https://doi.org/10.17221/304/2021-PSE

Decomposition of rice straw residues and the emission of CO_2, CH_4 under paddy rice and crop rotation in the Vietnamese Mekong Delta region – A microcosm study

Tran Van Dung[1], Tat Anh Thu[1], Vu Van Long[2], Chau Thi Da[3]*

[1]Soil Science Department, College of Agriculture, Can Tho University, Can Tho, Vietnam
[2]Faculty of Natural Resources – Environment, Kien Giang University, Kien Giang, Vietnam
[3]Faculty of Applied Sciences, Ton Duc Thang University, Ho Chi Minh City, Vietnam
**Corresponding author: vvlong@vnkgu.edu.vn*

Citation: Dung T.V., Thu T.A., Long V.V., Da C.T. (2022): Decomposition of rice straw residues and the emission of CO_2, CH_4 under paddy rice and crop rotation in the Vietnamese Mekong Delta region – A microcosm study. Plant Soil Environ., 68: 29–35.

Abstract: This study investigated the influence of soil undergoing different crop rotations on the CH_4, CO_2 emissions, and decomposition of rice straw. The studied soil undergoing crop rotation systems were rice-rice-rice (SR) and baby corn-rice-mungbean (SB). Two main microcosm set-ups: anaerobic (SR-AN, SB-AN) and aerobic (SR-AE, SB-AE) conditions. Litter bags containing rice stems were inserted into the soil and recollected at different time points for chemical analysing and the gas sampling was collected to measure the CO_2 and CH_4 emissions. The results indicated that the total carbon (TC) decreased around 30%, and the TC removal in anaerobic was significantly higher than in aerobic conditions. The residue cellulose content varied in a range from 68.2% to 78.6%, while the hemicellulose content varied from 57.4% to 69.3% at day 50 after incorporation. There were no significant differences in the total nitrogen removal, cellulose, hemicellulose, and lignin contents among the microcosm set-ups. CO_2 emission increased in all the microcosm set-ups with the treatments without rice straw (CTSR, CTSB) in both aerobic and anaerobic conditions. CH_4 release in the SR-AN treatments did not differ significantly compared with the SB-AN treatments. This study confirmed that the decomposition of rice straw residues is faster in the anaerobic paddy soil condition compared to the aerobic crop rotation condition.

Keywords: degradation; greenhouse gases emission; *Oryza sativa* L.; paddy field; upland soil

In the Vietnamese Mekong Delta (VMD) region, intensified paddy rice mono-cultivation is the primary cropping system (Thinh 2009). After harvest, rice straw residue is incorporated into the flooded rice paddy formed the nutrients or soil organic matter for rice growth of the next crop (Gorbunova et al. 2020). Rice straw is one of the main carbon sources in paddy soil, and it has frequently been demonstrated that the incorporation of rice straw strongly enhances the emission of CH_4 from rice fields (Weil and Brady 2017). Therefore, the processes involved in CH_4 formation in rice fields are of great interest.

Rice straw consists of different biopolymers, including cellulose (32–37%), hemicellulose (29–37%), lignin (5–15%), and also contains inorganic components such as silica (Yan et al. 2019). Transformation of lignin, hemicellulose, and cellulose into soil organic matter depends on different interacting factors such as the physical chemistry of the soil environment (Weil and Brady 2017), the type of field management (Singh et al. 2020), the quantity and quality of the plant residues (Puget and Drinkwater 2001). For instance, it has been shown that the dynamics of carbon (C) and nitrogen (N) in paddy fields where mainly anaerobic decomposition processes take place significantly differ from those in fields with upland crop cultivation in which aerobic decomposition processes are dominant (Nishimura et al. 2008). According to Guong et al. (2010), rotation of paddy rice with upland crops such as baby corn or mungbean resulted in essential changes in soil organic matter quality and its capacity to supply

https://doi.org/10.17221/304/2021-PSE

Table 1. Physico-chemical properties of the soils after implemented crops rotation

Soil	pH_{H_2O} (1:2.5)	SOC (%C)	CEC ($cmol_+$/kg)	Total N (%)	Total P (%)	Texture
SR	4.9	3.3	25.2	0.29	0.53	clay
SB	5.5	2.5	27.3	0.22	0.48	clay

SR – rice soil; SB – upland rotation soil; SOC – soil organic carbon; CEC – cation exchange capacity

available nitrogen compared to intensive triple rice cropping systems. Their results reported that net nitrogen mineralisation was higher in the rice-upland crop rotation systems than in the mono-culture rice systems. Rotation with upland crops in paddy rice cultivation has been proposed to constrain the practical problem of land degradation associated with continuous rice cropping.

The underlying hypothesis of this study was that the change in flooded paddy field conditions in undergoing different crop rotation systems could increase the rate of rice straw decomposition and decrease greenhouse gases emission. The objectives of this study were to evaluate the effect of upland crops rotation on rice straw decomposition and assess the emission of CO_2 and CH_4 in the paddy soil in Cai Lay district, Tien Giang province, Vietnam.

MATERIAL AND METHODS

Soil and rice straw used in this study. The site had been continuously cultivated with paddy rice (3 crops per year) for over 30 years and was partially converted into cultivation with intermittent upland crops about 10 years ago. The soil used in this study originated from the site at Cai Lay district, Tien Giang province. The soil at the field site was classified as Aeric Tropaquept (USDA). In the depth of 0–20 cm, soil texture as clay, slightly acidic (pH ranged from 4.9 to 5.5), soil organic carbon (SOC) (2.5–3.3% C) ranged in low level for paddy rice (Metson 1961). The principal characteristics of the two experimental soils are presented in Table 1. Soil SR originated from plots that had been cultivated as a continuous paddy rice system: rice (*Oryza sativa* L.)-rice-rice and was sampled during cultivation of rice crop. Soil SB originated from plots undergoing baby corn (*Zea mays* L.)-paddy rice-mungbean (*Vigna radiate* (L.) R. Wilczek) crop rotation system and was sampled during the baby corn crop cultivation. In total, the field site covered an area of 540 m^2. Each plot covered an area of 90 m^2 (6 m × 15 m). For both soils, the samples used in this study were taken at the soil surface (0–20 cm) using an auger sampler at day 60 after seeding of the respective crops, i.e., rice in case of SR and baby corn in case of SB. The samples were taken from three different replicate plots, well-mixed and stored at 4 °C in the dark till use.

The straw used in this study originated from fresh stems of rice plants grown at the field and sampled at rice harvest time. The rice straw was air-dried (till a water content of 10%) and stored at room temperature for one week before use. The stems were cut into approximately 2–3 cm pieces and used to fill small litter bags consisting of nylon material with a pore size of 200 μm. The filled litter bags were sterilised at 121 °C for 20 min. The chemical compositions of the rice straw are shown in Table 2.

Microcosm experimental set-up and sampling. The experiment consisted of two main microcosm set-ups that were implemented in the laboratory condition. The soils were incubated under aerobic (AE) and anaerobic conditions (AN), referred to as SR-AE, SB-AE for aerobic microcosm set-up, and SR-AN and SB-AN for anaerobic set-up. The soils were first dried at room temperature and then ground and sieved through a 2-mm mesh sieve. Then, add 50 g of the sieved soil and three litter bags containing 0.5 g rice straw residues to 160 mL glass vials.

For aerobic set-up, sterile distilled water was added to 80% of the soil water holding capacity. For anaerobic set-up, 45 mL sterile distilled water was added till the soil was wholly saturated with water height about 8–10 cm above the soil surface. The bottles were closed with latex stoppers, crimp sealed, and vigorously shaken by hand for homogenisation.

Table 2. Chemical composition (% on dry matter base) of rice straw stems used in this study

Nitrogen	Carbon	Lignin	Cellulose	Hemicellulose	C:N
0.35	35.7	5.9	35.1	27.3	102

https://doi.org/10.17221/304/2021-PSE

Besides the microcosms with rice straw residues, identically prepared microcosms were set up without rice straw (referred to as CTSR-AE and CTSB-AE for aerobic microcosm set-up, and CTSR-AN and CTSB-AN for anaerobic condition set-up, respectively. Subsequently, the microcosms were incubated at 25 °C in the dark without shaking.

During incubation, CH_4 and CO_2 concentrations in the gas phase were measured on days 5, 10, 15, 20, 25, 30, 35, 40, 45, and 50 by taking 0.2 mL gas samples using a pressure-lock syringe. Before taking gas samples, the bottles were shaken vigorously to achieve equilibrium between the gas and liquid phase and then left standing to settle the soil particles. Gas samples were transferred into a 12 mL vacuum glass vial and directly analysed. After gas phase sampling, the aerobic microcosms were opened and left for 1 h to exchange the gas phase with air to avoid the accumulation of toxic CO_2 concentrations.

Analyses. Rice straw residues were dried, homogenised, and ground to particles of ≤ 1 mm. Total organic carbon (TC) and total nitrogen (TN) concentration in rice straw residues were determined using a CN analyser-mass spectrometer (ANCA-GSL Preparation Module +20-20 Stable Isotope Analyser, Europa Scientific, Cheshire, UK) after pulverisation. Hemicellulose, cellulose, and lignin fractions were determined according to a gravimetric procedure modified from the method described by Van Soest (1963) using ANKOM bags (ANKOM Technology Methods 5 and Technology Methods 6, New York, USA). Briefly, after a neutral detergent solution (NDS) extraction, the residues were mixed with 250 mL acid detergent solution (ADS), boiled overnight, and washed with hot deionised water until no foam was observed, and then washed with acetone, dried, and weighed. The difference between the dry weight of the original residue and the dry weight after NDS and ADS extraction composes the hemicellulose fraction. The remaining part after acid detergent extraction was suspended in a 72% H_2SO_4 solution and the suspension was stirred with a glass rod until the consistency of a smooth paste was reached. Additional volumes of 72% H_2SO_4 were added with stirring at hourly intervals. Afterwards, the suspension was kept for 3 h at room temperature, washed with hot deionised water and acetone until no acid was present, and dried and weighed. The dry weight of the remaining residue after the 72% H_2SO_4 extraction composes the lignin fraction, while the cellulose fraction is the residue after the acid detergent extraction removed the lignin.

CH_4 and CO_2 concentrations in the gas samples were analysed using a gas chromatograph equipped with a flame ionization detector (GC-8A, Shimadzu Corporation, Kyoto, Japan) (Naser et al. 2007).

Statistical analyses. One-way ANOVA was applied to test for the effects of treatments on CO_2 emission and rice straw decomposition. Duncan's multiple range test was used for determining significant mean differences accepting a probability of 0.05 as significant. Means of treatment effects on the CH_4 emission were compared with the Student *t*-test with comparisons at a 5% significance level.

RESULTS AND DISCUSSION

Total carbon and total nitrogen. The results indicated that the content of TC in the rice straw residues decreased during the experimental period, but the decrease was quite similar in all treatments with around 30% of the carbon removed at the end of the experiment and the highest TC removal rate between day 0 and day 15 (Table 3). The decomposition rate of TC content in the microcosm set-ups was in the following order: SB-AE < SB-AN < SR-AE < SR-AN. This study showed that the decomposition rate of TC content in the treatments SR-AN, SR-AE, and SB-AN microcosms did not differ significantly, neither among the treatments SR-AE, SB-AN, and SB-AE. However, the final TC decrease was significantly higher ($P < 0.05$) in the SR-AN microcosm set-up compared to the SB-AE microcosm set-up.

This study compared the difference between aerobic and anaerobic conditions in the soil undergoing two different soil management types and determine their effects on the straw's C and N dynamics. The experiment was conducted using laboratory soil microcosms. At the end of the experimental period (50 days of incubation), around 30% of TC was removed in all set-ups. Rates of rice straw degradation varied among different studies. The rates based on TC removal recorded in this study belong to the lower range of observed rice straw decomposition rates, but a similar rate has been recorded (Yadvinder-Singh et al. 2004). Lu et al. (2003) found that about 50% of rice straw C was lost within the initial 60 days of incubation under anaerobic conditions. According to Yadvinder-Singh et al. (2004), three main factors affect crop residue decomposition in soil, i.e., (*i*) crop residue factors; (*ii*) edaphic factors, and (*iii*) management factors. The C:N ratio is often used as an essential crop residue bound factor to explain the

https://doi.org/10.17221/304/2021-PSE

Table 3. Total carbon and total nitrogen content of rice straw residues in the different microcosm set-ups

Treatment	0	15	30	50
	(day)			
Carbon (g C/kg soil)				
SR-AN	7.15^{A}	5.76^{aB}	4.97^{aC}	4.50^{aD}
SR-AE	7.15^{A}	5.86^{aB}	5.79^{bB}	4.83^{abC}
SB-AN	7.15^{A}	5.84^{aB}	5.37^{abC}	4.86^{abC}
SB-AE	7.15^{A}	5.87^{aB}	5.74^{bB}	5.19^{bC}
Nitrogen (g N/kg soil)				
SR-AN	0.071^{A}	0.068^{bA}	0.060^{aB}	0.061^{bC}
SR-AE	0.071^{A}	0.061^{aB}	0.059^{aB}	0.047^{aC}
SB-AN	0.071^{A}	0.058^{aB}	0.055^{aB}	0.051^{abB}
SB-AE	0.071^{A}	0.053^{aB}	0.053^{aB}	0.048^{abB}

SR-AN – rice soil + anaerobic; SR-AE – rice soil + aerobic; SB-AN – upland rotation soil + anaerobic; SB-AE – upland rotation soil + aerobic. Values marked with different small letters in the same column are significantly different between the microcosm set-ups. Values marked with different capital letters in the same row are significantly different between the time point ($P < 0.05$, Duncan test)

decomposition rate of plant residues (Kopittke et al. 2020). Usually, rice straw has a C:N ratio of around 60, making them less amenable for fast degradation (Kimura et al. 2004). The rice straw residues used in this study had a C:N ratio of 102, explaining the relatively low decomposition rate recorded in this study.

Total N removal at the end of the experiment was between 14% and 33% (Table 3). At all sampling times, the SR-AN microcosms showed a higher residual TN than the other set-ups. Especially during the first 15 days of the incubation, a decrease in TN content in the SR-AN microcosms was very low and even not significant, while in the other set-ups, a rapid TN decrease was noted. The anaerobic set-ups SR-AN and SB-AN showed a higher final TN content than the aerobic set-ups SR-AE and SB-AE. The final decline in TN content in the microcosm set-ups was in the following order: SR-AN < SB-AN < SB-AE < SR-AE, but differences were only significant (at 5% level) between the SR-AN and SR-AE set-ups (Table 3). The N content of the rice residue decreased slowly during the first 15 days its removal rate strongly increased in the next 15 to 50 days of the decomposition period. These results agree with a study by Juan et al. (2009), who observed a 9.9% decrease of TN in rice straw residues incubated under flooded conditions in paddy rice soil over a 25 days incubation period.

Residual cellulose, hemicellulose, and lignin contents. At the end of the experimental period, the residual cellulose contents in the rice straw were 68.2, 75.8, 70.8, and 78.6% in the SR-AN, SR-AE, SB-AN, and SB-AE microcosm set-ups, respectively (Table 4). The result showed that residual cellulose content in the aerobic microcosm set-ups (SR-AE and SB-AE) was significantly higher than the anaerobic set-ups (SR-AN, SB-AN). There was no significant difference in cellulose removal between two anaerobic set-ups SR-AN and SB-AN and between two aerobic systems SR-AE and SB-AE ($P < 0.05$).

The removal of hemicellulose appeared to be higher than that of cellulose with 63.8, 57.4, 69.3, and 65.1% of the original content remaining in set-ups SR-AN, SR-AE, SB-AN, and SB-AE, respectively (Table 4). In contrast to cellulose removal, anaerobic hemicellulose removal seems less efficient than aerobic removal in both soils, but only the difference between residual contents in the SR-AN microcosms and the SR-AE microcosms was significant (at a 5% level). In all microcosm set-ups, also lignin contents decreased.

Table 4. Residual cellulose, hemicellulose and lignin contents in rice straw residues in the different soil microcosm set-ups at the different sampling times

Treatment	0	15	30	50
	(day)			
Cellulose remaining (%)				
SR-AN	100	85.9^{a}	78.7^{a}	68.2^{a}
SR-AE	100	87.7^{a}	83.3^{a}	75.8^{b}
SB-AN	100	91.4^{a}	78.2^{a}	70.8^{a}
SB-AE	100	92.6^{a}	89.9^{b}	78.6^{b}
Hemicellulose remaining (%)				
SR-AN	100	79.3^{b}	73.9^{a}	63.8^{b}
SR-AE	100	82.1^{b}	73.7^{a}	57.4^{a}
SB-AN	100	80.8^{b}	75.0^{a}	69.3^{ab}
SB-AE	100	74.5^{a}	81.8^{b}	65.1^{ab}
Lignin remaining (%)				
SR-AN	100	98.4^{a}	95.9^{a}	94.6^{a}
SR-AE	100	95.3^{a}	95.1^{a}	93.3^{a}
SB-AN	100	98.0^{a}	99.7^{a}	97.2^{a}
SB-AE	100	94.5^{a}	93.0^{a}	91.5^{a}

SR-AN – rice soil + anaerobic; SR-AE – rice soil + aerobic; SB-AN – upland rotation soil + anaerobic; SB-AE – upland rotation soil + aerobic. Values marked with different letters in the same column are significantly different ($P < 0.05$)

https://doi.org/10.17221/304/2021-PSE

In all cases, lignin degradation was lower than cellulose and hemicellulose degradation, i.e., lignin contents decreased only by 5.4, 6.7, 2.3, and 8.5% in set-ups SR-AN, SR-AE, SB-AN, and SB-AE, respectively (Table 4). However, there was no significant difference in residual lignin content among the different microcosm set-ups. The results indicated that the different incubation conditions did not affect lignin degradation.

Cellulose, hemicellulose, and lignin are the organic compounds – long chains of sugar molecules or phenol structures – very slow decomposition in the soil (Yan et al. 2019). These are often observed to decompose much more slowly than other litter components, as relatively few specialised organisms are can produce the necessary enzymes to break them down (Weil and Brady 2017). In the anaerobic conditions, the decompositions of these compounds tended slowly compared with the aerobic conditions because of low oxygen. In addition, the products of anaerobic metabolism processes are toxic to many microbes, which are can decompose these organic compounds (Weil and Brady 2017). This study indicated that the decomposition of the cellulose, hemicellulose, and lignin content might be affected by the anaerobic/aerobic conditions or the incubation time. The results of this study reported that the order of hemicellulose > cellulose > lignin, which was consistent with the results of Yan et al. (2019).

Table 5. Cumulated CO_2 emission in the different microcosm set-ups

Treatment	Total CO_2 emission (μmol/g soil)		
	day 15	day 30	day 50
SR-AN	85.6 ± 12.9^{c}	87.2 ± 11.6^{b}	127 ± 11.6^{b}
SR-AE	488 ± 47.9^{e}	1 857 ± 127^{f}	2 608 ± 184^{e}
SB-AN	47.2 ± 7.91^{b}	112 ± 23.4^{b}	117 ± 7.01^{b}
SB-AE	601 ± 39.5^{f}	1 993 ± 80.2^{f}	2 650 ± 173^{e}
CTSR-AN	11.3 ± 0.42^{a}	29.3 ± 1.77^{a}	37.4 ± 3.56^{a}
CTSR-AE	101 ± 11.5^{c}	283 ± 42.2^{d}	360 ± 74.1^{c}
CTSB-AN	11.2 ± 1.85^{a}	27.8 ± 3.35^{a}	38.5 ± 15.5^{a}
CTSB-AE	153 ± 8.2^{d}	487 ± 47.1^{e}	612 ± 64.3^{d}

SR-AN – rice soil + anaerobic; SR-AE – rice soil + aerobic; SB-AN – upland rotation soil + anaerobic; SB-AE – upland rotation soil + aerobic; CTSR-AN – no rice straw + rice soil + anaerobic; CTSR-AE – no rice straw + rice soil + aerobic; CTSB-AN – no rice straw + upland rotation soil + anaerobic; CTSB-AE – no rice straw + upland rotation soil + aerobic. Values marked with different letters in the same column are significantly different ($P < 0.05$)

Greenhouses gasses emission. Generally, the CO_2 emission rates under aerobic conditions increased gradually during the incubation period in both the microcosm set-ups with rice straw and the microcosm set-ups without the rice straw (Table 5). In the microcosm set-up with rice straw, the CO_2 emission in the SB-AE (601 μmol/g soil) was significantly higher than the treatments SB-AN (47.2 μmol/g soil), SR-AN (85.6 μmol/g soil), and SR-AE (488 μmol/g soil) on day 15. In the microcosm set-up without rice straw, the CO_2 emission was also recorded in the highest in the treatment of upland rotation soil (153 μmol/g soil) and significantly different compared to the other treatments. The results indicated that the CO_2 emission in the aerobic condition (SR-AE, SB-AE, CTSR-AE, CTSB-AE) was significantly higher than the anaerobic condition (SR-AN, SB-AN, CTSR-AN, CTSB-AN) at days 30 and 50 after incubation. However, the CO_2 emission in the treatments SR-AE and SB-AE did not differ significantly among treatment SR-AN or SB-AN. In the set-ups without rice straw, CO_2 production in the treatment CTSB-AE tended significantly higher than CTSB-AN, CTSR-AE, and CTSR-AN treatments on both days 30 and 50.

The addition of rice straw to soil resulted in increased release of CH_4 in both the SR-AN and SB-AN systems regardless of the sampling time, while there was no release in the aerobic set-ups (Table 6). Production of CH_4 in the set-ups without rice straw was minimal. Generally, the emission of CH_4 in both SR-AN and SB-AN increased with incubation time in both set-ups. On day 15, the CH_4 emission rate in the SB-AN ranged in 23.9 μmol/g soil, significantly lower than the SR-AN treatment (119 μmol/g soil). However, there were no significant differences in CH_4 emission among the SB-AN and SR-AN on days 30 and 50. On day 50, the total CH_4 emission in SR-AN treatment (426 μmol/g soil) was similar to SB-AN treatment (445 μmol/g soil).

Table 6. Total of CH_4 emission in the different microcosm set-ups at indicated sampling times

Treatment	Total CH_4 emission (μmol/g soil)		
	day 15	day 30	day 50
SR-AN	119 ± 19.9^{b}	250 ± 50.7^{a}	426 ± 16.7^{a}
SB-AN	23.9 ± 8.30^{a}	205 ± 30.7^{a}	445 ± 28.7^{a}

SR-AN – rice soil + anaerobic; SB-AN – upland rotation soil + anaerobic. Values marked with different letters in the same column are significantly different ($P < 0.05$)

https://doi.org/10.17221/304/2021-PSE

The degradation of rice straw in the microcosms was accompanied by the production of CO_2 and CH_4 gases. Indeed, CH_4 was only produced when adding rice straw, while CO_2 emission was largely increased when rice straw was added compared with the control systems without rice straw. It suggests that the production of CH_4 and CO_2 originated primarily from the decomposition of straw and not from other soil organic matter and that the rice straw residues were being mineralised. Previous studies reported that rice straw into flooded rice soil enhances CH_4 emission (Naser et al. 2007). In flooded rice soils, CH_4 is known as an end product of the anaerobic decomposition of organic residues (Weil and Brady 2017), in which methanogens use the products of fermentation to produce CH_4. Significant CH_4 emission was only observed in case rice straw was added under flooded (SR-AN and SB-AN) conditions. Under aerobic conditions, only CO_2 was produced. The latter indicates that in the aerobic microcosms, methanogenic activity was inhibited. The production of CH_4 in the anaerobic microcosms containing the SR soil (SR-AN) started shortly after the start of the incubation with high production rates until a maximum was reached, whereas the production of CH_4 in the microcosms containing the SB soil (SB-AN) started after a lag phase of 10 days. The observed lag period might have been necessary for the sequential reduction of all-electron acceptors until a redox potential of below approximately –150 mV was reached, which is needed before reducing CO_2 to CH_4 and CH_4 production from acetate can proceed after submerging the soil (Patrick 1981). After collection in the rice paddy field, the waterlogged SR soil used in the SR-AN set-up was kept in the original condition until it was used for filling the microcosms so that the redox potential might have been suitable for CH_4 production immediately after starting incubation. Another explanation can be that in the SB soil, sampled under upland conditions, methanogenic populations had been largely decreased in number and that some time was needed for those populations to increase in size to produce detectable CH_4 amounts.

In this experiment, the total CO_2 emissions in the aerobic set-ups were higher compared to those in the anaerobic set-ups at all sampling times. Nishimura et al. (2008) reported that CO_2 production in paddy rice soil was severely restricted under anaerobic conditions during the submerged period of rice cultivation. Similarly, according to Koizumi et al. (2001), the amount of CO_2 emission from a paddy water surface was much lower than that from the soil surface in upland crop fields due to the submerged anaerobic condition. However, the total CO_2 emission was largely increased when rice straw was added compared to the control systems without rice straw in both anaerobic and aerobic microcosm set-up. Also, a previous study indicated that the CO_2 content in the soil solution increased with an increasing rate of straw amendment under flooding conditions (Liu et al. 2009).

The main factor affecting rice straw residue degradation is the incubation conditions, i.e., whether the set-ups were anaerobic or aerobic. Indeed, significantly different values were recorded in anaerobic and aerobic set-ups for some of the degradation variables, although differences were low. The cellulose removal significantly differed between the anaerobic conditions compared with the aerobic conditions in both SR and SB treatments. Also, significant differences were obtained in the remaining hemicellulose content between the SR-AN and SR-AE set-ups. Only a few studies compared in a direct way the degradation of rice straw under anaerobic and aerobic conditions. It has been widely accepted that decomposition processes under anaerobic conditions are slower compared to aerobic conditions. Villegas-Pangga et al. (2000) reported a 27–45% reduction in C evolution in rice straw when incubated under anaerobic conditions compared to under aerobic systems.

Similarly, another study showed that flooding results in a tendency to reduce C mineralisation (Devêvre and Horwáth 2000). In our research, the decomposing ability of the anaerobes under flooded conditions was sufficiently high to decompose the plant materials to a quite similar rate and extent of that of the aerobes under upland conditions (Yadvinder-Singh et al. 2004). On the other hand, rice straw decomposition under aerobic conditions might have been affected by the adverse effects of accumulated CO_2 in the aerobic flasks. In this study, the concentrations of CO_2 in the microcosm set-up under the aerobic conditions were often 6–10 times higher than the concentrations suitable for microbial activity (i.e., 1 vol%), which was reported by Šantrůčková and Šimek (1997). Soil microbial activity and bacterial diversity have indeed been shown to be significantly affected by elevated CO_2 (Jia 2010).

The soil history did not affect rice straw residues degradation. However, significant differences in the decomposition of rice straw residue were found between the SB and SR soils and under anaerobic/aerobic conditions. A sufficiently high microbial redundancy exists in the soil organic matter decomposition func-

https://doi.org/10.17221/304/2021-PSE

tion in rice paddy soil for coping with changes in land use and crop management patterns (Nannipieri et al. 2003). The application of upland crops rotation in the paddy soil could reduce the emission of CO_2 and CH_4 gases, toward reducing the impact of climate change, and improve soil fertility in the VMD region.

REFERENCES

Devêvre O.C., Horwáth W.R. (2000): Decomposition of rice straw and microbial carbon use efficiency under different soil temperatures and moistures. Soil Biology and Biochemistry, 32: 1773–1785.

Gorbunova A.Y., Korobushkin D.I., Kostina N.V., Degtyarev M.I., Gongalsky K.B., Zaitsev A.S. (2020): Level of soil moisture determines the ability of *Eisenia fetida* to re-incorporate carbon from decomposed rice straw into the soil. European Journal of Soil Biology, 99: 103209.

Guong V.T., Dong N.M., Khoi C.M. (2010): Soil organic matter quality and nitrogen supplying capacity in continuously triple rice and rice-upland crop rotation systems. Can Tho University Journal of Science, 16b: 147–154.

Jia X. (2010): Effects of elevated CO_2 on soil microbial activity and bacterial diversity in *Pinus koraiensis* seedlings fields in changbai mountain. In: Proceeding of the 4th International Conference on Bioinformatics and Biomedical Engineering (ICBBE), Chengdu, 18–20 June 2010.

Kimura M., Murase J., Lu Y. (2004): Carbon cycling in rice field ecosystems in the context of input, decomposition and translocation of organic materials and the fates of their end products (CO_2 and CH_4). Soil Biology and Biochemistry, 36: 1399–1416.

Koizumi H., Kibe T., Mariko S., Ohtsuka T., Nakadai T., Mo W., Toda H., Seiichi N., Kobayashi K. (2001): Effect of free-air CO_2 enrichment (FACE) on CO_2 exchange at the flood-water surface in a rice paddy field. New Phytologist, 150: 231–239.

Kopittke P.M., Dalal R.C., Hoeschen C., Li C., Menzies N.W., Mueller C.W. (2020): Soil organic matter is stabilised by organo-mineral associations through two key processes: the role of the carbon to nitrogen ratio. Geoderma, 357: 113974.

Liu J., Han Y., Cai Z.C. (2009): Decomposition and products of wheat and rice straw from a FACE experiment under flooded conditions. Pedosphere, 19: 389–397.

Lu Y., Watanabe A., Kimura M. (2003): Carbon dynamics of rhizodeposits, root-and shoot-residues in a rice soil. Soil Biology and Biochemistry, 35: 1223–1230.

Metson A.J. (1961): Methods of Chemical Analysis for Soil Survey Samples. New Zealand, New Zealand Department of Scientific and Industrial Research.

Nannipieri P., Ascher J., Ceccherini M., Landi L., Pietramellara G., Renella G. (2003): Microbial diversity and soil functions. European Journal of Soil Science, 54: 655–670.

Naser H.M., Nagata O., Tamura S., Hatano R. (2007): Methane emissions from five paddy fields with different amounts of rice straw application in central Hokkaido, Japan. Soil Science and Plant Nutrition, 53: 95–101.

Nishimura S., Yonemura S., Sawamoto T., Shirato Y., Akiyama H., Sudo S., Yagi K. (2008): Effect of land use change from paddy rice cultivation to upland crop cultivation on soil carbon budget of a cropland in Japan. Agriculture, Ecosystems and Environment, 125: 9–20.

Patrick W. (1981): The role of inorganic redox systems in controlling reduction in paddy soils. In: Proceedings of Symposium on Paddy Soils, Berlin, Springer, 107–117.

Puget P., Drinkwater L. (2001): Short-term dynamics of root-and shoot-derived carbon from a leguminous green manure. Soil Science Society of America Journal, 65: 771–779.

Šantrůčková H., Šimek M. (1997): Effect of soil CO_2 concentration on microbial biomass. Biology and Fertility of Soils, 25: 269–273.

Singh G., Dhakal M., Yang L.L., Kaur G., Williard K.W.J., Schoonover J.E., Sadeghpour A. (2020): Decomposition and nitrogen release of cover crops in reduced- and no-tillage systems. Agronomy Journal, 112: 3650–3618.

Soest P.V. (1963): Use of detergents in the analysis of fibrous feeds. II. A rapid method for the determination of fiber and lignin. Journal of the Association of Official Agricultural Chemists, 46: 829–835.

Thinh D.K. (2009): Socio-economic impacts of mutant rice varieties in Southern Vietnam induced plant mutations in the genomics era. In: Shu Q.Y. (ed.): Induced Plant Mutations in the Genomics Era. Rome, Food and Agriculture Organisation of the United Nations, 65–68. ISBN: 978-92-5-106324-8

Villegas-Pangga G., Blair G., Lefroy R. (2000): Measurement of decomposition and associated nutrient release from straw (*Oryza sativa* L.) of different rice varieties using a perfusion system. Plant and Soil, 223: 1–11.

Weil R.R., Brady N.C. (2017): The Nature and Properties of Soils. 15th Edition. London, Pearson Education, 1104. ISBN: 978-0133254488

Yadvinder-Singh Ladha J., Khind C., Khera T., Bueno C. (2004): Effects of residue decomposition on productivity and soil fertility in rice-wheat rotation. Soil Science Society of America Journal, 68: 854–864.

Yan C., Yan S.S., Jia T.Y., Dong S.K., Ma C.M., Gong Z.P. (2019): Decomposition characteristics of rice straw returned to the soil in northeast China. Nutrient Cycling in Agroecosystems, 114: 211–224.

Received: June 24, 2021
Accepted: December 13, 2021
Published online: January 4, 2022