Mitigating Carbon Emissions: The Impact of Peat Moss Feeding on CH$_4$ and CO$_2$ Emissions during Pig Slurry Storage

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Abstract: The present study investigated the impact of peat moss as a feed additive on the emission of methane (CH$_4$) and carbon dioxide (CO$_2$) from piggery slurry stored in slurry pits. There is no well-known study on the relationship between pig manure generated after feeding peat moss as a feed additive and CH$_4$ and CO$_2$ released during the storage period. A lab-scale experiment was conducted for two months using a slurry pit simulator composed of six vessels—three for pig slurry collected after feeding 3.0% peat moss as a feed additive (PFS) and three for pig slurry without feeding peat moss (CTL). PFS reduced CO$_2$ and CH$_4$ emissions ($p < 0.05$) from stored pig slurry by approximately 23% and 44%, respectively. PFS exhibits substantially elevated concentrations of humic substance (HS) such as humic acid, fulvic acid, and humin compared with CTL, with fold differences of 2.3, 1.8, and 1.1, respectively. Elevated HS levels in the PFS seemed to limit hydrolysis, resulting in lower total volatile fatty acid concentrations compared with CTL. A dominance of CH$_4$ in total carbon emissions was observed ($p < 0.05$), with CH$_4$ accounting for approximately 93% and 95% of total carbon emissions in PFS and CTL, respectively. PFS had a roughly 43% lower impact on cumulative carbon emissions than CTL, primarily due to decreased CH$_4$ emissions. These findings suggest that PFS may be a promising approach for mitigating carbon emissions and potentially impacting environmental sustainability and climate change mitigation efforts.

Keywords: pig slurry; slurry pit; storage; peat moss; humic substance; methane emission; carbon dioxide emission

1. Introduction

The United Nations Environment Program (UNEP) announced in 2021 that agriculture is responsible for 40% of anthropogenic methane (CH$_4$) emissions, with enteric fermentation and manure management accounting for 32% of the emissions and rice cultivation accounting for 8% [1]. Countries worldwide agree with the claim that CH$_4$ emissions and carbon dioxide (CO$_2$) must be reduced to improve global warming [1]. The number of countries that have endorsed the Global Methane Pledge (GMP) to curtail CH$_4$ emissions—known for their amplified impact on global warming—by 30% before 2030 has risen to 151 [2]. However, to accurately calculate the amount of CH$_4$ reduction, actual data on emission sources and emissions in various manure management environments are required.

The slurry pit stores slurry-type manure generated in slatted-floor pig houses for a certain period and then discharges it outside [3–6]. Stored pig slurry generally induces biochemical reactions depending on aerobic and anaerobic conditions resulting from pig house management [3,7–9]. Greenhouse gases such as CH$_4$, CO$_2$, and nitrous oxide (N$_2$O) can be emitted due to biochemical reactions, and studies have been conducted on greenhouse gas emissions from pig slurry pits under various environmental conditions [10–12]. During storage of the raw pig slurry, CH$_4$ and CO$_2$ emissions were reported to range from 5 to 75 g m$^{-3}$ d$^{-1}$ and 50 to 300 g m$^{-3}$ d$^{-1}$, respectively [12–14]. N$_2$O emissions occurred at negligible levels [14–17].
Various studies have been conducted to reduce greenhouse gas emissions from these pig slurry pits in terms of diet manipulation, housing system, and manure management, such as the use of feed additives [18], the use of cover agents [12,19], the acidification of manure [17,20], and the formation of aerobic conditions in the slurry [8]. In particular, for acidification, chemical amendments such as sulfuric acid and citric acid and organic-based compounds such as humic substances (HS) were used [21–23]. HS is composed mainly of humic acid, fulvic acid, and humin and is usually associated with acidification [24]. However, according to a recent study, the abundant electron transport function derived from the molecular structure of HS causes a biochemical reaction to inhibit hydrolysis and methanogenesis [25–28].

Peat moss contains such HS, and the contents of HS in peat moss have been reported as 76% humin, 18% humic acid, and 3% fulvic acid based on the total organic matter content [29]. When peat moss was used for feeding livestock, there were positive effects, such as promoting digestion and improving growth rate [24]. Feeding of HS improved broiler productivity by about 7% compared with the control, which was estimated to be due to increased absorption of nitrogen, phosphorus, and other nutrients according to chelating properties [30]. Several studies have shown that feed efficiency is improved when HS is fed as feed additives to livestock, especially in poultry and pigs [30–34]. The reasons for the increase in feed efficiency include the maintenance of intestinal microbial activity, improvement of animal gut health such as antibacterial activity [35–37], modification of protein digestibility [37], and activation of pancreatic enzymatic activity [35].

However, the prior studies mentioned above focus only on the utilization of HS themselves or on the effect of peat moss on the physiological changes of livestock. There is no well-known study on the relationship between pig manure generated after feeding peat moss as a feed additive and CH$_4$ and CO$_2$ released during the storage period. Hence, the purpose of this study is to investigate the impact of peat moss as a feed additive on the emissions of CH$_4$ and CO$_2$ originating from pig slurry stored in a slurry pit.

2. Materials and Methods

2.1. Experimental Design for Gas Emissions

A lab-scale experiment simulating a pig manure storage facility was conducted (Figure 1). The slurry pit simulator consisted of six vessels, three for pig slurry excreted after feeding a 3.0% peat moss (wet basis) as a feed additive (PFS) and three for pig slurry excreted from pigs fed conventional feed without peat moss supplement (CTL).

The room temperature at which the vessels were installed was measured at 30 min intervals using a T-type thermocouple connected to the module (NI-9213, National Instruments, Austin, TX, USA). The room temperature was maintained between 26 °C and 35 °C throughout the experiment to simulate summer conditions.

Each vessel (200 mm in diameter and 500 mm in depth) was made of polyvinyl chloride (PVC). The container was sealed with a plastic lid, and an inlet–outlet was installed on top of the cover. Piggery slurry was filled in to a height of 300 mm (9.4 L), which was 60% of the storage space of each vessel. Air corresponding to an exchange rate of 7.5 times the headspace volume per hour was ventilated (ventilation rate: 0.79 L·min$^{-1}$). In order to achieve uniform flow regulation across all six containers, six air flow meters (LF-101, Unicell Instruments, Bucheon, Republic of Korea) were affixed between the inlet tubes connecting the PFS and CTL vessels and the air pump (SWT-20, WITHUS AIR, Busan, Republic of Korea).

Since moisture due to condensation may occur inside the exhaust tube connected to the outlet valve of the vessel, a water trap made of a glass bottle was installed at the point before the air is discharged.
Since moisture due to condensation may occur inside the exhaust tube connected to waterers and washing water), equivalent to about 20% of the weight of the pig slurry, was evenly mixed with the pig slurry \cite{38}. The initial moisture content of CTL and PFS increased to 89.4% and 88.9%, respectively.

2.2. Animals and Housing Conditions

Six sows, aged over 8 months and weighing 215 ± 15 kg, were used. They were divided into two groups: PFS and CTL, each with three respiratory chambers. One sow was placed in each chamber with ad libitum access to feed and water. Chambers (1 × 2.4 × 1.5 m) had feeding pipes, waste removal doors, plastic slat flooring, and ventilation via a ring blower (HB-129s, Hae Sung Technologies, Seoul, Republic of Korea) providing 300 L·min\(^{-1}\) airflow. Airflow was monitored using a mass flow meter (HFM 200 LFE, Teledyne Hastings, Hampton, VA, USA). Chambers maintained a temperature-controlled environment (24 °C) using strategically placed thermocouples (T-type). Lighting mimicked natural patterns (6 a.m. to 8 p.m.). This lighting schedule not only contributed to the animals' natural rhythms but also facilitated meticulous observation and management of the sows to guarantee their well-being and adherence to the experimental conditions. The animal protocol used in this study has been reviewed by the Chungnam National University-Institutional Animal Care and Use Committee (CNU-IACUC) for ethical procedures and scientific management.

All sows in both groups (conventional diet and diet supplemented with 3.0% peat moss) underwent a feed adaptation period of five days. Following the adaptation period, excreted pig slurry from sows was collected for three days. The collected pig slurry (30 L of each group) was thoroughly mixed and immediately refrigerated at 5 °C. Conventional diet consisted of 12.9% crude protein, 2.6% crude fat, 0.7% calcium, 0.4% phosphorus, 17.2% neutral detergent fiber (NDF), 8.1% acid detergent fiber (ADF), and 0.7% lysine. The feed additive peat moss employed in this study was formulated with the following constituents on a dry matter basis: 0.73% crude fat, 0.51% calcium, 0.07% phosphorus, 43.7% NDF, and 37.4% ADF.

During the experiment (56 days), pig slurry was sampled from the vessel five times every two weeks. Total solid (TS) of raw pig slurry obtained from CTL and PFS was 127.5 and 133.5 g·kg\(^{-1}\), respectively. Volatile solid (VS) of CTL and PFS was 103.4 and 105.5 g·kg\(^{-1}\), respectively (Table 1). When the stored pig slurry was put into the vessel, distilled water (waste water from waterers and washing water), equivalent to about 20% of the weight of the pig slurry, was evenly mixed with the pig slurry \cite{38}. The initial moisture content of raw slurry was 87.3% for CTL and 86.6% for PFS. After adding water, the moisture content of CTL and PFS increased to 89.4% and 88.9%, respectively.
Table 1. Physico-chemical properties of raw pig slurry obtained from CTL and PFS.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>CTL</th>
<th>PFS</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>7.8 ± 0.0 n.s.</td>
<td>8.1 ± 0.0 n.s.</td>
</tr>
<tr>
<td>Total solid (TS, g kg⁻¹ slurry)</td>
<td>127.5 ± 1.7 n.s.</td>
<td>133.5 ± 3.8 n.s.</td>
</tr>
<tr>
<td>Volatile solid (VS, g kg⁻¹ slurry)</td>
<td>103.4 ± 1.7 n.s.</td>
<td>105.5 ± 3.9 n.s.</td>
</tr>
<tr>
<td>Carbon (C, g kg⁻¹ slurry)</td>
<td>57.4 ± 0.9 n.s.</td>
<td>58.6 ± 2.2 n.s.</td>
</tr>
<tr>
<td>Total volatile fatty acid (TVFA, g kg⁻¹ slurry)</td>
<td>24.0 ± 0.6 n.s.</td>
<td>13.8 ± 3.5 n.s.</td>
</tr>
</tbody>
</table>

Data (means ± S.E., n = 3) with superscript n.s. indicates no significant difference (p > 0.05) between CTL and PFS. Carbon was calculated by dividing VS by a factor of 1.8 [39].

2.3. Physico-Chemical Analysis

The TS and VS of pig slurry and peat moss were analyzed using APHA standard methods [40]. The humic acid, fulvic acid, and humin of pig slurry and peat moss were analyzed. About 5 g of sample (peat moss and pig slurry) was taken in a 50 mL centrifuge tube, 40 mL of CHCl₃/MeOH (3:1, v/v) was added, and the mixture was allowed to react for 24 h to extract free lipids, followed by centrifugation (Mega 17R, Hanil, Daejeon, Republic of Korea). After centrifugation, the supernatant (humic acid + fulvic acid) and the precipitate (humin) were separated, and 40 mL of sodium pyrophosphate alkali solution (0.5 M NaOH and 0.1 M Na₄P₂O₇) was added to the remaining residue except for the supernatant, followed by shaking for about 1 h.

All the extracted supernatants were combined, 6 N HCl was added little by little to adjust the pH of the solution to 1.0, and it was allowed to stand for about 6 h so that the humic acid precipitated to the bottom, followed by centrifugation. A total of 1 M NaOH solution was added to the precipitate, ultrasonic extraction was performed for about 1 h, left overnight, centrifuged, and the supernatant was filtered through a dry filter (Whatman No. 4) and diluted to 100 mL with distilled water. Humic and fulvic acid were measured using a UV/VIS spectrophotometer (UV-2450, Shimadzu Co., Kyoto, Japan). Humin was analyzed as a precipitate generated using sodium pyrophosphate alkali solution and 200 mL of 10% hydrofluoric acid. Table 2 presents the quantification of HS in pig slurry and peat moss.

Table 2. Humic substances (HS) concentration of raw pig slurry and peat moss.

<table>
<thead>
<tr>
<th>Humic Substances</th>
<th>Raw Pig Slurry</th>
<th>Peat Moss</th>
<th>% TS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g kg⁻¹ slurry</td>
<td>g kg⁻¹ slurry</td>
<td></td>
</tr>
<tr>
<td>Humic acid</td>
<td>0.08 ± 0.0 a</td>
<td>0.18 ± 0.0 b</td>
<td>6.43</td>
</tr>
<tr>
<td>Fulvic acid</td>
<td>7.8 ± 0.1 a</td>
<td>14.4 ± 0.2 b</td>
<td>8.03</td>
</tr>
<tr>
<td>Humin</td>
<td>54.3 ± 0.9 a</td>
<td>60.8 ± 1.0 b</td>
<td>26.5</td>
</tr>
</tbody>
</table>

Data (means ± S.E., n = 3) with different letters in the same row are significantly different (p < 0.05).

A pig slurry supernatant mixed with 25% metaphosphoric acid was injected into the gas chromatography–flame ionization detector (GC-FID) system (iGC 7200, DS Science, Daejeon, Republic of Korea) to analyze total volatile fatty acid (TVFA). The injector and detector temperatures were set to 280 °C as the default setting of the GC-FID. The GC carrier gas (N₂), detector H₂ gas, and airflow were set to 1.0, 30.0, and 300 mL·min⁻¹, respectively. The split ratio was 10.
2.4. Analysis of Methane (CH$_4$) and Carbon Dioxide (CO$_2$) Emissions

The gas discharged from each vessel was collected in a 10 L Tedlar bag (CEL Scientific Tedlar gas bag, Santa Fe Springs, CA, USA). The CH$_4$ concentration was measured using a methane gas sensing module (LGD Compact-A, axetris, Kaegiswil, Switzerland). The CO$_2$ concentration of the collected gas was analyzed using a GC fitted with a thermal conductivity detector (iGC 7200, DS Science, Daejeon, Republic of Korea). The temperature of the oven and detector was set to 50 °C. The total flow rate of He gas and air was set at 25.0 mL·min$^{-1}$. The CH$_4$ and CO$_2$ emissions were calculated using the following Equation (1) [5]:

\[
\text{Gas emission per day (g·d}^{-1}\text{)} = \left( C_E \times V \times \frac{273.15 \times MW}{(273.15 + T_E) \times 22.4 \times 10^3} \right) - \left( C_A \times V \times \frac{273.15 \times MW}{(273.15 + T_A) \times 22.4 \times 10^3} \right)
\]

$C_E$ = Target gas concentration of exhausted air (mL·m$^{-3}$).
$V$ = Headspace ventilation rate (m$^3$·min$^{-1}$).
$MW$ = Molecular weight of target gas (g·mol$^{-1}$).
$T_E$ = Exhaust air temperature (°C).
$C_A$ = Target gas concentration of ambient air (mL·m$^{-3}$).
$T_A$ = Ambient air temperature (°C).

2.5. Statistical Analysis

Taking into account the underlying normal distribution characteristics of the dataset, the investigation employed a one-way ANOVA (IBM SPSS STATISTICS 22) to evaluate the impact of pig slurry fed with peat moss on the cumulative emissions of CH$_4$ and CO$_2$ per VS over a defined temporal interval. Additionally, an independent $t$-test was employed to make a comparative assessment of the daily emissions of CH$_4$ and CO$_2$, as well as the outcomes derived from physico-chemical analysis, between PFS and CTL. Tukey’s test was used for post hoc analysis. The analysis of variance was conducted at a significance level of 0.05.

3. Results and Discussion

3.1. CH$_4$ and CO$_2$ Emissions during Storage of Pig Slurry

Cumulative CH$_4$ and CO$_2$ emissions during the experiment were reduced by about 44% and 23% in the PFS compared with the CTL (Figures 2 and 3). In the fresh slurry on the day of the start of the experiment, CH$_4$ emissions were not expected to be high due to the minor involvement of methanogenic microorganisms [20], so the measurement of CH$_4$ emissions was carried out seven days after the start of the experiment. A significant difference between PFS and CTL in cumulative methane emissions during the experimental period occurred from day 49 (Figure 2). The daily CH$_4$ emission of CTL ranged from 3.9 to 34.8 g·m$^{-3}$·d$^{-1}$, and the range of fluctuation was greater than that of the PFS (4.2 to 10.0 g·m$^{-3}$·d$^{-1}$). This study found that the amount of CH$_4$ emissions from pig slurry produced by CTL falls within the range of 5 to 75 g·m$^{-3}$·d$^{-1}$ that has been reported in other studies conducted under comparable conditions [12–14]. As a precursor study to this research, an evaluation was conducted using respiration chambers to assess the effect of peat moss diet supplementation (3.0% wet basis) on CH$_4$ emissions from sows during the pre-storage phase of manure [41]. The research conducted over eight days revealed that the average CH$_4$ emissions from the control and treatment groups were 14.96 g·d$^{-1}$·head$^{-1}$ and 14.57 g·d$^{-1}$·head$^{-1}$, respectively, indicating no significant effect of peat moss. Using a 3.0% peat moss feed additive affected CH$_4$ emissions in a storage environment rather than during the rearing stage.
Figure 2. Cumulative and daily methane (CH$_4$) emissions during the experiment. Error bars indicate standard error (n = 3). The statistical differences (p < 0.05) between PFS and CTL are marked as ***.

Figure 3. Cumulative and daily carbon dioxide (CO$_2$) emissions during the experiment. Error bars indicate standard error (n = 3). The statistical differences (p < 0.05) between PFS and CTL are marked as ***.
During most of the experimental period, CO$_2$ emissions in the CTL were higher than in the PFS, and the increase was considerable on the 28th day (Figure 3). PFS also showed a slight increase in daily CO$_2$ generation on the 28th day and decreased until the 49th day. Twenty-eight days after the initiation of the experiment coincided with the period of highest temperature (34 °C) observed throughout the experiment. Thus, it can be inferred that there was an increase in CO$_2$ emissions in both the PFS and CTL during this period [12].

The daily CO$_2$ emission of the CTL ranged from 23.3 to 83.7 g·m$^{-3}$·d$^{-1}$, indicating a considerable degree of emission fluctuation over time. This fluctuation range was greater than that of the PFS system, which exhibited a range of CO$_2$ emissions from 18.6 to 59.5 g·m$^{-3}$·d$^{-1}$. The CO$_2$ emissions from pig slurry produced by the CTL were slightly lower than the range reported in other research (50 to 300 g·m$^{-3}$·d$^{-1}$) conducted under comparable conditions [12].

The daily and cumulative emissions of CH$_4$ and CO$_2$ per VS for the five sampling periods were analyzed (Table 3). The daily CH$_4$ emission of CTL ranges from 0.05 to 0.54 g·kg$^{-1}$ VS·d$^{-1}$ and of PFS ranges from 0.05 to 0.15 g·kg$^{-1}$ VS·d$^{-1}$. Except for the second period of daily CO$_2$ emissions per VS, where a $p$-value of <0.05 was observed, there were no statistically significant differences between PFS and CTL in terms of daily CH$_4$ and CO$_2$ emissions per VS. Table 1 indicates that there were no significant differences in the concentrations of organic matter components, including TS, VS, and carbon, between the PFS and CTL. This result suggests that peat moss as a feed additive has no significant effect on the degradation of organic matter in pig slurry due to enhanced feed efficiency. Consequently, it can be surmised that the lower CH$_4$ emissions observed in PFS compared with CTL are attributable to the distinctive biochemical properties of HS rather than a reduction in organic matter. PFS has significantly higher levels of humic acid, fulvic acid, and humin than CTL, by a factor of 2.3, 1.8, and 1.1, respectively, which lends credence to this inference (Table 2). Prior research has documented that HS is critical in restraining methanogenesis or hydrolysis in anaerobic digestion [25–28].

Although the daily emissions of CH$_4$ and CO$_2$ per VS were not significantly different between PFS and CTL, the present study found that the decomposition of degradable substances in the pig slurry of CTL occurred primarily during the second and third period, while the decomposition of recalcitrant substances occurred slowly after that, leading to a gradual decrease in the daily emissions of CH$_4$ and CO$_2$ over time.

The cumulative emissions of CH$_4$ and CO$_2$ per VS were lower in the PFS than in the CTL, but no statistically significant differences were observed ($p > 0.05$). The cumulative CH$_4$ emission of the CTL was 7.74 g·kg$^{-1}$ VS, which was approximately 3.5 times lower than the CH$_4$ emission reported in a previous study [12].

The discrepancy between our experimental results and those reported in other studies is likely attributable to differences in the characteristics of the pig slurry and variations in temperature conditions. The notable variation in CH$_4$ emissions observed during a specific period in the control group is attributed to the intermittent release of CH$_4$ through ebullition [42]. Furthermore, the high variability of gas concentrations, including CO$_2$ and CH$_4$, in livestock manure slurry and their tendency to reach maximum values are well-established phenomena in laboratory-scale studies [42,43].

Based on the daily and cumulative emissions of CH$_4$ and CO$_2$ per VS, the present study suggests that incorporating 3.0% peat moss into conventional pig feed may be an effective way to reduce CH$_4$ and CO$_2$ emissions. This finding can be explained by the improved feed efficiency that leads to a lower organic matter content in pig slurry, ultimately reducing the emissions of CH$_4$ and CO$_2$ [20].
Table 3. CH\textsubscript{4} and CO\textsubscript{2} emissions per VS during the experiment period (56 days).

<table>
<thead>
<tr>
<th>Period</th>
<th>Methane (CH\textsubscript{4})</th>
<th>Carbon Dioxide (CO\textsubscript{2})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Daily Emissions</td>
<td>Cumulative Emissions</td>
</tr>
<tr>
<td></td>
<td>PFS</td>
<td>CTL</td>
</tr>
<tr>
<td></td>
<td>g kg\textsuperscript{-1} VS d\textsuperscript{-1}</td>
<td>g kg\textsuperscript{-1} VS</td>
</tr>
<tr>
<td>1st period (0–7 d)</td>
<td>0.14 ± 0.05</td>
<td>0.16 ± 0.06</td>
</tr>
<tr>
<td>2nd period (8–14 d)</td>
<td>0.15 ± 0.04</td>
<td>0.54 ± 0.21</td>
</tr>
<tr>
<td>3rd period (15–28 d)</td>
<td>0.07 ± 0.01</td>
<td>0.06 ± 0.01</td>
</tr>
<tr>
<td>4th period (29–42 d)</td>
<td>0.05 ± 0.01</td>
<td>0.05 ± 0.02</td>
</tr>
<tr>
<td>5th period (43–56 d)</td>
<td>0.08 ± 0.02</td>
<td>0.10 ± 0.03</td>
</tr>
</tbody>
</table>

Data (means ± S.E., n = 3) with different letters in the same column are significantly different (p < 0.05).
3.2. Concentration of Volatile Fatty Acid (VFA) in Pig Slurry

Figure 4 depicts the changes in VFA concentration in the pig slurry over the storage period. Considering the temporal variations in TVFA concentration observed in the pig slurry of PFS and CTL, it can be concluded that the concentration decreased until day 28, increased until day 42, and then decreased again until day 56. This trend indicates a complex dynamic in the formation and degradation of VFA in the pig slurry. A negative correlation between VFA concentration and CH$_4$ emissions in pig slurry [20] implies that the period of TVFA accumulation (28–42 days) was related to a decrease in CH$_4$ emissions, whereas the periods of TVFA decrease (0–28 days, 42–56 days) were related to an increase in CH$_4$ emissions.

During anaerobic digestion, VFA is sequentially generated through hydrolysis and acidogenesis. Methanogenic microorganisms then utilize this VFA to produce CH$_4$. As a result, the concentration of VFA tends to increase immediately before the increase in CH$_4$ emissions and then decrease shortly after the increase in CH$_4$ emissions. This pattern is because the production of VFA precedes the production of CH$_4$ in the anaerobic digestion process.

In the first two weeks of storage (0–14 d), the concentration of TVFA and emission of CO$_2$ decreased, and CH$_4$ emission increased (Table 3, Figure 4). It is assumed that the methanogenesis activity increased due to the slurry’s anaerobic decomposition of organic substances. In the third period (15–28 d), CO$_2$ increased, and TVFA concentration and CH$_4$ emission decreased. From the second week of pig slurry storage, the rate of methanogenesis was stagnant, while fermentation and aerobic respiration of pig slurry...
were presumed to be active [20]. In the fourth period (29–42 d), only TVFA concentration increased, while emissions of both CO₂ and CH₄ decreased. The proliferation of acidogenic fermentative bacteria in the pig slurry led to the buildup of VFA, which, in turn, suppressed the emissions of CO₂ and CH₄. During the fifth experiment period (43–56 d), a decrease in TVFA concentration and CO₂ emission was observed, accompanied by an increase in CH₄ emission.

The results indicate that PFS tended to lower TVFA concentrations by 37 to 44% compared with CTL (Figure 4). However, statistical analyses revealed no significant differences between the PFS and CTL regarding TVFA, except propionic and butyric acid. Previous research has demonstrated that HS can elicit hydrolysis inhibition within a concentration range of 0.5–5.0 g L⁻¹ [28]. Two putative mechanisms underlying this inhibition have been posited: threshold-type inhibition, which involves the binding of humic acid to active sites of hydrolytic enzymes, thereby blocking substrate access and disrupting crucial cellular transport processes via binding to bacterial cell walls [26].

HS represent an important outcome of the aerobic composting process and aerobic digestion, such as autothermal thermophilic aerobic digestion (ATAD), and are a crucial indicator for evaluating compost maturity [44,45]. As a core product of the process, they are vital for achieving a mature compost that can be used for soil amendments, which have been shown to enhance plant growth [46]. Therefore, aerobic digestion or composting systems are a better method for treating pig slurry with high levels of humic substances than anaerobic digestion.

Previous studies have explored the increased VFA content in pig slurry resulting from fibrous feedstuffs [47,48]. However, even though the peat moss used in our study had a high fiber content, a 3% inclusion of peat moss had a limited impact on enhancing VFA levels in the pig slurry. The authors of [49] examined factors affecting VFA content in stored pig slurry, encompassing diet, season, storage location, conditions (covered or aerated), and pig operation type (finishing, sow, mixed), with pig operation type emerging as the most prominent factor. In the present study, maintaining consistent conditions except for dietary variations, the utilization of excreted sow slurry enabled the attribution of the observed difference in VFA content between the PFS and CTL mainly to the presence or absence of peat moss supplementation.

During the experimental period, the pH of the CTL and PFS ranged from 7.4 to 7.8 and 7.5 to 8.1, respectively. The relationship between VFA accumulation and pH decrease in the pig slurry did not show a clear trend in either group.

3.3. Changes in CH₄ Carbon (CH₄-C), CO₂ Carbon (CO₂-C), and Carbon Dioxide Equivalent (CO₂-eq.) Emissions during Storage of Pig Slurry

A comparative analysis of carbon emissions was conducted to determine the gaseous carbon sources contributing to decreased CO₂ and CH₄ emissions in PFS. Figure 5 presents the total carbon emissions (CH₄-C + CO₂-C) of PFS and CTL. As previously observed, cumulative CO₂ and CH₄ emissions decreased by 23% and 44% in PFS compared with CTL, respectively.

On the 7th day of storage, CTL and PFS showed higher carbon emissions in the form of CO₂ compared with CH₄. CO₂ accounted for 66% and 84% of the total carbon emissions in CTL and PFS, respectively. On the 14th day of storage, the contribution of carbon emissions from CH₄ in CTL increased, accounting for 65% of the total carbon emissions. PFS increased CH₄-C emissions compared with the previous week, but CO₂ still accounted for about half of the total carbon emissions. During the subsequent storage period, the proportion of CO₂ in the total carbon emissions was dominant in PFS until day 49 (average of 66% of total carbon emissions) and in CTL until day 42 (average of 78% of total carbon emissions). The percentage of CH₄ in total carbon emissions ranged from 16 to 46% and 14 to 65% in PFS and CTL, respectively, comparable to the maximum values of 50–70% reported in other studies [16,50,51].
In the storage of pig slurry, CO₂ emissions exceed those of CH₄ when assessed based on total carbon emissions. However, when expressed in terms of CO₂-eq., CH₄ significantly influences greenhouse gas emissions. During the experimental period, the emissions of CH₄-C and CO₂-C converted to CO₂-eq. displayed a different trend from the total carbon emissions (Table 4). The results of this study indicate that, in both PFS and CTL, the amount of CH₄ emissions converted into CO₂-eq. exceeded that of CO₂ emissions throughout the entire storage period. This persistent pattern of CH₄ dominance in the total carbon emissions is consistent with CH₄ accounting for about 93% and 95% of the total carbon emissions in PFS and CTL, respectively. These findings are in contrast to those presented in Figure 5. Furthermore, PFS was found to have approximately 43% less impact on greenhouse gas emissions than CTL.

Table 4. Cumulative CO₂-eq. emissions during the experiment period (56 days).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Cumulative CO₂-eq. Emissions</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CH₄-C</td>
<td>CO₂-C</td>
</tr>
<tr>
<td>PFS</td>
<td>g CO₂-eq. m⁻³</td>
<td>g CO₂-eq. m⁻³</td>
</tr>
<tr>
<td></td>
<td>7423 ± 601 a</td>
<td>541 ± 34</td>
</tr>
<tr>
<td>CTL</td>
<td>13,205 ± 1164 b</td>
<td>717 ± 61</td>
</tr>
</tbody>
</table>

To estimate CO₂-eq., CH₄ emissions were multiplied by a factor of 28 [52]. Values (means ± S.E., n = 3) followed by different letters such as a and b within columns are significantly different (p < 0.05).

Overall, these results suggest that CH₄ emissions during the 56-day storage period are a significant contributor to greenhouse gas emissions in pig slurry storage and should be carefully monitored and managed in efforts to mitigate the environmental impacts of agricultural waste management practices. Although CH₄ emissions from pigs contribute a smaller proportion compared with the cattle’s impact from enteric fermentation on greenhouse gas generation, their significance remains pronounced in CH₄ production through their integral role in manure management [1]. The methane emission factor originating from the storage of slurry in pig housing exhibits a range of 63.3 to 42.2 g·kg⁻¹ VS·yr⁻¹ within cool climate zones, 116.6 to 123.6 g·kg⁻¹ VS·yr⁻¹ within temperate climate zones, and 177.9 to 223.1 g·kg⁻¹ VS·yr⁻¹ within warm climate zones [52].
These findings suggest that implementing PFS may be a promising approach for mitigating carbon emissions, with potential implications for environmental sustainability and climate change mitigation efforts.

4. Conclusions

During the experiment period of about two months, peat moss feeding reduced CO₂ and CH₄ emissions from pig slurry by 23 and 44%, respectively, compared with the control group. The daily CH₄ and CO₂ emission fluctuations were lower in PFS compared with CTL. The present study’s results indicate that the HS levels were significantly higher in PFS than CTL. These findings suggest that the elevated HS levels observed in the PFS may play a pivotal role in constraining hydrolysis during anaerobic digestion. Consequently, the PFS tended to lower TVFA concentrations compared with the CTL.

When converting CH₄ and CO₂ emissions to carbon emissions (CH₄-C + CO₂-C), it was found that more carbon was emitted from CO₂ than CH₄ during the storage period. However, when expressed as CO₂-eq., CH₄ dominated carbon emissions during the entire storage period in both PFS and CTL, with CH₄ accounting for 93% and 95% of the total carbon emissions, respectively. PFS was also found to have a lower impact on greenhouse gas emissions than CTL, with a reduction of approximately 43% according to cumulative CO₂-eq. emissions.

Overall, this study suggests that implementing PFS may be a practical approach to mitigating carbon emissions and promoting environmental sustainability and climate change mitigation. This study provides fundamental data on the impact of peat moss feeding on CH₄ and CO₂ emissions during pig house storage periods, and these data can be utilized to conduct additional scaled-up experiments. It is hypothesized that aerobic digestion or composting systems could be more appropriate for treating stored pig slurry with high HS levels rather than anaerobic digestion. Further pilot- or field-scale experiments are required to identify the most suitable subsequent treatment processes for stored PFS.

However, the short-term experimental duration and the inherent variability in CH₄ and CO₂ emission measurements associated with laboratory-scale experiments are limitations of this study. Peat moss feeding can be a cost-effective approach for achieving carbon neutrality in the livestock industry. To this end, it is crucial to determine the optimal peat moss feeding ratio for pigs to maximize the reduction in CH₄ and CO₂ emissions. Furthermore, further research is needed to examine the effect of peat moss on greenhouse gas reduction in various livestock species and at different breeding stages.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app131810492/s1, Figure S1: Changes in VFA (isobutyric acid, isovaleric acid, n-valeric acid, isocaproic acid, n-caproic acid, and heptanoic acid) concentration over time in PFS and CTL during the experimental period (56 d).

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