in turn reduces the release of $CO_2$ into the atmosphere (Fageria, 2012; Gayathri *et al.,* 2021). Such materials include biochar, animal manure, plant residues etc. as against inorganic fertilizers.

To increase crop yield, it is becoming standard practice to apply excessive amounts of synthetic fertilizer. Only one or two nutritional components can be supplied to the crop by employing chemical fertilizers alone (Hou *et al.,* 2010), thus leading to nutrient imbalance (Pahalvi *et al.,* 2021). Their use has been found to be effective as a short-term solution and it demands consistent use on a long-term basis (Makinde *et al*., 2007; Olowoake *et al*., 2015; Ghosh *et al.,* 2021). However, they are most times too expensive for low-income, small-scale farmers (Makinde *et al*., 2007; Ghosh *et al.,* 2021). Conversely, organic amendments are considerably less costly and supply significant carbon and vital nutrients to meet the needs of soil microbes (Ilahi *et al.,* 2020). Their use cannot be overemphasized because of their ability to improve the physical, chemical and biological properties of the soil (Wang *et al.,* 2019; Zhang *et al.,* 2019). They improve the conditions in which crops grow and develop which in turn culminates into better production of economic plants (Olowoake, 2014; Ulzen *et al.,* 2020). For example, organic fertilizer application (and the resultant C input) increases soil organic carbon (SOC) pool, whereas, the inorganic fertilizer application may increase, decrease, or have no significant effect on SOC stock (Olowoake, 2014; Yang *et al.,* 2017). Zougmore *et al*. (2009) reported that organic fertilizer application improves water-holding capacity (WHC) and infiltration as a result of well-developed aggregates. The drawback of a low supply of plant nutrients has been reported for organic manures (Mahmood *et al.,* 2017). However, a nutrient management technique that employs the integration of fertilizers (both organic and inorganic) so as to safeguard the sustainable condition of the soil and give plants the ideal amount of nutrients needed to sustain yield productivity seems promising (Ayinla *et al.,* 2019, Panta and Parajulee, 2021). Thus, the complementary use of organic and inorganic fertilizer (organomineral) generally improves the yield and quality of crops and increases SOC stock as compared with the sole application of mineral fertilizer (Olowoake, 2014; Oshunsanya and Akinrinola, 2014; Yang *et al.,* 2017). Babalola *et al.* (2007), Hou *et al*. (2010), Gai *et al.* (2018) and Smith *et al.* (2020) reported that SOC retention, soil C sequestration and soil infiltration are significantly affected by organomineral fertilizer (OMF). Also, vegetable growers reported that organomineral fertilizers (OMF) improved physico-chemical characteristics of soil and the growth of vegetables (*Amaranthus cruentus*, *Abelmoschus esculentus*) compared to the control (non-additive/untreated soil) (Makinde *et al*., 2011; Olowoake, 2014; Olowoake *et al*., 2015).

One of the crops gaining prominent attention in Nigeria is vegetables. Vegetables are an important part of healthy eating and have been found to be a source of many nutrients including potassium, fibre, folate and vitamins A, E and C (Olowo *et al.,* 2022). Nutrients in vegetables can help to maintain healthy blood pressure, reduce blood cholesterol levels and lower the risk of heart disease (Moyo *et al.,* 2020). In Nigeria, there are two broad categories of vegetables, the exotic and the indigenous. Exotic vegetables that are not indigenous to the country (Sayeed *et al.,* 2021). Some have been domesticated and grown in some parts of the country (such as broccoli, kale, strawberries etc.) while some are imported (such as apples, Egyptian grapes, etc.) (Amfo and Baba-Ali, 2020). On the other hand, the indigenous vegetables are native to Nigeria (Adenegan *et al.,* 2016). Generally, these indigenous vegetables are cheap to procure and excellent sources of proteins, carbohydrates, minerals, vitamins and dietary fibres, and sources of income for smallholder farmers (Amujoyegbe *et al.,* 2015; Lawal *et al.,* 2018). Some examples of prominent Nigerian indigenous vegetables include *Amunututu* or Ceylon/Malabar spinach (*Basella alba*), *Ila* or Okra (*Abelmoschus esculentus* L.), *Efinrin* or African Basil (*Ocimum gratisssimum* L.), *Igba* or Garden egg (*Solanum macrocarpon*), *Odu* or Nightshade (*Solanum nigrum*), *Ewuro* or Bitter leaf (*Venonia amygdalina*), *Ugwu* or Fluted pumpkin (*Telfaria occidentalis*), Ebolo or Ragleaf (*Crassocephalum crepidioidess*), *Isapa* or Roselle (*Hibiscus sabdariffa*), Eggplant leaf (*Solanum melogyena*), Wild leaf Marugbo or *Eweta* (*Clerodendrum volubile*), *Sokoyokoto* or Cocks' comb (*Celosia argentea* L.), *Gbure* or Water leaf (*Talinum triangulare*), *Tete* or Amaranth (*Amaranthus hybridus*), Snake tomato or *Tomato elejo* (*Trichosanthes cucumerina*) (Lawal *et al.,* 2018).

Studies on these indigenous vegetables have shown that the application of OMF allows a comprehensive soil fertility management strategy which will give benefits of applying an organic fertilizer as well as applying a little dose of inorganic fertilizer (Oyedele *et al.,* 2017). According to a study on fertilizer micro-dosing of indigenous Nigerian vegetables by Adebooye *et al.* (2018), it was observed that applying Urea (inorganic fertilizer) at 20 kg, 40 kg and 60 kg Urea-N/ha, along with basal application of organic fertilizer, gave better income

($40.51, $45.89 and $61.08, respectively, in a plot size of 6 $m^2$) than 80 kg Urea-N/ha ($39.52 from 6 $m^2$ plot size). This result confirmed that fertilizer micro-dosing can be used to sustainably produce these indigenous vegetables, particularly when co-applied with organic manure (Akponikpe *et al.,* 2018; Ayanwale *et al.*, 2018). Organic fertilizers have been reported to improve carbon sequestration (Wang *et al.,* 2019; Ghosh *et al.,* 2021); thereby, mitigating the release of $CO_2$ to the atmosphere. Despite the promising results obtained from OMF application for vegetable production, little research has been done on the carbon sequestration potential of the OMF, particularly on $CO_2$ efflux. With differences in organic materials and their combinations with mineral fertilizers such as OMF, and possible variation in carbon loss over time, there is the need for more investigation not only on their capacity to improve soil properties and yield but also on the implications of these amendments on the carbon in the atmosphere. Therefore, the knowledge of $CO_2$ emissions from soil and how this emission changes with time are of great importance to estimate atmospheric $CO_2$ concentration and ascertain carbon sequestration of the capacity of the soil system (Shi *et al.,* 2006; Kuzyakov *et al.,* 2019). In most soil and water studies, researchers have relied on low-frequency monitoring such as monthly or yearly (Bowes *et al.,* 2009; Bah *et al.,* 2012; Sale *et al.,* 2021). However, such low-frequency data can obscure a timely response and decisions that pertain to rapid changes in soil $CO_2$ efflux (Bah *et al.,* 2012; Cândido *et al.,* 2020). Soil carbon dioxide efflux which is an index of microbial activities and nutrient mineralization, is closely associated with soil functioning, and carbon sequestration, and has environmental implications (Gomes *et al.,* 2016; Lopez-Canfin *et al.,* 2018). The possible obscurity that exists in low-frequency or coarse monitoring of $CO_2$ efflux has suggested that carbon efflux processes occur at very fine resolution and require high-frequency monitoring (Chen *et al.,* 2019). High-frequency monitoring is necessary for a better understanding of nutrient dynamics and carbon response in the soil as well as its release into the atmosphere (Zeng *et al.,* 2016; Sith *et al.,* 2017; Bréchet *et al.,* 2021). Therefore, this study hypothesized that temporal variability at the sub-daily scale exists with $CO_2$ efflux and that its loss to the atmosphere varies with the rate of fertilizer application. The objectives of this study were to (1) investigate the difference in sub-daily, daily and weekly monitoring of $CO_2$ and (2) assess the temporal variability of $CO_2$ efflux as affected by temperature and organomineral fertilizers, and their effect on the selected properties of soil.

## MATERIALS AND METHODS

### Study site and soil

The study was conducted in a screenhouse of the Faculty of Agriculture, Obafemi Awolowo University, Ile-Ife, Nigeria (latitude 7°31′14.76″ and longitude 4°31′49.13″). The maximum daily temperatures ranged between 27 and 35°C, and the minimum temperature between 18.9 and 23.3°C. The soil used for the experiment was an Ultisol, a low base-status forest soil developed from coarse-grained gneiss and granite parent rocks (Okusami and Oyediran, 1985). It is classified as Typic Paleustult (Soil Survey Staff, 1975) and also classified as the Iwo series (Okusami and Oyediran, 1985).

### Sample collection and preparation, experimental design and layout

Bulk soil samples were taken from a field that has been subjected to continuous cultivation (with maize) for over 15 years (degraded) in the Teaching and Research Farm (T & R), OAU, Ile-Ife, Nigeria. The sampling was done on a relatively flat terrain to a depth of 15 cm. The samples were air-dried, gently crushed and then passed through a 2-mm mesh sieve. Composite samples were taken from the bulked soil samples for physical and chemical analyses.

Urea fertilizer and un-amended compost (organic fertilizer (OF); Sunshine Grade B) developed by the Ondo State Government of Nigeria and were used to prepare the OMF. The results of analyses of the organic fertilizer are Nitrogen (3.5%), Phosphorous (1.0%) and Potassium (2.5%) (Ondo State Government, 2012). Table 1 shows the treatment combinations used for the experiment. Each treatment was thoroughly mixed with 4 kg air-dried soil and repacked in plastic pots of 4.5 $m^3$ volume (perforated at the bottom for free drainage and air movement). The experiment was arranged in a completely randomized design (CRD) consisting of three treatments replicated four times giving a total of 12 pots. They were maintained at 75% field capacity (FC).

### Measurement of released $CO_2$ during soil incubation

The amount of $CO_2$ released during soil incubation was measured as described by Oyedele and Tijani (2010). Twelve potted samples of non-amended soil and soils amended with organomineral fertilizer that were maintained at 75% field capacity (FC) were placed in a static chamber. During the $CO_2$ sampling (incubation) period, specifically 2 hours, the pots were kept in the air-tight condition. Each pot had a beaker containing 10 ml of 0.5 M NaOH solution. An empty pot (without soil) that had a beaker (10 ml of 0.5 NaOH solution) was taken as blank (Kim *et al.,* 2010; Oyedele and Tijani, 2010; Gelfand *et al.,* 2015). The ambient temperature was assessed by measuring the temperature of water in a beaker within the chamber using a mercury thermometer. The incubation was carried out at a sub-daily time scale (7.00 GMT and

**Table 1.** The description of the study's treatment.

| No. | Treatment | Code |
|---|---|---|
| 1 | Control (0 kg Urea-N/ha + 0 tons/ ha OF) | OMF1 |
| 2 | First Rate (40 kg Urea-N/ha + 2.5 tons/ha OF) | OMF2 |
| 3 | Second Rate (40 kg Urea-N/ha + 5 tons/ha OF) | OMF3 |

12.00 GMT) and each incubation lasted 2 hours for each measurement for thirty-one days for the determination of $CO_2$ evolution. The emitted $CO_2$ from the soil was trapped in the base solution in the beaker, in each static chamber which was later titrated with 0.5 M $H_2SO_4$ using methyl red indicator.

## Laboratory analyses

Preliminary soil sampling was carried out on the soil to determine its antecedent soil properties (such as soil texture, bulk density, soil organic matter, pH, and available phosphorus) before imposing the treatment. The soil pH was determined by a digital pH meter (Walk lab Ti 9000) in a 2:1 0.01 M $CaCl_2$ solution to soil suspension calibrated to buffers pH 4 and 7 (Thomas, 1996). The other soil parameters were; particle size distribution determined using a modified hydrometer method as described by Gee and Or (2002); soil organic matter determined using the dichromate oxidation method (Nelson and Sommers, 1996) and available phosphorus determined by Bray-1 method (Bray and Kurtz, 1945; Kuo, 1996). The FC was the volumetric moisture content after gravitational drainage as adapted from Flint and Flint (2002). The bulk density was obtained via the use of the core method described by Stolte and Veerman (1997).

## Statistical analysis

The data obtained was subjected to analysis of variance (ANOVA). Means were separated using Duncan's Multiple Range Test (DMRT) at $p \le 0.05$.

# RESULTS AND DISCUSSION

The section revealed that significant differences in $CO_2$ release from soil to the environment, that was hidden when sampling at weekly and other coarser sampling frequencies were noticeable at a finer resolution such as daily and sub-daily monitoring scales. Furthermore, the loss of the gas increased at noon in response to the increase in temperature and also soil treated with OMF2 (40 kg urea + 2.5 tons organic fertilizer) was environmentally preferable because the soil released less carbon than OMF3 (40 kg urea + 5 tons organic fertilizer). Although the study was conducted in a screenhouse and it will also be interesting to make observations on the field, this monitoring scale is not often considered in soil studies and it is the area this study draws its strength. Details of the findings are presented in the sub-sections below.

## Properties of the soil before imposing the treatments

The soil properties before application of the amendments are presented in Table 2 indicating a sandy loam soil having a bulk density of 1.56 $gcm^{-3}$, which was close to the critical value (1.63 $gcm^{-3}$) when soil is considered impaired for good crop performance. Soil organic matter (SOM) and available P were below the critical level reported by Adepetu *et al*. (2014). More detailed discussion of these antecedent soil properties and further investigation on them, which include the soil texture, bulk density, soil hydraulic conductivity, pH, SOM and available P have been reported (Tijani *et al*., 2024).

## Carbon emission at a relatively low sampling frequency in response to the application of organomineral fertilizer

Table 3 reveals the $CO_2$ loss at the beginning and end of the experiment. Though week 5 has a lower soil $CO_2$ loss than that of week 1 for all the treatments and there was no significant difference ($p>0.05$) among the treatments at week 5, there was less percentage loss of C (73.8% loss) between week 1 and week 5 for soil on OMF2 as against OMF1 and OMF3 which have 84.7% and 89.3% losses of C, respectively, at the same temperature. Changes in C release to the atmosphere from the treated soils and its dynamics could also be due to the fact that SOM was quickly used up at the beginning by microorganisms for their metabolic activities which resulted in increased respiration, which only became more pronounced as the rate increased, as observed in OMF3. Further, at week 1, OMF3 emitted more $CO_2$ than both OMF1 and OMF2 while the two were not significantly different. This indicates that OMF2 posed a relatively less C threat to the environment probably due to the lower rate of the fertilizer applied, relative to OMF3 and the slow nutrient release attribute of the organic component of the fertilizer. The latter may have caused the difference between OMF2 and OMF1 in per

**Table 2.** The antecedent properties of soil.

| Soil property | Value |
|---|---|
| Sand ($gkg^{-1}$) | 702 |
| Clay ($gkg^{-1}$) | 197 |
| Silt ($gkg^{-1}$) | 101 |
| Textural class | Sandy loam |
| Bulk density ($Mgm^{-1}$) | 1.56 |
| SOM (%) | 1.55 |
| pH | 5.1 |
| Avail. P (Bray-1) (mg/kg) | 8.3 |

SOM = soil organic matter, Avail. P = Available phosphorous.

**Table 3.** Soil emission of $CO_2$ and ambient temperature at the beginning and end of the study.

| Treatments | Week 1 | Week 5 |
|---|---|---|
| Temp. ($^0C$) | 31 | 29 |
| $CO_2$ (kg ha $day^{-1}$) | | |
| OMF1 | 255.0b | 39.0a |
| OMF2 | 240.4b | 62.8a |
| OMF3 | 345.3a | 37.1a |

OMF1, OMF2 and OMF3 = (0 tons/ha OF + 0 kg Urea-N/ha), (2.5 tons/ha OF + 40 kg Urea-N/ha) and (5 tons/ha OF + 40 kg Urea-N/ha). Means in a column with the same alphabet are not statistically different at $p \leq 0.05$.

**Table 4.** Evolution of $CO_2$ and associated ambient temperature from the soil at weekly time scale.

| Treatments | Week 1 | Week 2 | Week 3 | Week 4 | Week 5 |
|---|---|---|---|---|---|
| Temp. ($^0C$) | 31 | 29 | 31 | 30 | 29 |
| $CO_2$ (kg ha $day^{-1}$) | | | | | |
| OMF1 | 255.0b | 88.7a | 118.2a | 59.1a | 39.0a |
| OMF2 | 240.4b | 85.0a | 113.1a | 77.6a | 62.8a |
| OMF3 | 345.3a | 62.83a | 110.5a | 70.2a | 37.1a |

OMF1, OMF2 and OMF3 = (0 tons/ha OF + 0 kg Urea-N/ha), (2.5 tons/ha OF + 40 kg Urea-N/ha) and (5 tons/ha OF + 40 kg Urea-N/ha). Means in a column with the same alphabet are not statistically different at $p \leq 0.05$.

cent C loss between weeks 1 and 5. The reduction in $CO_2$ evolution from 255.0, 240.4 and 345.3 kg $ha^{-1}$ $day^{-1}$ in week 1 to 39.0, 62.8 and 37.1 kg $ha^{-1}$ $day^{-1}$ in week 5 for OMF1, OMF2 and OMF3, respectively, is in agreement with Ghosh *et al.* (2021) who linked such occurrence to SOM dynamics in soil.

Table 4 reveals the weekly $CO_2$ evolution and associated ambient temperature. There was no significant difference ($p>0.05$) in $CO_2$ evolution between the treatments across the weeks of sampling except week 1 (Table 4). Furthermore, there was an initial increase in $CO_2$ efflux in week 1 that was higher than those in weeks 2 to 5. This may be due to the rapid disintegration of OMF by microorganisms that needed nitrogen for their activities, such that there was an increase in microbial activity leading to the release of more $CO_2$. Pandey *et al.* (2010) and Zamanian *et al.* (2018) reported that the addition of inorganic fertilizer especially nitrogen appears to have a priming effect on increasing $CO_2$ efflux from the soil as it releases its nutrients faster within a short time. $CO_2$ evolution responded to mild temperature changes from week 2 to week 4. This aligned with the reports that ascertained that a strong positive correlation exists between soil temperature and $CO_2$ efflux (Fenn *et al.,* 2010; Oyedele and Tijani, 2010; Galic *et al*., 2020; Bréchet *et al.,* 2021).

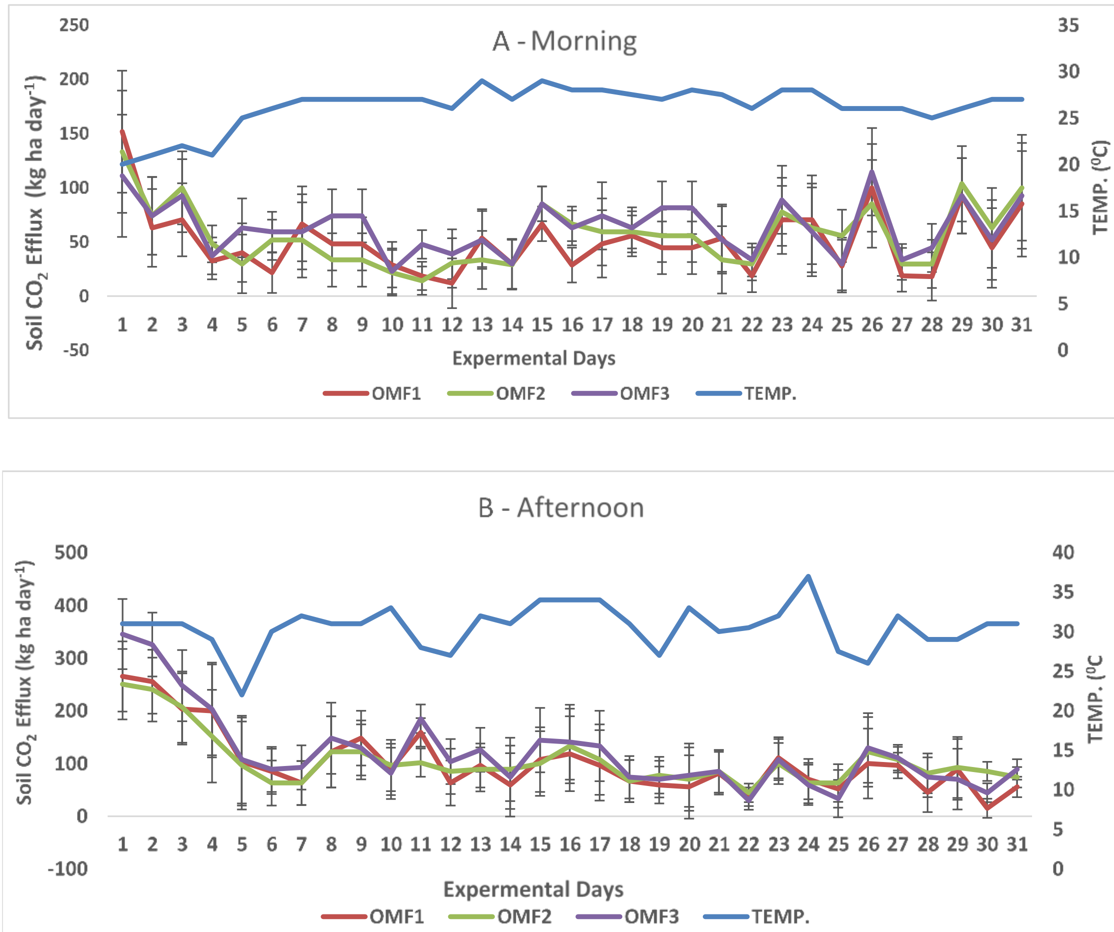


Figure 1 (A & B). Effect of varied rate of organomineral fertilizer on soil $CO_2$ efflux among the treatments at sub-daily time scale. A – morning sampling; B – afternoon sampling; OMF1 - Control, OMF2 – organomineral fertilizer at 40 kg Urea-N/ha + 2.5 ton/ha OF, OMF3 – organomineral fertilizer at 40 kg Urea-N/ha + 5 ton/ha OF.

**Soil $CO_2$ efflux of the treated soil at daily and sub-daily time scales**

Figure 1 shows the trend in $CO_2$ loss to the ambient air in the morning and at noon at a daily time scale in response to the different rates of the OMF treatment. The comparison of the $CO_2$ signals between the morning and noon represents the sub-daily monitoring frequency. At either morning or noon, days in which there were significant ($p<0.05$) emissions of $CO_2$ from the soil to the ambient air and potentially to the atmosphere were about 10% of the experimental period. The emission was dominated by OMF3. As the temperature rose at noon, carbon loss from soil more than doubled. The occurrence of higher carbon efflux was predominant in the early days of the experiment and this was more pronounced at noon. This is to re-emphasize the strong relationship that exists between temperature and $CO_2$ evolution (Subke *et al*., 2003; Shi *et al*., 2006; Saiz *et al*., 2007; Kim *et al*., 2010; Bréchet *et al.,* 2021) and the importance of proper sampling regime for the all-encompassing understanding of $CO_2$ dynamics. Figure 2A to C depict the variation in $CO_2$ signals from the soil when sampled in the morning and noon (sub-daily monitoring of $CO_2$) for each of the treatments. The $CO_2$ evolution in the first three days (at the beginning) at noon was significantly higher ($p<0.05$) than in the morning (with lesser temperatures) for all treatments (a few days after imposing OMF) implying an initial rise in $CO_2$ evolution for all the treatments. This indicates the effect of microbial decomposition on the SOM. Considering the number of days (10 days; 32.3% of the experimental period) that soil $CO_2$ efflux was significantly higher at noon than $CO_2$ efflux in the morning for each of OMF1 (the control) and OMF2 against OMF3 that has 13 days (41.9% of the experimental duration) of significant $CO_2$ efflux, therefore, OMF3 created more $CO_2$ concern to the environment. Consequently, OMF2 (2.5 tons/ ha + 40 kg Urea-N/ha) added relatively no additional carbon

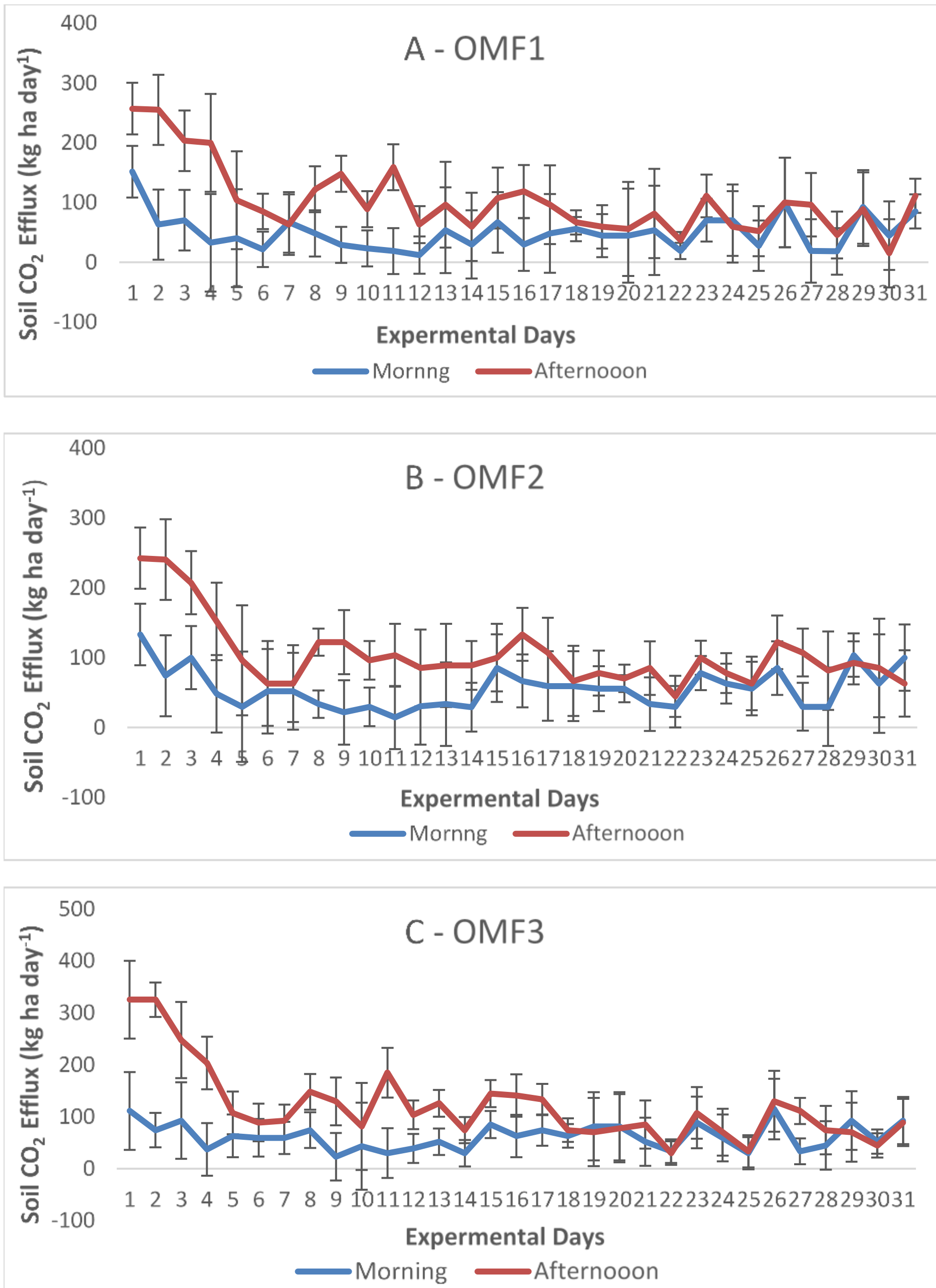


Figure 2 (A, B & C). Sub-daily sampling of soil $CO_2$ efflux from soil treated with organomineral fertilizer. A –Control, B – organomineral fertilizer at 40 kg Urea-N/ha + 2.5 ton/ha OF, C – organomineral fertilizer at 40 kg Urea-N/ha + 5 ton/ha OF.

burden to the environment (due to its rate), while at the same time improving soil properties (Tijani *et al*., 2024), implying it could lower the amount of the greenhouse gas and its effect to the environment. These higher significant differences recorded (at noon) showed the variation that exists at different times of the day which is a pointer to the higher potential threat of the evolution of $CO_2$ to the environment in warmer climates. However, $CO_2$ release from soil treated with OMF3 translated to the highest cumulative carbon mineralization during the incubation period. This also indicates that the mixture of organic and mineral fertilizers applied could improve soil microbial activity (Smith *et al.,* 2020), although with attendant higher $CO_2$ loss, unlike the comparatively lower mineralization that was observed in soils having OMF2 (compared to OMF3).

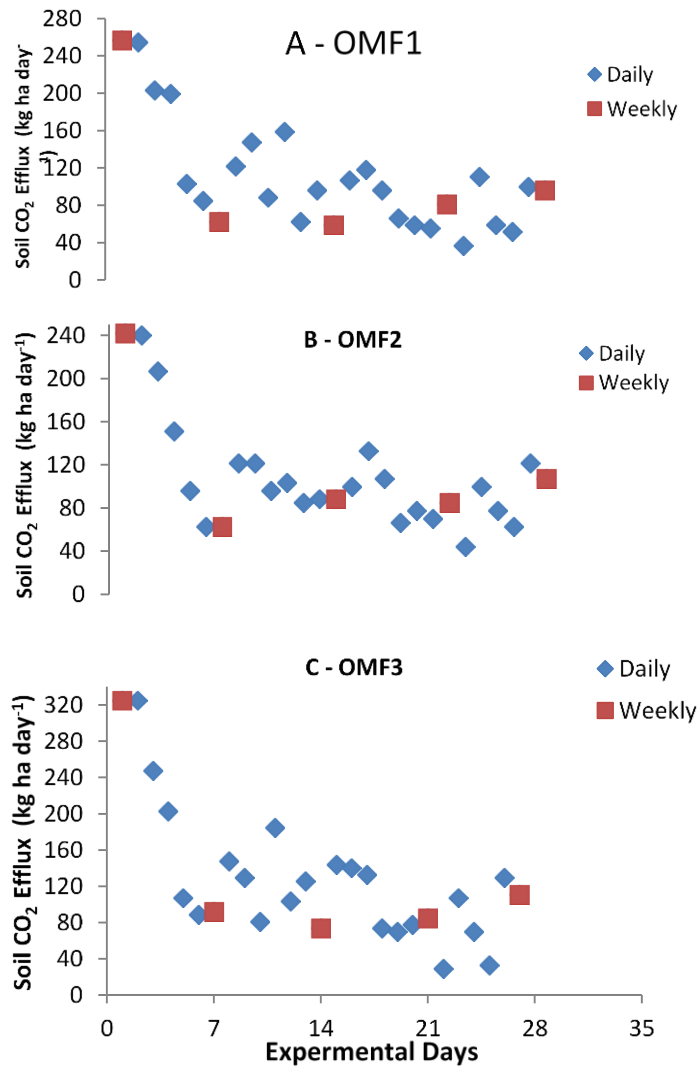


Figure 3 (A, B & C). Comparison of $CO_2$ efflux of the treatments at daily and weekly time scale. A – Control, B – organomineral fertilizer at 40 kg Urea-N ha$^{-1}$ + 2.5 ton ha$^{-1}$ OF, C - organomineral fertilizer at 40 kg Urea-N ha$^{-1}$ + 5 ton ha$^{-1}$ OF.

This indicates that OMF2 had the greatest potential in safer C management than OMF3. The resultant effect is a reduction in the amount of $CO_2$ evolution and a potential reduction in leached nutrients released to the environment. Therefore, management practices such as balanced application of fertilizer could play important roles in soil C sequestration or safe C management and thereby GHG mitigation, and reduction in the pollution of ground/surface water (Ghosh *et al*., 2010; Fageria, 2012; Lorenz and Lal, 2014). The results also revealed that temporal variability exists with soil $CO_2$ efflux at sub-daily scale. However, OMF2 exhibited comparatively less variations between morning and noon, than OMF3 across the days of the experiment, despite the higher temperature recorded at noon. This could be due to less quantity of SOM added through OMF2 compared to that of OMF3 leading to a reduction in the amount of $CO_2$ released to the environment. Zhang *et al.* (2014), Wang *et al.* (2016) and Liang *et al.* (2022) also reported that low fertilizer application could lower the release of GHGs and reduce global warming**.**

## Comparisons between measurements of $CO_2$ evolution at daily and weekly time scales

The daily sampling clearly shows more details of the trend and decline of $CO_2$ evolution as against the weekly sampling (Figure 3A, B and C) which obscures such details. The combined low and high sampling frequency of $CO_2$

efflux revealed that high-frequency monitoring was more accurate (or revealing) in the understanding of carbon dynamics. Although the weekly monitoring reasonably captured the trend in carbon dynamics, there was an underestimation of carbon ($CO_2$) emissions from the soil. This underscores the importance of this monitoring approach in carbon management in soil as done for rivers by Kooistra *et al.* (2012) and Grift *et al*. (2015) who advocated for combined low and high-frequency monitoring for crop status in precision agriculture and estimates of nutrients in lowland rivers. Therefore, fine resolutions (such as sub-daily or daily measurements) would facilitate the synthesis of relevant information (Blackford *et al.,* 2017). This will endear end users to make informed agronomic and economic decisions for better carbon and nutrient management, and profitable agricultural production and ecosystem health (Bah *et al.,* 2012). It is, therefore, reasonable to state that such high-resolution monitoring would be required for soil $CO_2$ dynamics variability (Tang *et al.,* 2003; Cao *et al.*, 2021). Sub-daily soil $CO_2$ efflux monitoring has also been suggested by other authors Chédin *et al*. (2003), Cao *et al.* (2021) and Chamizo *et al.* (2022).

## Conclusions

This study elucidates the effect of OMF on soil $CO_2$ efflux (C dynamics). It was observed that OMF2 (40 kg Urea-N/ha + 2.5 tons of OF) was at a safer rate in terms of $CO_2$ evolution than OMF3 (40 kg Urea-N/ha + 5 tons/ha of OF). High-resolution monitoring (e.g. daily sampling) of $CO_2$ efflux was more revealing and accurate than low resolution monitoring and it is necessary for holistic understanding and management of carbon exchange between the soil and the atmosphere. Therefore, a cautious management strategy in the use of OMF could play a vital role in GHG mitigation in view of the fertilizer rate for the production of Nigerian indigenous vegetables in the environmental context.

## CONFLICT OF INTEREST

The authors declared that no competing interest exists.

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