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# Enhancing biodegradability and reducing acidity of dry fecal sludge in arid tropical conditions

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**Abstract**

The acidity of dry fecal sludge (DFS) significantly hinders its agricultural use. This study focuses on enhancing the agronomic efficiency of DFS through liming. DFS were categorized into three groups based on storage duration: recent (less than 2 years), intermediate (2 - 3 years), and old (more than 3 years). The lime rates applied (in kg/ton of DFS) were as follows: F1 = 0 (control); F2 = 3.125; F3 = 6.25; F4 = 12.5; F5 = 25; F6 = 50; and F7 = 75. The impact of liming on microbial activity was assessed by measuring $CO_2$ emissions. The results indicate that acidity and biodegradability of DFS improved proportionally with the rate of lime applied. The pH levels ranged from 6.50 ± 0.05 to 11.58 ± 0.99 for recent DFS, 6.67 ± 0.27 to 12.35 ± 0.09 for intermediate DFS, and 4.96 ± 0.31 to 11.58 ± 0.99 for old DFS. The formulation F2 exhibited the highest microbial activities, with $CO_2$ emissions ranging from 21.78 to 34.76 mg/day for recent DFS, 20.66 to 39.58 mg/day for intermediate DFS, and 22.66 to 41.58 mg/day for old DFS. These findings suggest that liming at reduced doses can effectively enhance the agronomic potential of DFS by correcting their acidity and improving biodegradability.

***Keywords:*** Burkina Faso; Dry Fecal Sludge; Hydrated Lime; Ph; Microbial Activity



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## 1. Introduction

The deficiency of organic matter in soils across Sub-Saharan Africa, a result of its intrinsic nature and the limited access of producers to organic fertilizers, poses a significant challenge (FAO, 2019). This region frequently experiences a decline in soil fertility due to unsuitable agricultural practices, representing a major biophysical constraint that limits the productivity of cropping systems. Such issues are especially critical given the large proportion of the population dependent on farming (Lompo et al., 2009; Koulibaly et al., 2010). In Burkina Faso, for example, soils are notably poor in organic matter and nutrients, unable to sustainably support plant growth (Lompo, 1993). Furthermore, the cropping systems here are characterized by limited access to organic and/or mineral amendments and low nutrient recycling through crop residues and agri-livestock integration (Traoré et al., 2019). Predominantly, small-scale farmers, organized in household units with scarce economic resources, engage in extensive agricultural practices that lead to soil depletion (Shipper and Sparling, 2000).

Recognizing the vital role of organic matter in agricultural soil systems, extensive research has been conducted to develop alternative organic fertilizers, focusing on the availability of components and affordability for farmers (Traoré et al., 2015). Dry fecal sludge (DFS) has been identified as a promising organic substrate for soil fertility restoration and improvement, given its high nutrient and organic matter content, essential for plant development and soil physicochemical property enhancement (Koné et al., 2016; Héma et al., 2022). Despite its widespread use in agrosystems (Niang, 2012; Koné et al., 2016; Lo et al., 2019), direct application of DFS as a soil amendment can pose environmental risks and health hazards (Tadjouwa, 2017; Défo et al., 2015). According to Strande et al. (2018) and Héma et al. (2022), such application can lead to soil acidification. To circumvent these issues, studies have explored co-composting DFS with crop residues (Lompo et al., 2009; Koné et al., 2016), but the resultant compost often has limited agronomic value, and logistical challenges further hinder this method of sewage sludge valorization (Dakuo et al., 2011).

This study aims to enhance the agronomic value of DFS by adjusting their acidity with varying rates of hydrated lime and to assess the effects of this liming on the biodegradability of DFS. The underlying research hypothesis is that liming can correct the acidity and improve the biodegradability of DFS.

## 2. Material and methods

### 2.1. Site of dry fecal sludge collection

The DFS used in this study was collected from the Kossodo fecal sludge treatment plant. This facility is located in the industrial zone northeast of Ouagadougou, Burkina Faso (coordinates: 12° 20' 60" N, 1° 31' 0.00" W; altitude: 249 m). Ouagadougou, the country's largest city and a significant producer of DFS, lacks adequate processing options for further use of the sludge. Notably, Ouagadougou has been one of the hottest locations in the country, experiencing consistently high temperatures over the past decade (Figure 2). The Kossodo plant, with an estimated treatment capacity of about 180,000 $m^3$ per year, stands as one of the key sludge treatment sites in Burkina Faso (Koné et al., 2016). The DFS were sourced from unplanted drying beds after 15-20 days of drying. Post drying bed treatment, this sludge is stored in piles on the ground and continues to dry naturally in an outdoor environment.

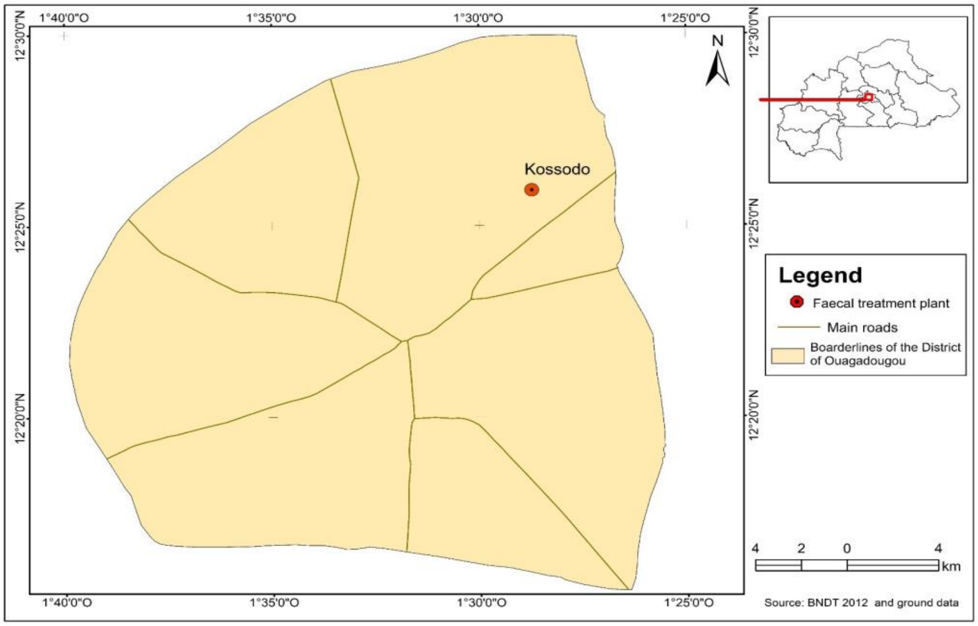


**Figure 1.** Location of the Kossodo station in the commune of Ouagadougou

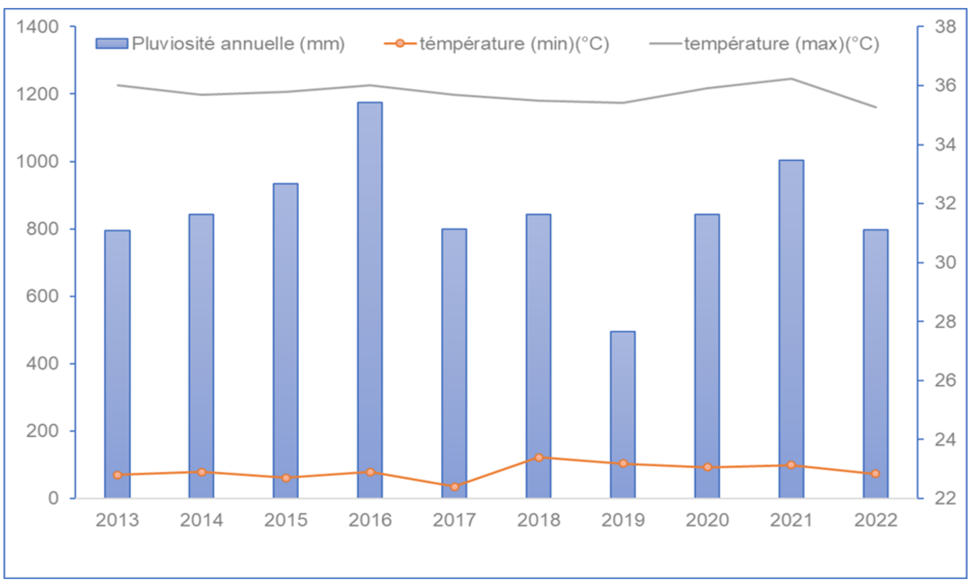


**Figure 2.** Average Rainfall and temperature variation in the Kossodo fecal sludge treatment station for the last ten years

## 2.2. Collection and chemical characterization of dry fecal sludge

The sludges were initially categorized into three classes based on their storage duration. Accordingly, they were classified as old sludges with a storage time exceeding three years, intermediate sludges stored between two and three years, and recent sludges stored for less than two years. The classification of DFS was grounded in semi-structured interviews and focus groups with the technical staff responsible for managing the drying beds and the collection of sludge post-drying. A total of 16 workers were individually interviewed, and three group interviews were conducted with groups of five workers each. This information was cross-referenced to ascertain the average duration of sludge in different classes.

**Table 1.** Physico-chemical composition of dry fecal sludge from the Kossodo plant (Hema et al., 2022)

| **Storage duration** | **DS > 3 years** | **2 ≤ DS < 3 years** | **DS < 2 years** |
|---|---|---|---|
| **Parameters** | **Old sludge** | **Intermediate sludge** | **Recent sludge** |
| **pHwater** | 4.95 ± 0.31 | 5.01 ± 0.28 | 5.16 ± 0.05 |
| **CE (mS/cm)** | 2.30 ± 0.51 | 3.51 ± 0.24 | 2.64 ± 0.52 |
| **CO (%)** | 13.64 ± 3.75 | 12.83 ± 3.96 | 17.79 ± 0.91 |
| **MO (%)** | 23.52 ± 6.46 | 22.12 ± 6.83 | 30.66 ±1.58 |
| **N-t (%)** | 1.21 ± 0.36 | 1.08 ± 0.37 | 1.46 ± 0.11 |
| **C/N** | 11.34 ± 0.49 | 12,06 ± 1.11 | 12.17± 0.60 |
| **P-t (mg/kg)** | 12603.90±1847.90 | 12922.95±1155.06 | 13476.13 ±2882.28 |
| **K-t (mg/Kg)** | 556.22 ±71.68 | 576.13 ± 189.23 | 704.72 ±113.15 |
| **Na (mg/Kg)** | 152.31 ± 44.99 | 169.69 ± 61.43 | 148.90 ± 27.76 |
| **Ca (mg/Kg)** | 3680.58 ± 665.33 | 3931.76 ±741.89 | 4702.55 ±502.39 |
| **Mg (mg/kg)** | 2012.57 ± 597.70 | 1425.57 ± 87.61 | 1503.04 ± 400.78 |

**Table 2.** Heavy metal content of dry sewage sludge from the Kossodo plant (Hema et al., 2022)

| MTE | Contents (mg/kg) | Agricultural use standards (Brouzes and Chauvière, 2009) |
|---|---|---|
| Copper | 137 ± 25.69 | 1750 |
| Zinc | 922.30 ± 7.04 | 4000 |
| Lead | 39.32 ± 3.80 | 1200 |
| Cadmium | 1.76 ± 0.04 | 40 |
| Nickel | 52.32 ± 3.60 | 400 |
| Chrome | 1697.83 ± 55.11 | 1750 |

For sample collection, a randomized approach was adopted within each class to ensure representative sampling. In each DFS category, samples were collected from various locations and depths, and then combined to form a composite sample. Four samples were collected from each group. The collection process adhered to safety protocols, including the use of personal protective equipment. The physico-chemical characteristics of the DFS are detailed in Table 1. Since these sludges are intended for agricultural use, we proceeded to determine their trace metal contents (Table 2).

## 2.3. Characteristics of the chemical additive

Slaked lime ($Ca(OH)_2$), which is 95% soluble and has a CaO content of 89.54% ([Equation I]), was used at various doses to lime DFS. Lime is applied for its ability to improve the acid-base status by reducing the acidity of DFS through the action of carbonates on protons ($H^+$) ([Equation II]):

$CaCO_3 \leftrightarrow CO_3^{2-} + Ca^{2+}$ (carbonate dissolution) ([Equation I])

$CO_3^{2-} + 2^{H+} \leftrightarrow HCO_3- + H^+ \leftrightarrow H_2CO_3 \leftrightarrow CO_2 + H_2O$ (proton neutralization) ([Equation II])

In Burkina Faso, lime, sourced from limestone, is readily available and inexpensive. It is extracted by the Village Mining Company (COVEMI), located in the village of Tiarra in the western part of the country. A global policy exists that encourages the use of lime as a mineral amendment to enhance soil productivity. Consequently, farmers are provided with lime at prices subsidized by the state.

## 2.4. Liming of dry fecal sludge

Three classes of DFS were subjected to lime treatment. For each DFS class, seven different formulations were applied, corresponding to combinations of (BVS + $Ca(OH)_2$) in kg per ton of DFS (see Table 3). The pH of each formulation was measured in a "distilled water + formulation" solution, maintaining a 1:10 ratio of formulation to water, following AFNOR guidelines (1999). To ensure the representativeness of the results, three replicates were conducted for each sample. The mixture was stirred for 10 minutes and then left to stabilize for 30 minutes before the pH was measured using a glass electrode pH meter.

**Table 3.** Different formulations (BVS + $Ca(OH)_2$) tested by sludge class

| Formules | (Kg) ($Ca(OH)_2$/T)DFS) |
|---|---|
| F1 | 0 |
| F2 | 3.125 |
| F3 | 6.25 |
| F4 | 12.5 |
| F5 | 25 |
| F6 | 50 |
| F7 | 75 |

## 2.5. Sample preparation and measurement of $CO_2$ emissions

Samples from various formulations (sludge + lime) were mixed with soil at a ratio of limed DFS (1.7 kg) + 100 g of dry soil, sieved to 2 mm. The soil samples for the mixture were collected from the top layer (0-20 cm) of soil in a 5-year fallow at the Farako-Bâ experimental station (11°06' north latitude; 4°20' west longitude), located in western Burkina Faso. This soil is a leached tropical ferruginous type, the most common in the country (BUNASOLS, 1990). Its physico-chemical properties indicate it is very poor in carbon (0.38%), nitrogen (0.034%), and assimilable phosphorus (2.72 mg.kg^-1), with a very low cation exchange capacity (1.98 Cmol.kg^-1 soil) (BUNASOLS, 1990).

For determining microbial activities in the mixtures, the respirometric method was used (Bachelier, 1973). Microbial activities were gauged through $CO_2$ emissions over a 21-day incubation period. The preparation of samples and $CO_2$ measurement involved moistening the different composites (formulations + soil) to 4/9 of their maximum water holding capacity. Incubation was conducted at 25°C in a tightly sealed jar containing NaOH (0.1N) (Bachelier, 1973). $CO_2$ emitted was trapped by sodium hydroxide (NaOH: 0.1N) and precipitated by barium chloride ($BaCl_2$: 20%). The excess NaOH was determined using hydrochloric acid (HCl: 0.2N), with phenolphthalein as a color indicator. A control jar containing only sodium hydroxide beakers and distilled water was used to establish initial carbonization of the sodium hydroxide and the air in the jar. $CO_2$ emissions were measured daily for the first seven days, and then every two days from the 7th day. $CO_2$ evolved was quantified using the formula (Bachelier, 1973):

$$Q \text{ (mg / Day)} = [V_{Hcl} \text{ (blank)} - V_{Hcl} \text{ (treatement)}] \times 2{,}2.$$

## 2.6. Measurement and comparison of pH values to the agricultural standard

The pH values measured in the different mixtures post-liming were compared to standard values defined by Koné et al. (2016) in relation to the valorization of fecal sludge. According to these authors, pH values between 6.5 and 7.5 were considered “suitable” for crop production, while values between 7.5 and 9.5 were “moderately suitable”. Values strictly above 9.5 and below 6 were deemed “unsuitable” for agricultural activity.

## 2.7. Data processing

Data processing was conducted using R software version 4.1.3 (R Core Team, 2022). Two tests were utilized: correlation tests and Principal Component Analysis (PCA). PCA, a highly effective tool for synthesizing information, is particularly useful when handling a large amount of quantitative data. It was employed to assess linkages between various measured variables. The Shapiro test checked data normality, while the Tukey HSD test was used for separating mean values at a significance level of 5%.

# 3. Results

## 3.1. Effects of slaked lime rates on dry fecal sludge pH

Analysis of Table 4 shows that before liming, all three classes of DFS were highly acidic, with pH values of 4.96 ± 0.31, 5.01 ± 0.28, and 5.16 ± 0.05 for old, intermediate, and recent DFS respectively. The application of increasing rates of hydrated lime caused a proportional increase in the pH values of DFS across all classes. Extreme values varied from 6.50 ± 0.05 to 11.58 ± 0.99; 6.67 ± 0.27 to 12.25 ± 0.87; and 7.81 ± 0.45 to 12.78 ± 0.79 for old, intermediate, and recent sludge, respectively. The lowest pH value was observed with the 3.125

kg lime/ton sludge formulation (F2), and the highest with the 75 kg formulation (F7), irrespective of DFS class. With the same dose of hydrated lime, pH values varied among DFS classes, with more pronounced variation in recent DFS. Formulations F2, F3, and F4 resulted in pH values from 6.50 ± 0.05 to 7.81 ± 0.45. Conversely, with F5, F6, and F7, the pH values were more or less suitable for agricultural activities.

**Table 4.** pH of different classes of dry fecal sludge according to the rate of lime

| Rate of hydrated lime (Kg/Ton of DFS) | Classes of dry fecal sludge | | | | | | pH limit values (Koné et al., 2016) |
|---|---|---|---|---|---|---|---|
| | Old DFS | Apprecia-tion | Intermediaries DFS | Apprecia-tion | Recent DFS | Apprecia-tion | |
| F1 (0) | 4.96 ± 0,31 | * | 5.01 ± 0.28 | * | 5.16 ± 0.05 | * | |
| F2 (3.125) | 6.50 ± 0,05 | *** | 6.67 ± 0.27 | *** | 8.33 ± 0.16 | ** | |
| F3 (6.25) | 6.89 ± 0,22 | *** | 7.08 ± 0.13 | *** | 8.62 ± 0.09 | ** | |
| F4 (12.50) | 7.46 ± 0,64 | *** | 7.58 ± 0.52 | *** | 7.81 ± 0.45 | ** | 6.5 - 9 |
| F5 (25) | 8.16 ± 0,98 | ** | 8.52 ± 0.73 | ** | 8.97 ± 0.58 | ** | |
| F6 (50) | 9.07 ± 0,71 | * | 9.98 ± 0.92 | * | 10.32 ± 0.89 | * | |
| F7 (75) | 11.58 ± 0,99 | * | 12.25 ± 0.87 | * | 12.78 ± 0.79 | * | |
| Probability | 0.015 | | 0.043 | | 0.006 | | |

** Suitable; ** : moderately suitable; *** : unsuitable*

## 3.2. Effects of liming on microbial activity in dry fecal sludge

Increasing rates of lime resulted in variations in the amounts of $CO_2$ released during incubation (Figures 3 to 5). In recent DFS, two groups emerged in relation to hydrated lime rates. The first group, comprising formulations F2 and F3, showed higher $CO_2$ emissions than the control (F1) during the 21-day incubation period. The second group, consisting of formulations F4, F5, F6, and F7, exhibited lower $CO_2$ emissions than the control throughout the incubation. In the first group, $CO_2$ emissions continuously increased from day 1 to day 3 after incubation, before decreasing from day 4 to day 6. From day 6 to day 17, the overall $CO_2$ emission trend was increasing, with a peak on day 17 (41.58 and 40.70 mg $CO_2$/day for F2 and F3, respectively). After day 17, emissions decreased slightly until day 19 and stabilized by day 21. In the second group (F4, F5, F6, F7), $CO_2$ emissions consistently increased from day 1 to day 21, with significant amounts in the F4 formulation throughout the incubation period. The highest emissions were recorded on day 21 (10.14; 12.88; 14.78; 17.80 mg $CO_2$/day for F7, F6, F5, and F4, respectively). For the control (F1), $CO_2$ emissions peaked on day 9 (18.91 mg $CO_2$/day) and stabilized until day 21.

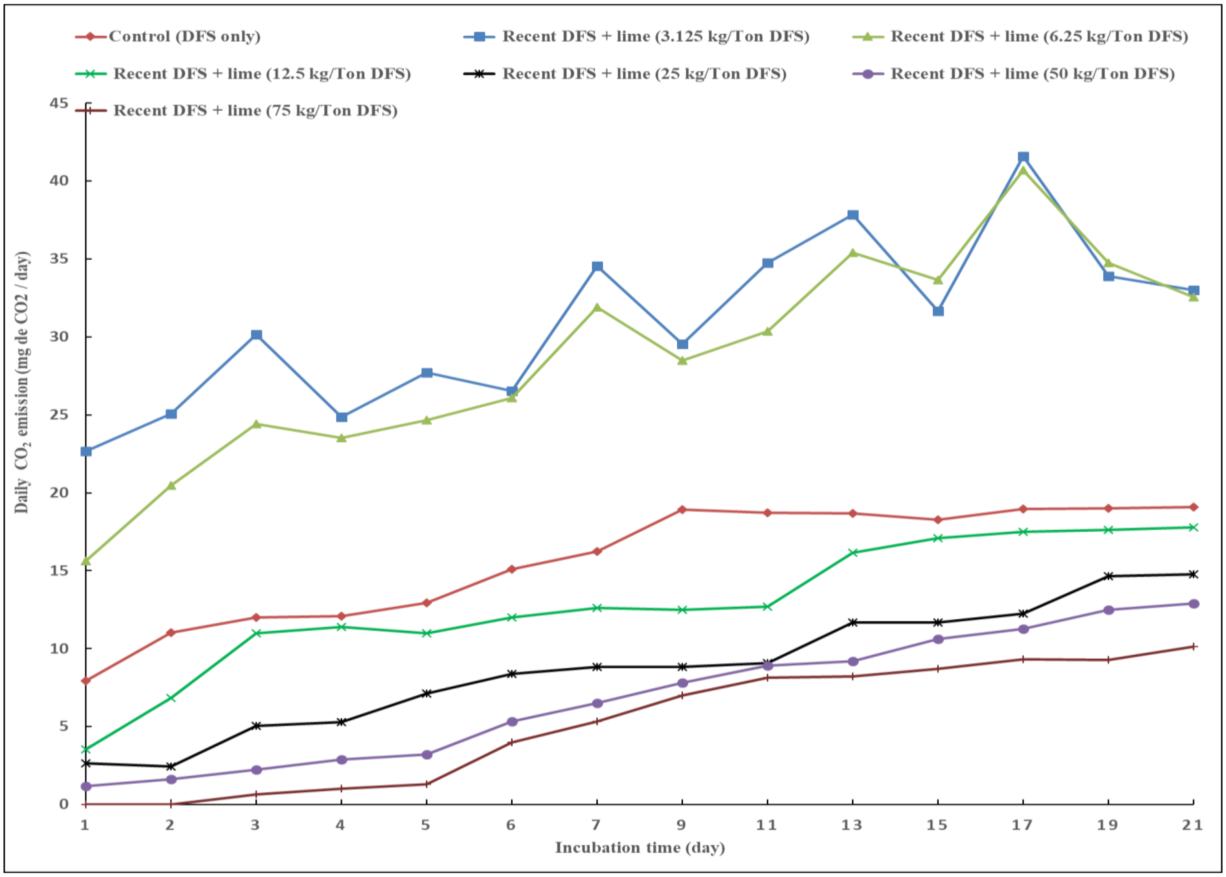


**Figure 3.** Variation of $CO_2$ emissions in recent dry Fecal Sludge class according to the incubation time

The increasing addition of hydrated lime to the intermediate DFS led to the identification of two groups based on the amounts of $CO_2$ evolved (Figure 4). The first group included formulations F2 (3.125 kg of lime/Ton of DFS) and F3 (6.25 kg of lime/Ton of DFS), where $CO_2$ emissions were higher than those of the control formulation (F1) during the 21-day incubation period. The second group consisted of formulations F4 (12.50 kg of lime/Ton of DFS), F5 (25 kg of lime/Ton of DFS), F6 (50 kg of lime/Ton of DFS), and F7 (75 kg of lime/Ton of DFS), with $CO_2$ emissions lower than those recorded for the control (F1). In the first group, $CO_2$ emissions gradually increased, peaking on the 17th day, with values of 37.70 mg $CO_2$/day for F3 and 39.58 mg $CO_2$/day for F2. From the 17th to the 21st day after incubation, a slight decrease in $CO_2$ emissions was observed, with values of 29.56 mg/day for F3 and 31 mg/day for F2. Except for the 7th and 9th days, $CO_2$ emissions were consistently higher with F2 compared to F3 throughout the incubation period.

Regarding the second group, $CO_2$ emissions started from the 1st day for the mixtures of F4, F5, and F6, and from the 3rd day for F7. The highest $CO_2$ emission (15.60 mg/day) was recorded on the 19th day for F4. For F5 and F6, the peak occurred on the 21st day with respective values of 11.01 and 13.78 mg CO2/day. For the F7 treatment, the peak emission of 7.30 mg $CO_2$/day was observed on the 17th day. In this class, $CO_2$ emissions from the control (F1) reached their maximum (16.36 mg $CO_2$/day) on the 19th day, which remained constant until the 21st day.

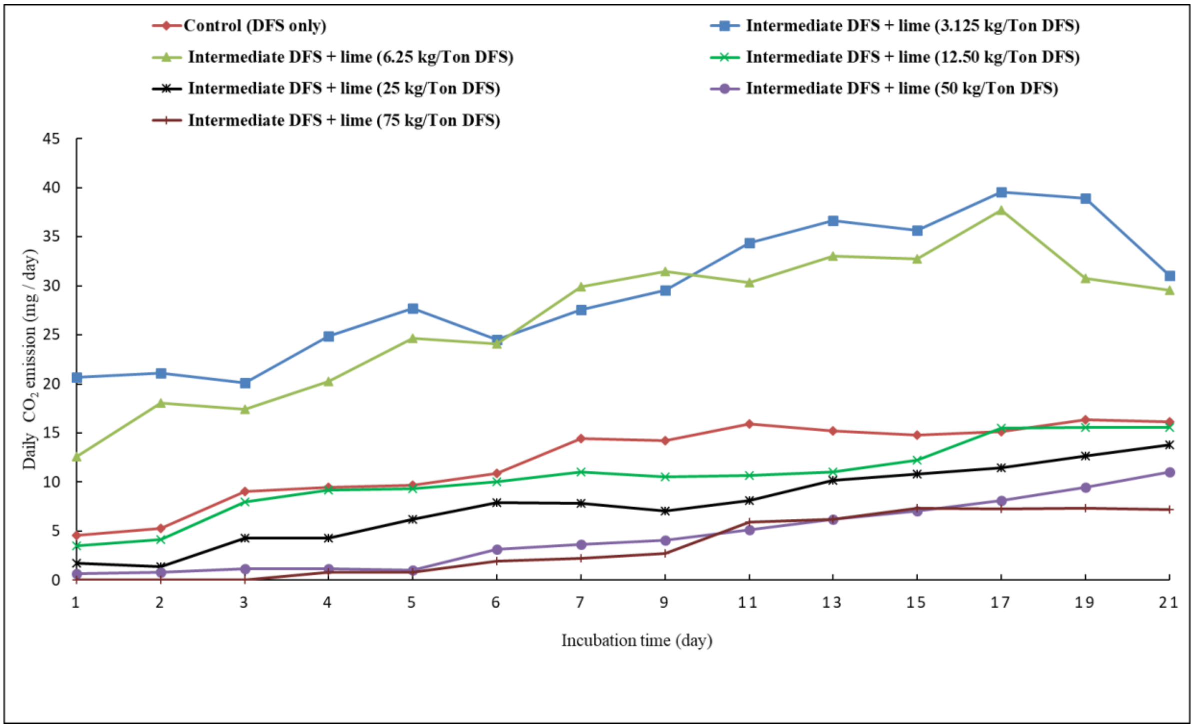


**Figure 4.** Variation of $CO_2$ emissions in intermediate dry Fecal Sludge class according to the incubation time

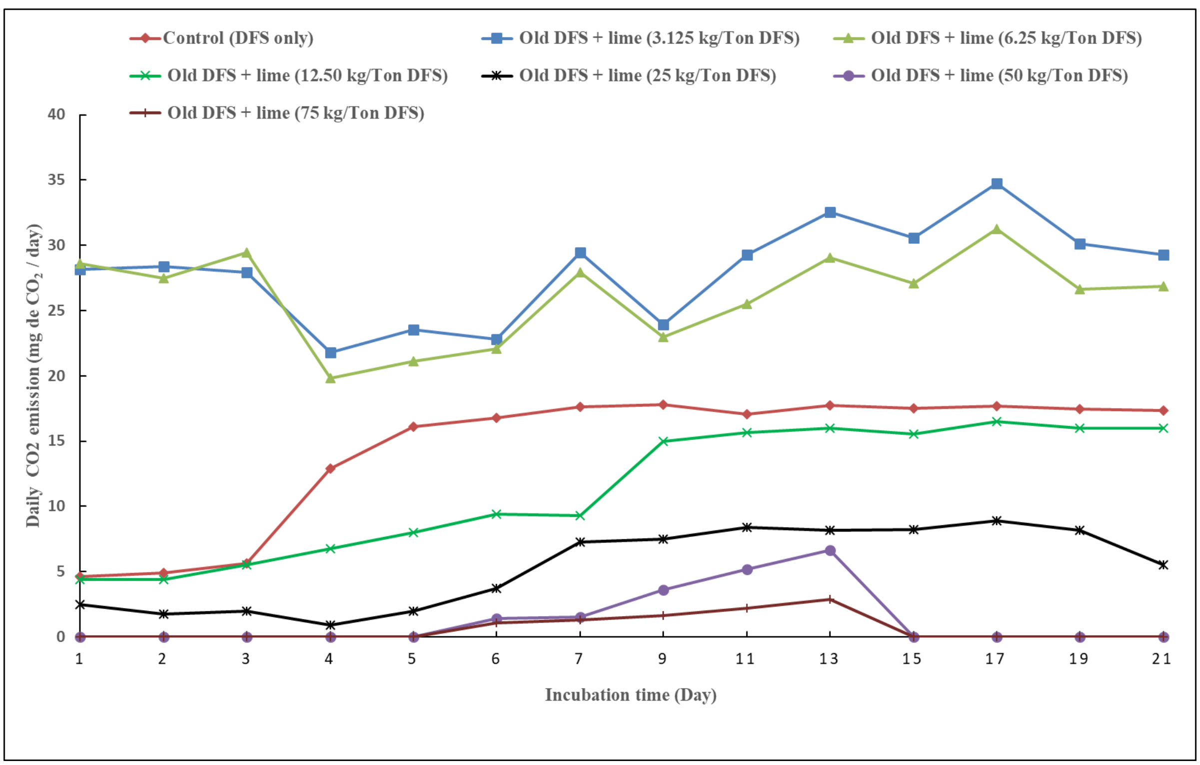


**Figure 5.** Variation of $CO_2$ emissions in old dry fecal sludge class according to the incubation time

In the mixtures derived from older DFS, two groups were identified based on $CO_2$ emissions (Figure 5). The first group, consisting of formulations F2 (3.125 kg of lime/Ton of DFS) and F3 (6.25 kg of lime/Ton of DFS), exhibited higher $CO_2$ emissions compared to the control without lime (F1). The second group, characterized by lower $CO_2$ emissions than the control, comprised mixtures from formulations F4 (12.5 kg of lime/Ton of DFS), F5 (25 kg of lime/Ton of DFS), F6 (50 kg of lime/Ton of DFS), and F7 (75 kg of lime/Ton of DFS). In the first group, $CO_2$ emissions continuously increased from the first day, reaching a maximum of 34.76 mg $CO_2$/day for F2 and 31.24 mg $CO_2$/day for F3 on the 17th day. After this peak, emissions kept increasing until the 21st day. In the second group, initial emissions for F4 and F5 were 4.40 mg $CO_2$/day and 2.50 mg $CO_2$/day, respectively, on the first day. These emissions peaked on the 17th day, then stabilized for F4 and decreased for F5. The trend of $CO_2$ emissions with F1 (control) and the mixture from F4 was similar, with more pronounced values for the control except on the first day when the emissions were nearly identical at 4.40 mg $CO_2$/day. The control (F1) reached its maximum $CO_2$ emission of 17.82 mg $CO_2$/day on the 9th day, which then stabilized until the 21st day. For mixtures from F6 and F7, maximum $CO_2$ emissions occurred on the 13th day before dropping to zero in the following days.

The combined analysis of Figures 3 to 5 indicates that for the same rate of hydrated lime, the $CO_2$ release is higher in mixtures from recent sludge compared to those from intermediate and older sludge. Furthermore, regardless of the sludge class, $CO_2$ emissions decrease as lime rates increase. These emissions are more significant with the doses of 3.125 and 6.250 kg of lime per ton of DFS (F2 and F3) compared to the control without lime application (F1). At higher doses of 50 and 75 kg of lime per ton of DFS (F6 and F7), a lag time in $CO_2$ release was observed, the duration of which varied depending on the type of DFS. This lag time was two, three, and five days for recent, intermediate, and old DFS, respectively, in mixtures using F7.

## 3.3. Biodigestibility of different dry fecal sludge formulations as affected by their acidity levels

The biodigestibility of the various formulations of dry fecal sludge was evaluated using the correlation matrix (Table 5). Principal Component Analysis (PCA) revealed that changes in pH and $CO_2$ emissions are positively correlated with the storage time of the DFS. Specifically, $CO_2$ emissions showed a strong positive correlation with DFS types, exhibiting correlation coefficients of 0.93 for old, 0.88 for recent, and 0.86 for intermediate DFS. Regarding pH, the correlation coefficients were 0.69 for recent, 0.53 for intermediate, and 0.52 for old DFS.

**Table 5.** Biodigestibility of the different classes of DFS as affected by the acidity

| Variables | DFS-R | DFS-I | DFS-A | $CO_2$ emitted -R | $CO_2$ emitted -I | $CO_2$ emitted -A |
|---|---|---|---|---|---|---|
| $CO_2$-evolved | 0.93 | 0.88 | 0.86 | - | - | - |
| pH | 0.69 | 0.53 | 0.52 | -0.43 | -0.62 | -0.72 |

*DFS-R: Recent Dry Sludge; DFS-I: Intermediate Dry Sludge; DFS-A: Old Dry Sludge; $CO_2$ emitted -R: $CO_2$-emitted in recent DFS; $CO_2$ emitted -I: $CO_2$-emitted in intermediate DFS; $CO_2$ emitted -R: $CO_2$-emitted in old DFS.*

### 3.4. Expressed eigenvalues and variances

The Principal Component Analysis (PCA) indicates that the factorial designs (F1-F2) account for 99.58% of the explained variance (Figure 6), representing the majority of the anticipated information. Factor 1 (F1), contributing to 78.86% of the explained variance, is positively correlated with changes in the pH of recent DFS (pH-R), intermediate DFS (pH-I), and old DFS (pH-A) as shown in Figure 6. This factor reflects the variability of pH across different classes of DFS. Factor 2 (F2), representing 20.72% of the explained variance, is strongly correlated with $CO_2$ emissions in formulations derived from recent ($CO_2$ emitted-R), intermediate ($CO_2$ emitted-I), and old ($CO_2$ emitted-A) DFS. Thus, this factor captures the variability of $CO_2$ emissions according to DFS storage time.

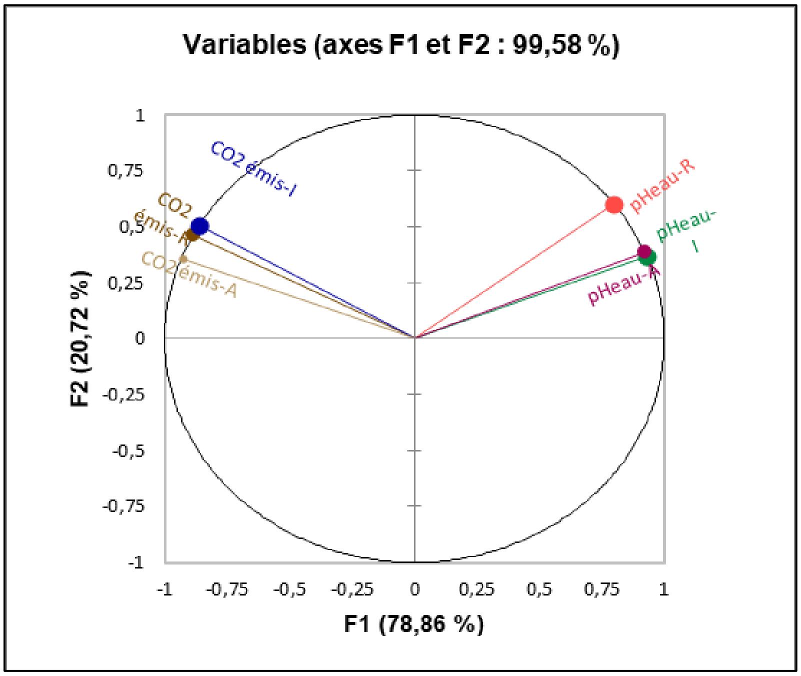


**Figure 6.** Correlation circle of the variables in the first two factorial designs (pHwater-R: pHwater of recent DFS; pHwater-I: pHwater of intermediate DFS; pHwater-A: pHwater of old DFS; $CO_2$ emitted-R: $CO_2$ emitted in recent DFS; $CO_2$ emitted-I: $CO_2$ emitted in intermediate DFS; $CO_2$ emitted-A: $CO_2$ emitted in old DFS)

## 4. Discussion

### 4.1. Effects of liming on dry fecal sludge acidity

Physico-chemical analysis revealed high acidity in raw DFS before liming, across all classes. The recorded pH values, ranging from 4.95 ± 0.31 to 5.16 ± 0.05 before liming, are not conducive to bacterial development and microbial population growth. As a result, without liming, the DFS proved unsuitable for agricultural use. The pH value is a critical limiting factor for the mineralization of organic substrates by bacteria. Optimal pH values for this process are between 6.5 and 9 (Koné et al., 2016). Specifically for bacteria responsible for nitritation, such as the Nitrosomonas genus, optimal activity is noted in a pH range of 7.4 to 9 (Degrémont, 2005). The pronounced acidity in the various classes of DFS can be attributed to anaerobic conditions caused by sludge accumulation during storage. During storage, DFS was piled up without being turned over, likely leading to asphyxiating conditions. This could have fostered incomplete oxidation of organic matter and the production of organic acids. Under anaerobic conditions, an organic substrate undergoes two primary chemical reactions: the dissolution of carbon dioxide, and the production of organic acids (Bernal et al., 1996; Amir, 2006). These reactions generate protons ($H^+$) which are responsible for acidification. According to these authors, the reactions proceed as follows:

$CO_2 + H_2O \rightarrow H_2CO_3 \rightarrow HCO^{-3} + H^+$ (dissolution of carbon dioxide)

Organic C $\rightarrow$ RCOOH $\rightarrow$ $RCOO^- + H^+$ (production of organic acids)

In a related study conducted on fresh fecal sludge from the unplanted drying beds of the Zagtouli plant in Ouagadougou, Koné et al. (2016) found pH values in water of 7.44 and 7.75. These values are compatible with the growth of bacteria responsible for sludge purification. These findings suggest that the high acidity observed in the DFS likely developed during storage, due to piling up which limits oxygenation within the piles. Additionally, the low calcium (Ca) and magnesium (Mg) content in dry sewage sludge, as compared to standard norms (Héma et al., 2022), could also contribute to its high acidity. The cation exchange capacity of an organic substrate is saturated when $H^+$ ions are replaced by cations ($Ca^{2+}$ and $Mg^{2+}$). A deficiency in these cations, or their low content, leads to a high concentration of H+ ions, causing acidification. Héma et al. (2022) in their study on the physico-chemical characterization of DFS in Burkina Faso, reported an increase in sludge acidity with storage time. They indicated that high acidity in DFS could be attributed to the leaching of $NO_{-3}$ and $SO^{2-}{}_4$. Conversely, Lochon (2019) stated that the leaching or washing away of anions $NO_{-3}$ and $SO^{2-}{}_4$ alters soil solution balances and contributes to acidification.

The addition of slaked lime ($Ca(OH)_2$) at 95% purity, at rates of 3.125, 6.25, and 12.50 kg/Ton of DFS, helped to remedy the acidity of the dry sewage sludge. These doses brought the pH within ranges suitable for agricultural recovery of BSV ($6.5 \leq pH < 9$) (Koné et al., 2016). These pH values are not only compliant with agricultural valorization standards but also favorable for macro-organisms involved in DFS mineralization. The decrease in acidity with the addition of hydrated lime can be explained by the lime's action on carbonic acid ($H_2CO_3$) in the sludge. It neutralizes H+ ions, leading to an increase in pH. The dissolution of lime releases anions ($CO^{2-}{}_3$) and cations ($Ca^{2+}$). The released anions neutralize some of the H+ ions, allowing the cations to bind to humic colloids. The substitution of H+ by $Ca^{2+}$ leads to a decrease in acidity. Bolan et al. (2003), Henri et al. (2008), and Lochon (2019) have shown that liming enables $Ca^{2+}$ ions from carbonate dissociation to enrich the adsorbent complex, resulting in an increase in pH values and effective cation exchange capacity (CEC). The neutralization of $H^+$ ions allows a partial or total reduction of organic acids from the incomplete oxidation of organic matter due to DFS piling up, leading to an increase in pH values and a decrease in acidity (Lochon, 2019). This reduction in acidity across different sludge classes can be explained by the release of ions ($Ca^{2+}$) from the dissolution of lime in wet conditions, as shown in the following equation (Lochon, 2019; Esilaba et al., 2023):

$Ca(OH)_2 \rightarrow Ca^{2+} + 2OH^-$ (lime dissolution)

$2OH^- + 2H^+ \rightarrow 2H_2O$ (proton neutralization)

Once released, the $Ca^{2+}$ cations increase the saturation rate, leading to a decrease in acidity. These cations prevent the release and action of $H_3O^+$ and $Al^{3+}$ ions, which are responsible for acidity (Youcef and Achour, 2005). Haynes and Naidu (1998) noted that liming induces the precipitation of exchangeable aluminum in the form of hydroxide, reducing the mobility of aluminum ions and consequently the acidity. Angui et al. (2009) demonstrated that the inclusion of lime, incorporated at a dose of 550 kg/ha, can address acidity through the reduction of exchangeable aluminum content.

## 4.2. Effects of slaked lime rates on the biodigestibility of dry fecal sludge

The formulations F2 and F3, which contained 3.125 and 6.25 kg of $Ca(OH)_2$ per ton of DFS, respectively, effectively corrected the acidity of the DFS. These formulations brought the pH values into a range favorable for agricultural activity. The observed high $CO_2$ emissions in these treatments are likely related to the induced acidity, which was suitable for microbial activity. Indeed, pH is one of the limiting factors for the development and activity of purifying bacteria, which generally thrive in a pH range of 6 to 9 (Dégremont, 2005). For instance, nitritation bacteria like Nitrosomonas multiply in an alkaline medium with a pH between 7.4 and 9, while nitratation bacteria grow in a medium with a pH between 8.5 and 9. Koné et al. (2016) noted that pH values between 7.44 and 7.75 are compatible with the development of bacteria responsible for purifying sludge stored in non-planted drying beds.

For higher rates of hydrated lime (25, 50, and 75 kg/Ton DFS), the pH values induced by liming were outside the range suitable for microbial activity. Consequently, $CO_2$ emissions decreased with these rates, highlighting an orderly relationship between pH variations induced by liming and $CO_2$ evolution. Moreover, liming induces a variation in temperature which, within a certain range, is conducive to microbial activity. Though not measured in this study, temperature would have contributed, alongside pH, to the variations in $CO_2$ emissions. Sédogo (1993) stated that temperature and nitrogen content of an organic substrate drive microbial activities, and consequently, $CO_2$ emissions. Andreasen (2001) reported that liming can induce an exothermic reaction that is more or less favorable to microbial activities. He also showed that liming can induce temperatures over 60°C depending on the liming rate. Low rates of hydrated lime typically induce temperatures suitable for microbial activities, while high rates often result in the inhibition of microbial activity (Strande et al., 2018). Strande et al. (2014) noted that at 60°C, most microorganisms involved in the biogeochemical cycle of organic substrates become inactive due to protein denaturation (e.g., psychrophiles and mesophiles), leading to a reduction in microbial activities and low $CO_2$ emissions. Liming contributes to greenhouse gas emissions and can reduce $CO_2$ emissions at the ecosystem respiration scale, with efficiency depending on the lime dose (Lochon, 2019). Therefore, the rates of 3.125 and 6.25 kg/Ton of sludge would have induced a temperature conducive to microbial activity and consequently to $CO_2$ emissions under the conditions of our study.

Compared to the mixtures of F1, F2, and F3, the rates F4, F5, F6, and F7, corresponding to 12.5, 25, 50, and 75 kg of lime/Ton of DFS, respectively, emitted a low amount of $CO_2$ regardless of the DFS class. The addition of these rates of liming likely disturbed the mechanisms of microbial activities, necessitating an adaptation period for the microorganisms to the new conditions. This could explain the low levels of $CO_2$ emission compared to raw sludge. According to Paradelo et al. (2015) and Lochon (2019), responses to liming would be modulated by the response of each species within the microbial communities, including their reaction to changes in pH, temperature, and nitrogen availability. Generally, a more or less slight decrease in $CO_2$ emissions was observed at the end of the incubation period in different formulations across all DFS. This gradual decrease in $CO_2$ release could be due to the presence of recalcitrant compounds that inhibit microbial growth (Marstorp, 1996; Lompo et al., 2009).

Regardless of the lime rate and incubation time, $CO_2$ emissions were higher in recent DFS compared to other classes. This result could be attributed to the intrinsic properties of the organic substrates, including organic matter content, nitrogen availability, and C/N ratio. Dumale et al. (2011) and Grover et al. (2017) showed an increase in $CO_2$ emission according to the nitrogen content, C/N ratio, and organic matter content in about 40 incubated and limed acid soils. In the current study, chemical analysis revealed a higher organic matter content in recent DFS compared to old and intermediate sludge. The high $CO_2$ emissions observed with recent sludge are likely related not only to the high organic matter content but also to its biodegradability. The abundant organic matter and its biodegradability would have alleviated constraints on nutrient access and stimulated the activity of microbial communities (Lochon, 2019). Furthermore, Lompo et al. (2009) stated that nitrogen stimulates $CO_2$ emissions and is a limiting factor for biological activity. They also demonstrated a strong positive correlation between the microbial activity potential of an organic substrate and its organic matter content.

### 4.3. Feasibility, socio-economic and environmental implications of liming dry fecal sludge

The technique of liming DFS for agricultural use is accessible to producers. Hydrated lime is widely utilized due to its ability to correct the pH of acidic soils. In Burkina Faso, this product is available at a low cost (320 FCFA/Kg) from various regional agricultural departments. Additionally, lime can be substituted with other locally available materials like dolomite and biochar, which serve similar functions.

From an economic perspective, using limed fecal sludge as a base fertilizer can significantly reduce the need for NPK and urea inputs in corn cultivation, with reductions of 83.33% and 75% respectively (Héma, 2023). Therefore, incorporating hydrated lime into DFS could help lower the production costs of cropping systems, thereby improving the economic conditions of producers.

Environmentally, the agricultural reuse of DFS represents an important alternative for preserving both the living environment and public health. In many developing Sahelian countries, fecal sludge management policies are still in their infancy. Consequently, most fecal sludge is discarded outside treatment plants (Lo et al., 2019; Soumbougma et al., 2020), posing significant threats to human health and the environment. The agricultural recycling of fecal sludge through liming could be a substantial step in mitigating these threats.

## 5. Conclusion

The valorization of DFS in agriculture necessitates an understanding of its physico-chemical properties. A study conducted on the DFS from the Kossodo plant revealed that it is rich in major nutrients essential for sustainable plant production. However, this sludge is notably more acidic compared to standard manure used for soil amendment in crop production. The addition of varying rates of hydrated lime effectively addressed the acidity of the DFS, bringing it into a range suitable for agricultural use. The formulations with 3.125 and 6.25 kg of lime per ton of DFS provided an optimal acidity level for crop production and were found to be conducive to microbial activities, compared to the control and other formulations. However, disturbances in microbial activities were observed, becoming more pronounced with higher rates of lime in the three classes of DFS. Despite their agronomic potential and the successful correction of acidity, the agricultural valorization of DFS requires microbiological analysis and tests for residual phytotoxicity. Once these aspects are addressed, liming of DFS could significantly contribute to solving soil fertility management challenges in the context of sub-Saharan countries.

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