

Article

Field Incubation Studies on Nutrient Mineralization of Bagasse on Spodosols and Histosols in Florida

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Abstract: The addition of organic byproducts to soils is a vital source of essential nutrients for plant uptake. To reuse the nutrients effectively, there is a need to estimate the release patterns of nutrients from the byproducts. This study aimed to investigate the release patterns of nutrients [nitrogen (N), phosphorus (P), and potassium (K)] from bagasse, a sugarcane milling byproduct, at two soil depths (surface at 0 cm vs. buried at 15 cm) in sugarcane and fallow fields on two soil types (Histosols vs. Spodosols) in Florida. In addition, field incubation studies were conducted using the mesh bag technique for one year of sugarcane production. The nutrient release patterns and bagasse decomposition rates were determined under each scenario. The results indicated that bagasse decomposed faster when buried (totally decomposed after approximately 450 days) than when placed on the soil surface (about 50% remained after 450 days) in both sugarcane and fallow fields on Spodosols and Histosols. Bagasse decomposed faster in Histosols compared to Spodosols. N and P showed net immobilization after approximately one month of bagasse application when buried, which indicated additional N and P fertilizers should be considered to meet crop demand. K presented no immobilization, with a rapid initial release in Spodosols and a gradual release in Histosols.

Keywords: bagasse; field incubation; nutrient release; sugarcane



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1. Introduction

Sugarcane (*Saccharum officinarum*) is one of the most extensively grown row crops planted on approximately 1600 km² in South Florida [1]. Approximately 71.1% of the crop is grown on Histosols in the Everglades Agricultural Area in 2020/21, while the remaining occurs on mineral soils, mainly Entisols, Alfisols, and Spodosols [1,2]. Since all available land on these Florida Histosols are used for crop production, there is an increasing trend toward expanding sugarcane production to mineral soils. Most Histosols have low mineral content, with limestone as the bedrock under the organic soil layer [3]. Additional N fertilizer is not recommended for sugarcane production on these organic soils, but P and K fertilizers are recommended [3–5]. However, for sugarcane production on mineral soils, nutrient deficiencies are a major concern due to the low organic matter (OM) content and

poor nutrient holding capacity. Currently, growers rely on large amounts and frequent fertilizer applications to achieve an acceptable sugarcane yield on mineral soils.

The sugarcane industry in South Florida produces substantial amounts of organic waste during sugar extraction. Common sugarcane mill by-products include bagasse, mill mud, and mill ash. Bagasse is a fibrous material left after sugar juice extraction from sugarcane. Although it is currently used as fuel to run sugar facilities, bagasse remains, representing a waste in need of disposal [6]. Previous studies have reported that applying sugarcane by-products such as bagasse enhanced soil properties, improved sugarcane quality and yield, and reduced nutrient leaching [7–9]. Thus, utilizing organic sugarcane by-products as soil amendments in agricultural soils can benefit crop production while simultaneously providing an efficient and cost-effective method of disposing of waste. Integrating organic waste into agricultural production systems assists in promoting a circular economy in Florida.

The inputs from these organic wastes are a vital source of essential nutrients for plant uptake. They can also increase soil carbon (C) and nitrogen (N) levels, which can enhance the growth and activities of soil microbes. Moreover, incorporating organic materials into soils has the potential to increase soil C stocks, offset soil nutrient deficiencies, and reduce the use of commercial inorganic fertilizers [10]. According to Xu et al. (2021) [8], bagasse contains approximately 33.91% C, 0.51% N, 0.26 g kg⁻¹ P, and 1 g kg⁻¹ K, with a C/N ratio of 65.88. The nutrient levels can vary in different batches. To reuse the nutrients effectively, there is a need to estimate the release patterns of nutrients, especially the major nutrients (N, P, and K), from bagasse. Nutrient release during the decomposition process is a net result of mineralization, leaching, consumption, or transformation by soil biota. Understanding how much and when these nutrients become available for plant use after bagasse application into fields is essential for evaluating it as a nutrient source and will assist in determining the appropriate time and rate to match nutrient supply with crop demand.

The existing methods to estimate nutrient release from organic amendments include laboratory and in situ methods. Laboratory incubations are relatively easy to carry out but cannot reflect actual conditions in the fields because the nutrient release process is affected by many dynamic and site-specific factors such as fluctuating temperatures, water, and aeration [11,12]. One method that can measure organic amendments/crop residue decomposition, and nutrient release/mineralization under field conditions is the mesh bag technique. This approach is simple, inexpensive, and widely used [13]. For example, the trend of N release and decomposition rate was studied in buried and surface residues of three different cover crops (forage radish, winter pea, and cereal rye) on a fine sandy loam in Massachusetts over two years [14]. Other previous studies conducted on Albright silt loam (a Dark Grey Luvisol in the Canadian classification) in Canada [15] and on sandy loam soil and coarse sand with other plant residues [16] were reported to use the mesh bag technique as well. This method consists of using a given amount of organic amendments/plant residues enclosed in bags with appropriate mesh sizes that are smaller than the sizes of the enclosed materials and buried in the soil or laid on the soil surface [17]. The mesh bags are installed at the beginning of the experiment and destructively sampled over time. The decomposition rate and nutrient release are determined by the mass and nutrient loss of the materials contained in the bags.

The major purpose of this study was to investigate the release patterns of nutrients (N, P, and K) from bagasse at two soil depths (surface at 0 cm vs. buried at 15 cm) in sugarcane and fallow fields on two major soil types for sugarcane production (Histosols vs. Spodosol) in South Florida since no studies have been conducted to determine the decomposition and nutrient release of bagasse in this region. The specific objectives of this study were to: (1) determine and compare the major nutrient (N, P, and K) release patterns at two soil depths (surface at 0 cm vs. buried at 15 cm) in sugarcane and fallow fields on Histosols and Spodosols; and (2) develop models for bagasse decomposition at two soil depths (surface at 0 cm vs. buried at 15 cm) in sugarcane and fallow fields on Histosols and Spodosols.

2. Materials and Methods

2.1. Study Location

Field incubation studies were conducted in sugarcane and fallow fields on Histosols and Spodosols in South Florida (shown in Figure 1). The field experiment on Spodosols was carried out in Clewiston, Florida ($26^{\circ}45'26''$ N $80^{\circ}57'30''$ W). The predominant soil series in the study area is Myakka sand (sandy, siliceous, hyperthermic Aeric Haplaquods). The experiment conducted on Histosols was at the Everglades Research and Education Center (EREC), Belle Glade, Florida ($26^{\circ}39'42''$ N $80^{\circ}38'04''$ W), with a mix of soil series Lauderhill and Dania (Euic, hyperthermic Lithic Haplosaprists).



Figure 1. Study sites.

2.2. Bagasse Characteristics

Bagasse was produced from the sugarcane mills in Clewiston and provided by U.S. Sugar Corp. Ten bagasse samples were analyzed at the Soil, Water, and Nutrient Management Laboratory at the EREC in Belle Glade, Florida. The basic physical and chemical characteristics of bagasse are shown in Table 1. Moisture content (MC%) was determined using the loss-on-drying method. OM was determined by the loss of ignition method [18]. The total C and N of bagasse were determined by a Costech ECS 4010 elemental analyzer, and then the C/N ratio was calculated. Total P and K were measured by ashing bagasse samples, which were then extracted using 6 M HCl and analyzed by Agilent 5110 ICP-OES (Santa Clara, CA, USA) [18].

Table 1. Physicochemical properties of bagasse (reported as a dry basis; $n = 10$; mean and standard deviation).

Properties	Value
MC (%)	56.35 ± 3.02
OM (%)	95.77 ± 0.44
Total C (%)	33.91
Total N (%)	0.51
C/N ratio	65.88
Total P (g kg^{-1})	0.38 ± 0.01
Total K (g kg^{-1})	1.16 ± 0.05

2.3. Mesh Bag Technique and Experimental Design

In order to examine the decomposition of bagasse buried in soils or on the soil surface, a mesh bag technique [14,15,19] was used (shown in Figure 2a,b). Window screen (Charcoal Super Solar Screen, 2 mm mesh size) was used to make mesh bags that were 10 cm $\times$ 15 cm. Fresh bagasse was air-dried until it reached a constant weight and sieved using the window screen to retain the relatively large size of this material. Approximately 10 g of dry bagasse was weighed and placed in mesh bags, and then the bags were sealed using a heat sealer. There were three replications for each soil depth and each soil type in each cropping system for each retrieval date.

Fallow plots were within 50 m of the sugarcane fields. The bags placed horizontally on the soil surface were fixed with a metal wire (together with flags) to prevent the bags from moving. The bags buried under the soil surface (15 cm) were marked with colored flags to recognize their locations.



(a)

Figure 2. Cont.



(b)

Figure 2. (a). Mesh bags buried at 15 cm under soil surface. (b). Mesh bags placed on the soil surface. A randomized complete block design was used for each soil depth in sugarcane and fallow fields on both Histosols and Spodosols. All bags were installed in the fields approximately 5–7 weeks after sugarcane was planted on two soil types (3 November 2020 on Spodosols; 20 January 2021 on Histosols). Sugarcane received standard chemical fertilizers based on recommendations for commercial sugarcane production in South Florida over the entire period of the current study. Daily temperature and precipitation throughout the experiment were shown in Figure 3a,b (Florida Automated Weather Network Data).

The bags were retrieved on 12 dates: 3, 7, 14, 21, 28, 42, 56, 70, 100, 130, and 190 days, and until the first year of sugarcane harvest (461 days on Spodosols and 443 days on Histosols), after the bags were installed in the fields. At each retrieval date, 12 bags (1 bagasse bag $\times$ 3 replications $\times$ 2 soil depths $\times$ 1 soil type $\times$ 2 cropping systems) were recovered from Histosols or Spodosols. The attached soil of the bags was removed gently with a brush, and then the bags were air-dried until they reached a constant weight before measurements. The bagasse in the bags was weighed, ground, and analyzed for N, P, and K contents using the method discussed in Section 2.2 [18]. N was analyzed using the total Kjeldahl N (TKN) digesting method followed by colorimetric determination (EPA method

351.2). Total P and K were measured by ashing bagasse samples, then extracted using 6 M HCl and analyzed by an Agilent 5110 ICP-OES (Santa Clara, CA, USA). The differences in dry weight, N, P, and K contents of bagasse at each timepoint were compared with the very first sample (Day 0 sample) to estimate N, P, and K release and decomposition rates.

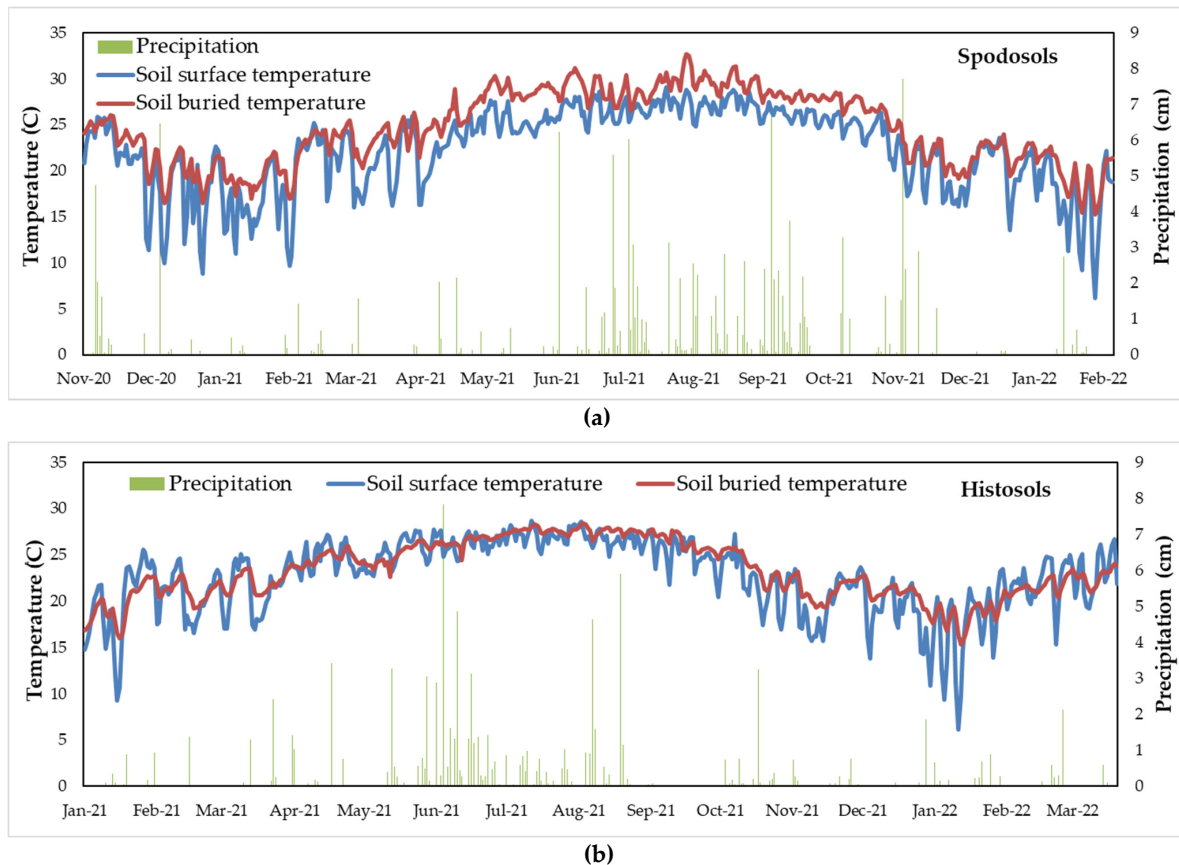


Figure 3. (a). Daily temperature and precipitation throughout the duration of the experiment on Spodosols. (b). Daily temperature and precipitation throughout the duration of the experiment on Histosols.

2.4. Data Analysis

The nutrient remaining (NR) was calculated from the change in nutrient content during bagasse decomposition [20]. The equation was

$$NR(\%) = \frac{NtMt}{N0M0} \times 100$$

in which NR is the percentage of remaining nutrients (%), $M0$ is the initial oven-dry mass (g), $N0$ is the initial nutrient concentration (g kg^{-1}), Mt is the oven-dry mass (g) at time t , and Nt is the nutrient concentration at time t .

As the retrieval dates were a continuous array of treatments, trends in bagasse dry weight loss during its decomposition were evaluated by regression analysis. The negative exponential decay model was used to fit the data (percent dry weight remaining at each retrieval date) for nonlinear regression based on R^2 values. The general form of the exponential model

$$PR = ae^{-kt}$$

in which PR is the percent of dry weight remaining at time t , a is constant, and k is the decay rate constant expressed on a daily basis (per day).

Two-way analyses of variance were performed using a mixed model in 9.4 (SAS Institute, 2011). The soil depth (surface at 0 cm vs. buried at 15 cm) and cropping systems (sugarcane vs. fallow) were fixed main effects, while the block was considered a random effect. The least significant mean differences ($p < 0.05$) were used to determine the significant treatment effects.

3. Results

3.1. Precipitation and Soil Temperature

For the Spodosols, daily soil surface temperatures ranged from 6.14 °C to 29.08 °C, while soil temperatures below the soil surface ranged from 15.24 °C to 32.7 °C during the study period. Soil surface temperature had more fluctuations, as shown in Figure 3. Rainfall was concentrated during the rainy season in Florida, from June to November.

For the Histosols, daily soil surface temperature ranged from 6.1 °C to 28.72 °C, while soil temperature below the soil surface ranged from 15.37 °C to 28.39 °C during the study period. Rainfall events occurred mainly from June to October.

3.2. Dry Matter Loss

Bagasse lost a larger portion of its initial biomass (approximately 10 g) when buried compared to being on the surface in sugarcane and fallow fields (no cane) for both Histosols and Spodosols. For the Spodosols, when bagasse was buried under the soil surface at 15 cm, after 130 days, approximately 40% of its original dry matter had been lost, whereas only approximately 20% had been lost when bagasse was placed on the surface. For the Histosols, buried bagasse lost 40% or more of its original dry matter in only 70 days, while bagasse placed on the surface lost about 20% (Figure 4a,b). The differences between the two soil depths (0 cm vs. 15 cm) were significant ($p < 0.01$) after Day 21 for Spodosols and Day 28 for Histosols. The differences between the bags placed in sugarcane and fallow fields were negligible at most of the sampling dates, especially at the beginning. At the end of the experiment (after 461 days), for Spodosols, only approximately 2% of bagasse was left in bags buried at 15 cm; however, about 50% of bagasse remained on the surface. Similarly, for Histosols, almost all bagasse (<1% remaining) was decomposed at the end of the experiment (after 443 days) when buried, and approximately 45% of bagasse remained when placed on the soil surface in sugarcane fields (Figure 4a,b). The bags left in the fallow field were lost.

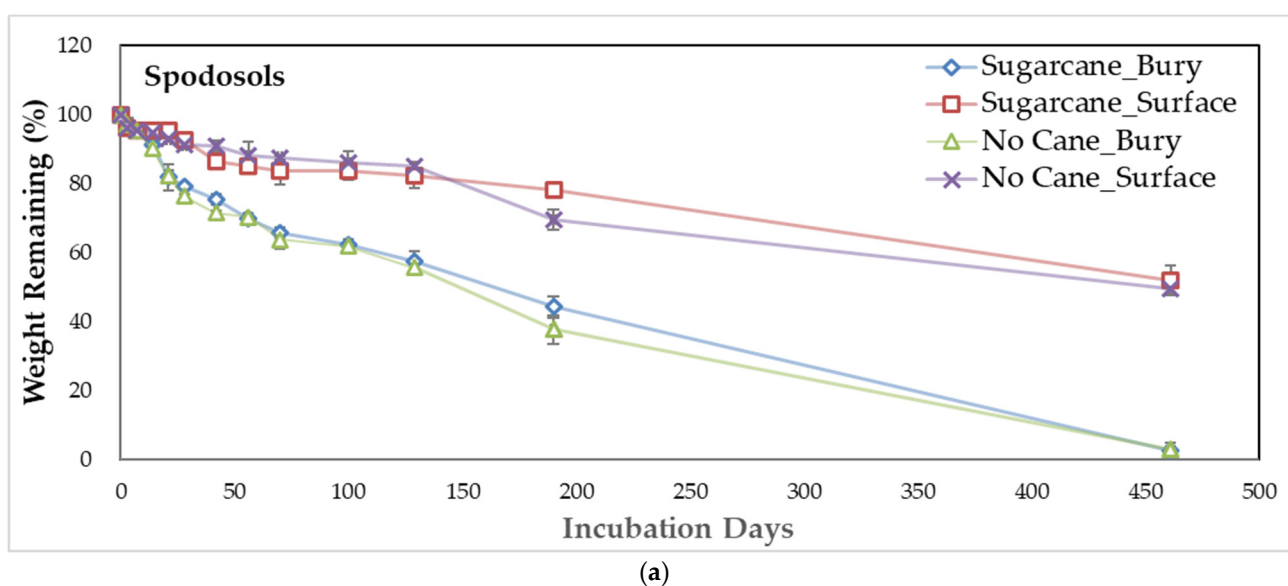


Figure 4. Cont.

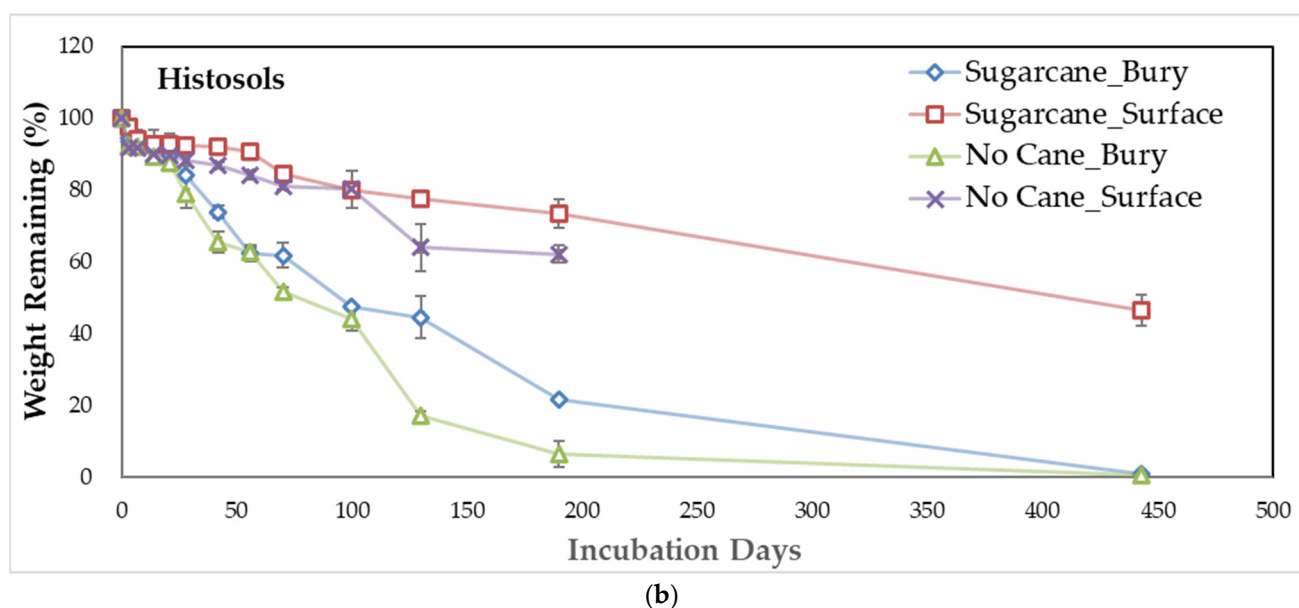


Figure 4. (a). Dry Matter Weight Remaining (%) of bagasse throughout the experiment on Spodosols. (b). Dry Matter Weight Remaining (%) of bagasse throughout the experiment on Histosols.

Dry matter losses at both soil depths in sugarcane and fallow fields (no cane) for Histosols and Spodosols followed an exponential trend with R^2 larger than 0.92 (Table 2). The daily decomposition rate constant (k) for dry matter was significantly higher in the buried (0.008 in sugarcane fields and 0.007 in fallow fields on Spodosols; 0.01 in sugarcane fields and 0.012 in fallow fields on Histosols) than on the surface (0.001 in both sugarcane and fallow fields on Spodosols; 0.002 in both sugarcane and fallow fields on Histosols).

Table 2. Exponential models for decomposition rate of bagasse for Spodosols and Histosols.

Treatment	Exponential Regression Equation	R^2
Spodosols		
SB	$y = 110.24e^{-0.008x}$	0.94
SS	$y = 95.916e^{-0.001x}$	0.95
FB	$y = 106.76e^{-0.007x}$	0.95
FS	$y = 97.03e^{-0.001x}$	0.97
Histosols		
SB	$y = 116.17e^{-0.01x}$	0.97
SS	$y = 96.94e^{-0.002x}$	0.98
FB	$y = 106.82e^{-0.012x}$	0.96
FS	$y = 94.891e^{-0.002x}$	0.92

SB = buried at 15 cm in sugarcane field, SS = surface at 0 cm in sugarcane field, FB = buried at 15 cm in a fallow field, FS = surface at 0 cm in a fallow field.

3.3. Nutrient Release Patterns

3.3.1. Nitrogen

For Spodosols, approximately 30% of the initial N (29.2 mg N existed in the bags when they were first put in the fields) was released in the initial seven days after bagasse was buried or placed on the surface in both sugarcane and fallow fields. No N was lost when bagasse was buried 15 cm under the soil surface between sampling Day 28 and Day 56. At the end of the experimental period (after 461 days), only approximately 6% of the buried bagasse remained, while 70–80% of the bagasse remained when it was placed on the soil surface (Figure 5a).

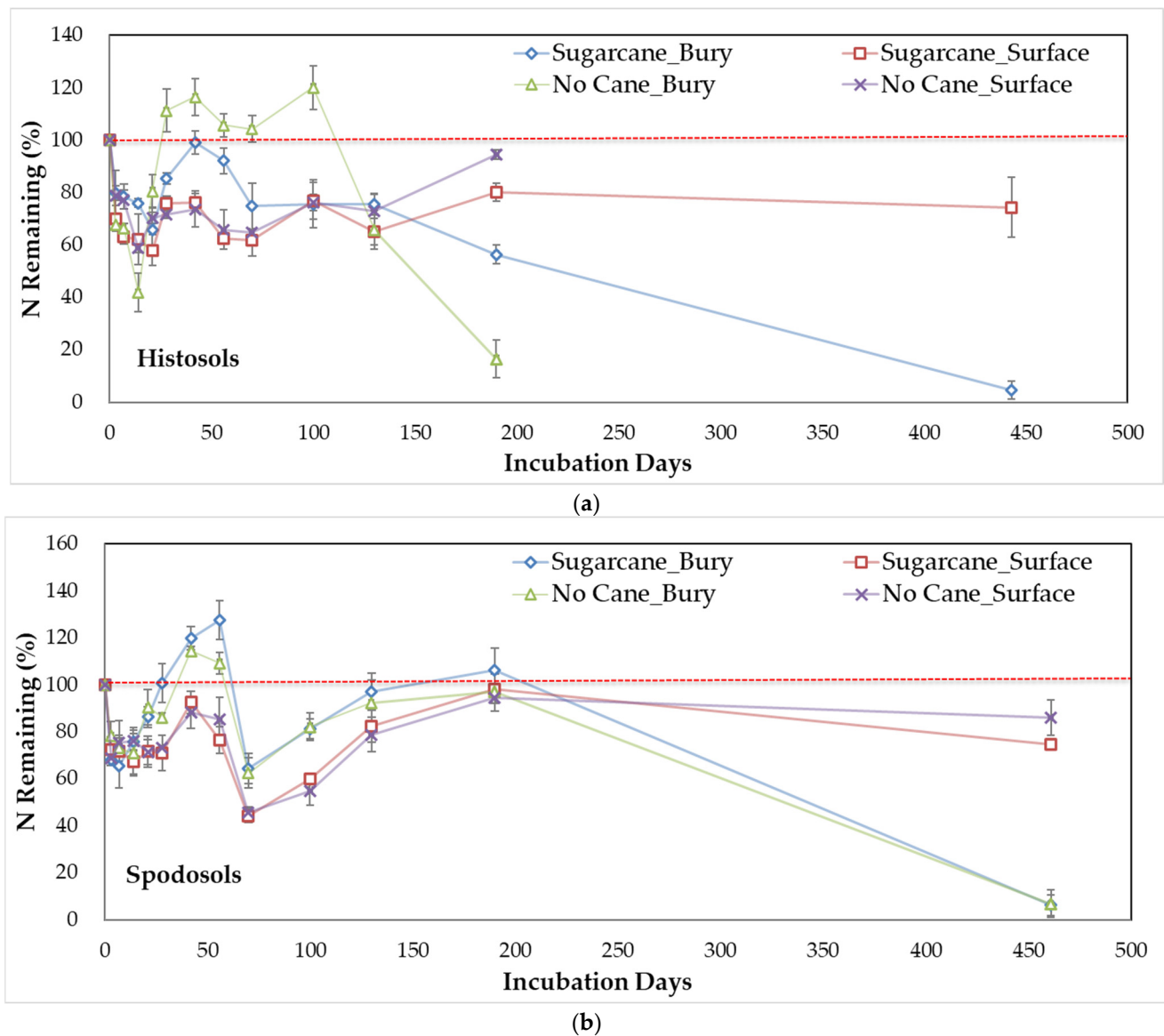


Figure 5. (a). N remaining (%) in bagasse during the experiment in Spodosols. (b). N remaining (%) in bagasse during the experiment in Histosols.

For Histosols, approximately 40% of the initial N (29.2 mg) was released from the bagasse within 70 days when placed on the soil surface in both sugarcane and fallow fields. No N was lost from buried bagasse in fallow fields between sampling Day 28 and Day 100. At the end of the current study (after 443 days), N was almost totally released (<5% was remaining) when bagasse was buried. In fallow fields, the remaining bagasse was below the detection limits for N (Figure 5b).

Overall, more N was released from the buried bagasse than bagasse on the soil surface for both Spodosols and Histosols. No significant differences were detected in the amount of N released between the sugarcane production system and fallow fields for both Spodosols and Histosols (Figure 5b).

3.3.2. Phosphorus

Approximately 50% of the initial P (3.8 mg) was released from all bagasse bags for both Spodosols and Histosols in the initial 14 days (Figure 6a,b). For Spodosols, the P (%) remaining in buried bagasse in sugarcane fields significantly increased after Day 28, then slowly decreased after Day 56. Conversely, bagasse buried in fallow fields for Histosols

had over 100% P between Day 28 and Day 70. After 461 days (the end of the study), less than 4% of P was left when bagasse was buried in Spodosols; however, approximately 45% of P remained when placed on the soil surface. Additionally, for Histosols less than 2% of P remained when bagasse was buried, and about 30% of P remained when bagasse was on the soil surface in sugarcane fields. Overall, similar to N, more P was released when buried under the soil surface on both Spodosols and Histosols over the entire experimental period. Significant differences were detected between sugarcane production systems and fallow fields on most of the sampling dates after Day 21 when bagasse was buried.

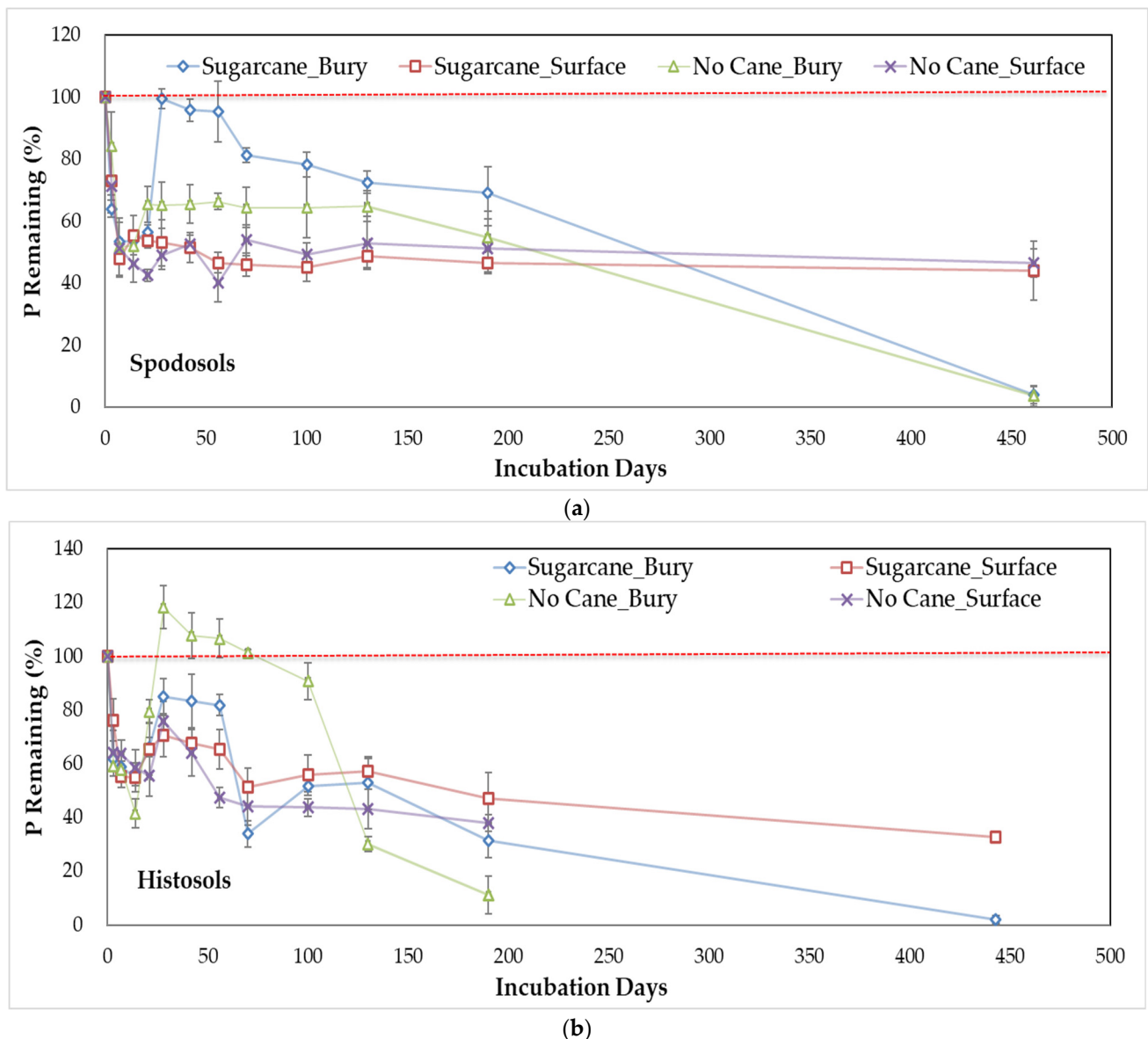


Figure 6. (a). P remaining (%) in bagasse during the experiment in Spodosols. (b). P remaining (%) in bagasse during the experiment in Histosols.

3.3.3. Potassium

For Spodosols, approximately 80% of the initial K (11.6 mg) was released during the initial seven days, both when bagasse was placed on the soil surface and buried in both sugarcane and fallow fields. After the first seven days, the remaining K (%) slowly decreased until the end of the experiment. However, for Histosols K, it was gradually released in an exponential pattern over the study period. Almost all K was released (<1%

remaining) in the buried bagasse after 443 days, while less than 20% of K remained when bagasse was placed on the soil surface in sugarcane fields (Figure 7a,b).

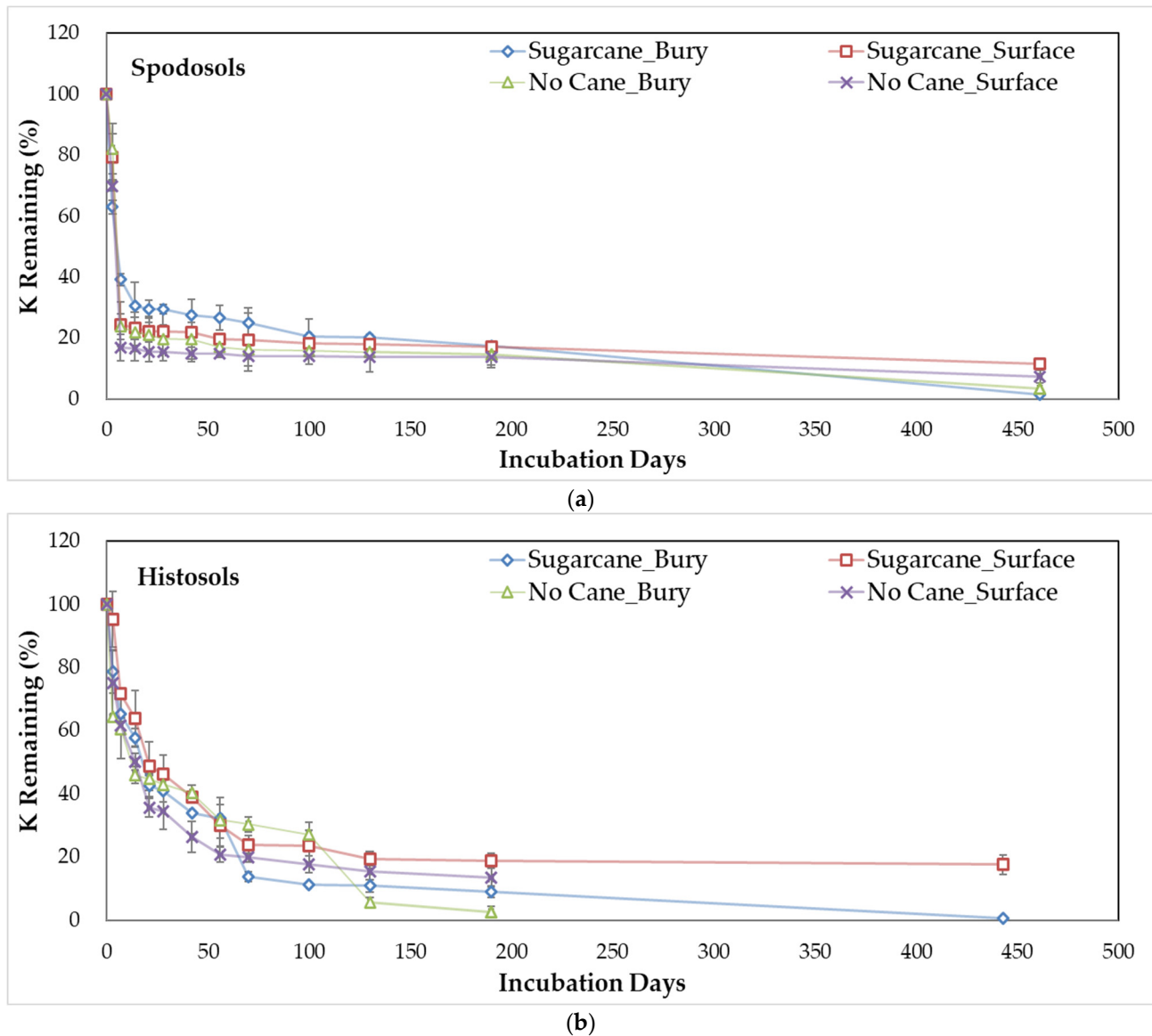


Figure 7. (a). K remaining (%) in bagasse during the experiment in Spodosols. (b). K remaining (%) in bagasse during the experiment in Histosols.

4. Discussion

4.1. Dry Matter Loss

The results of the dry matter loss experiments suggested that bagasse decomposed faster when it was buried instead of placed on the surface, regardless of soil type and whether it was in a sugarcane production system or a fallow field. One previous study reported that three types of cover crops, including forage radish (*Raphanus sativus* L.), winter pea (*Pisum sativum* subsp. *Arvense* L.), and cereal rye (*Secale cereale* L.), had faster residue decomposition when buried in the soil [14]. Another study also reported a similar result, as the rate of decomposition of cornstalk residue contained in bags on the soil surface was noticeably slower than that in bags buried in the soil. The faster decomposition of the buried bagasse likely resulted from the placement itself, as buried bags had twice the bagasse-soil contact [21]. A larger surface area was exposed to greater microbial activity, which may have accelerated decomposition [14]. The daily decomposition rate calculations

indicated that bagasse decomposed faster in Histosols than in Spodosols. Although the decomposition experiments in Histosols and Spodosols began at different times, they occurred under similar climatic conditions, as shown in Figure 3a,b, and described in Section 3.1. Therefore, climate variables may not be dominant factors affecting bagasse decomposition, while differences between bagasse decomposition rates in Spodosols and Histosols are likely primarily due to differences in the microbial biomass and activities of these two soil types. Histosols may have higher microbial biomass and activity than Spodosols because of the higher soil OM (35.89 ± 7.07 , $n = 16$ compared to 2.72 ± 0.21 , $n = 16$) in our study. Both microbial biomass and activities can have a significant positive correlation with soil OM [22].

No significant differences were observed between bagasse decomposition in sugarcane and fallow fields at the beginning of the study, which could be because the sugarcane was still in the early growth stage and thus the sugarcane root system and canopy were still developing. However, on Day 130 and Day 190, especially in Histosols, significant differences were observed in bagasse decomposition between sugarcane production systems and fallow fields, indicating that differences such as root exudates from sugarcane and microclimates caused by sugarcane canopies might have some effects on bagasse decomposition. The root exudate components in the rhizosphere were reported to stimulate residue decomposition [23] due to the enhanced soil biological activity and altered microbial community structure. However, in the current study, on Days 130 and 190 in Histosols, significantly more bagasse was released in fallow fields compared with sugarcane systems when it was either buried or placed on the surface. This result suggests that temperature could be the primary factor affecting bagasse decomposition rate in Florida since fallow fields are exposed more to the sun, which results in a higher temperature compared with a sugarcane system with a canopy. No clear effects from the root exudate components were detected in our study.

4.2. Nutrient Release Patterns

In our study, an initial N release was observed during the first 7–21 days from all the bagasse bags, both buried and those placed on the surface, in sugarcane and fallow fields in both Histosols and Spodosols. During the first three weeks, the bagasse was likely rapidly consumed by soil microorganisms, releasing N from easily degraded N-compounds. Later, N may have become immobilized in both soil types, during which part of the N was bound to bagasse's low soluble compounds such as lignin. This immobilized N could not be released until more complex and recalcitrant chemical compounds were broken by specific microorganisms [24,25]. The weight loss of bagasse from decomposition and increased N remaining in the residual material may reflect C mineralization and N immobilization by microorganisms. It was not surprising that we measured immobilization as bagasse is a high C/N ratio material (approximately 65.88 as shown in Table 1). Organic materials with a high C/N ratio stimulate soil microbial activity, thus increasing demand for N and eventually leading to immobilization. The results indicate that the buried bagasse was more likely to have a net immobilization in the first 2–3 months (between Day 28 and Day 56 in Spodosols and Day 28 and Day 100 in Histosols). This may be due to the higher microbial activities in buried conditions, as discussed above, where a higher N demand is required by soil microorganisms to support their own growth. Previous studies reported that plant residue C/N values higher than 45 [26] and 40 [27] are required for net N immobilization. Therefore, additional N may be required to meet crop demand approximately 1 month after bagasse is incorporated into the soil. Although the buried bagasse was more likely to experience an initial net N immobilization, more N was later released from the buried bagasse over the entire experimental period as it was almost totally decomposed in this case.

In the case of P, approximately half or more of it was released from all the bagasse bags, both buried and on the surface, in sugarcane and fallow fields in both Histosols and Spodosols in the initial 14 days. Phosphorous release in the early stages of decomposition

may be due to the leaching of soluble P containing compounds [28]. After this period, P became immobilized in both Spodosols and Histosols. Compared to bagasse placed on the soil surface, the buried bagasse was more likely to show immobilization, and the bagasse buried in fallow fields on Histosols presented a net immobilization between Day 28 and Day 70.

In addition, K presented a different release pattern compared to N and P, as no immobilization was observed. Unlike N and P, K was likely more readily released from bagasse as it is less dependent on microbial mineralization [29]. K is a non-structural nutrient that is presented as a C moving freely in the cell fluid, and when the cell wall disintegration occurs during decomposition, it is quickly released [28]. Approximately 70%–80% of the K was rapidly released during the initial 7 to 14 days in Spodosols, while K was gradually released in Histosols, with 70%–80% not released until after approximately 70 days. The faster release of K in Spodosols might be attributed to greater leaching of K from bagasse, as there were more rainfall events in the initial days in Spodosols compared to Histosols (Figure 3a,b), with one storm bringing 4.75 cm of rainfall on Day 6 to the Spodosol site. Therefore, it is not recommended to apply bagasse during the rainy season, when there is a greater potential for K leaching.

5. Conclusions

Bagasse decomposed faster when buried under the soil surface (total decomposition after approximately 450 days) than when placed on the soil surface (about 50% remained after 450 days) in both sugarcane and fallow fields in both Spodosols and Histosols. Therefore, incorporating bagasse into the top layer of soil facilitates decomposition and potential nutrient release compared to using it as a surface mulch. Bagasse decomposed faster in Histosols compared to Spodosols. For nutrient release, both N and P had net immobilization approximately one month after bagasse application (buried under the soil surface), which indicated that additional N and P fertilizers should be considered to meet crop demand. K presented different release patterns from N and P, as no immobilization was observed. Bagasse is not recommended to be applied during the Florida rainy season as the increased precipitation enhances K leaching, especially in Spodosols.

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Data Availability Statement: All analyzed datasets have been reported here in the paper.

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Conflicts of Interest: The authors declare no conflict of interest.

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