

Article

Nutrient Release Dynamics in Argentinean Pampean Soils Amended with Composts under Laboratory Conditions

Luciano Orden ^{1,2,*}, Gastón A. Iocoli ², María Ángeles Bustamante ³ , Raúl Moral ³ and Roberto A. Rodríguez ²

¹ Estación Experimental Agropecuaria INTA Ascasubi, Ruta 3 km 794, 8142, Hilario Ascasubi, Buenos Aires 8000, Argentina

² Departamento de Agronomía, Universidad Nacional del Sur, San Andrés 800, Bahía Blanca, Buenos Aires 8000, Argentina; gaiocoli@criba.edu.ar (G.A.I.); rrodrig@uns.edu.ar (R.A.R.)

³ Department of Agrochemistry and Environment, Miguel Hernández University, EPS-Orihuela, ctra. Beniel 7 km 3.2, 03312 Orihuela, Alicante, Spain; marian.bustamante@umh.es (M.Á.B.); raul.moral@umh.es (R.M.)

* Correspondence: orden.luciano@inta.gob.ar

Abstract: Composted manure is the greatest nitrogen (N) source in organic agriculture, where the use of chemical fertilizers, except the use of rock phosphate as P source, is not allowed. The aim of this study was to evaluate the effect of the soil type and compost characteristics on the potential rates of mineralization and on the kinetics of the nitrogen (N), phosphorus (P), and carbon (C) release patterns. For this, an aerobic incubation study was conducted over the course of 119 days at 25 °C using two different composts as amendments: a compost from biosolids and wood shavings (CRUB), and a compost from poultry manure with wheat straw (CSP). The composts were incorporated into two different soils of contrasting texture, sandy loam (S1) and silty clay loam (S2), at the dose of 160 kg N ha⁻¹. Samples were collected eight times during the incubation period. The N and C dynamics were studied separately according to the different soil type. In both soils, a predominance of the nitrification process immediately after compost application was observed, showing a higher mineralization in the sandy loam soil, this trend being followed by a decrease and even an immobilization process, associated with stable organic materials such as compost. Moreover, both composts presented high contents of available P, but without exceeding 50 mg P kg⁻¹, due to the slow release from the stable organic P fractions present in compost. The results obtained showed that despite the initial mineralization, both composts showed a significant period of N immobilization after their application into the pampean soils, which makes it necessary to anticipate their incorporation to avoid this lack period for crops. Furthermore, the application of these composts to the pampean soils implied an incorporation of available P, but with a slow release that avoided overfertilization, but also reducing N:P ratio and producing a relative deficit of N. Therefore, the results obtained suggested that it is necessary to study nutrient mineralization processes of the amendments prior to their use, according to the edaphoclimatic condition of each crop, in order to predict the release dynamics on soils and the fertilization potential to minimize potential environmental impacts.

Keywords: composted manure; composted biosolids; C, P, and N dynamics; soil respiration



Citation: Orden, L.; Iocoli, G.A.; Bustamante, M.Á.; Moral, R.; Rodríguez, R.A. Nutrient Release Dynamics in Argentinean Pampean Soils Amended with Composts under Laboratory Conditions. *Agronomy* **2022**, *12*, 795. <https://doi.org/10.3390/agronomy12040795>

Academic Editor:
Dionisios Gasparatos

Received: 3 March 2022

Accepted: 23 March 2022

Published: 25 March 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Composting is a simple and worldwide applied method to transform organic waste into stabilized organic matter that may be added to soils as an amendment [1]. Furthermore, this biological treatment of organic wastes can constitute the way to reduce the environmental and human health risks derived from direct manure application in agriculture [2,3]. The difference between direct application and incorporation of unprocessed residues and stabilized residues (e.g., from composting) in relation to the nutritional response of a crop lies in the amount and timing of mineralizable nutrients available to plants [4–6]. The incorporation of organic amendments such as compost into soils has a great influence

on microbial proliferation and activity, which are linked to the nutritional status of soils, and to the organic matter added, generally improving the microbial development and activity [7]. It is not easy to estimate the availability of nutrients for plants due to the great variability of this type of organic amendments and the influences of edaphoclimatic conditions post-application. Thus, the incorporation of organic amendments such as compost into soils has a great influence on microbial proliferation and activity, which are linked to the nutritional status of soils, and to the organic matter added, generally improving the microbial development and activity [7]. It is not easy to estimate the availability of nutrients for plants due to the great variability of this type of organic amendments and the influences of edaphoclimatic conditions post-application. Furthermore, the organic amendments prepared from different organic wastes (raw material), with different kinds (composting) and times of process, produce a final product that differs in its quality [8,9]. Therefore, the quality of the compost used does not only depend on its total nutrient content, because the nutrients will not necessarily be accessible to crops until the organic fraction applied to the soil is mineralized by microbial action [10]. Thus, the characteristics of different organic materials may have a different effect on the soil microbiota, determining the availability of the different nutrients, such as N and P, as well as on the microbial use of the C contained in these materials, with direct implications on CO₂ emissions from amended soils [11]. Furthermore, different studies have reported that soil texture is another important factor controlling organic matter cycling in soils [12,13].

Thus, the transformations of N in the soil, including the native N of the soil and the N applied with the amendments, are strongly controlled by the interaction between the environment and the soil conditions, and by the composition or quality of the substrate [14]. It is difficult to make an estimation of amount and timing of organic N mineralization to predict compost N availability [15]. Therefore, it is very important to take into account in the application of compost, the type of soil, the timing, and the adequate dose, to avoid high levels of accumulation of N in the soil, which are subject to losses in the environment [16]. The dynamics of N mineralization of organic amendments is predominantly determined by soil properties and was reviewed by many authors [17,18].

On the other hand, phosphorus (P) is also an essential nutrient for plant growth and development, which is often a limiting nutrient in its plant-available form in the soil of organically managed systems [19]. In this sense, the use of chemical fertilizers to provide available P for crops is prohibited in organic farming systems, only including natural sources of P fertilizer, such as composts and ground rock phosphate. However, rock phosphate presents the drawback of having a low inherent reactivity that limits the availability of P in the soil in the short-term [20]. Different studies have been conducted concerning the dynamics of P from rock phosphate and how to improve it, especially in organic farming systems [19,21–23]. However, there is little information regarding the soil P dynamics when composts are used in these systems.

In this context, it is essential to optimize the recycling of compost nutrients considering not only agronomic, but also environmental criteria, and for this reason, it is essential to know the dynamics of their release after application to the soil. Among the most widely accepted ways of estimating nutrient mineralization are laboratory tests of incubations under controlled conditions [24]. This type of test allows for predicting the maximum potentials of nutrient release from organic fertilizers. In addition, the use of specific technologies for the treatment of organic solid wastes by composting has been increasing in Argentina. Therefore, in view of the growing demand for the application of compost of different origins in Argentinean pampean soils, it is necessary to have precise information on the dynamics of nutrients in different types of soils. The application of organic amendments on these types of soils has been poorly studied.

Therefore, the aim of this study was to evaluate the effect of the type of soil and the compost characteristics on the potential rates of mineralization and on the kinetics of the N, P, and C release patterns, in order to predict the release dynamics on this type of soil and on the fertilization potential, minimizing the potential environmental impacts.

2. Materials and Methods

2.1. Soil Sampling and Compost Analyses

There were two soils of contrasting textures collected from the soil surface (0–20 cm) of two sites under organic farming management. The soils used were: (1) sandy loam Hapludol Éntico, from Hilario Ascasubi Agricultural Experimental Station of INTA (S1) (39°23'38.6" S and 62°37'46.9" W), and (2) silty clay loam soil Argiudol Vertico, from San Pedro Agricultural Experimental Station of INTA (S2) (33°45'43.8" S and 59°43'53.5" W). Soil samples were air-dried and sifted (<2 mm mesh sieve) prior to performing chemical analyses (Table 1).

Table 1. Characteristics of the different soils.

Soil	pH	EC (dS m ⁻¹)	C _{ot} (g kg ⁻¹)	N _{ot} (g kg ⁻¹)	C _{ot} /N _{ot}	Pe (mg kg ⁻¹)	K (mg kg ⁻¹)	Ca (mg kg ⁻¹)	Mg (mg kg ⁻¹)
S1	8.4	0.14	14.1	1.4	10	13	86	130	177
S2	6.5	0.13	18.0	1.5	12	8	102	67	100

S1: Hilario Ascasubi soil; S2: San Pedro soil. EC: electrical conductivity; Cot: total organic carbon; Not: total organic nitrogen; Pe: extractable P. Data values reported as mean values ($n = 3$).

The composts used were the following: compost CSP, prepared with poultry manure and wheat straw (60:40 *v/v*), and compost CRUB, from biosolids with wood shavings and yard trimmings (60:40 *v/v*). Both composts were obtained using the turning windrow composting system. Compost samples were air-dried and homogenized by hammer milling and sifted (<5 mm mesh sieve) prior to analytical determinations.

2.2. Analytical Methods

The following determinations were performed for the soils samples, according to the methods used by Sparks et al. [25]. pH and electrical conductivity (EC) were determined in a sample: water solution (1:2.5) and extractable P (Pe) were analyzed after being extracted with a 0.5 M sodium bicarbonate solution (1:20, *p:v*) by colorimetric quantification using the ascorbic acid-molybdate method. Extractable cations (Ca, Mg, and K) were determined in the 1 M ammonium acetate extracts by flame photometry. Organic C (Cot) was analyzed by wet combustion method, while total N content (N_{ot}) was determined by semi-micro Kjeldahl. In the compost samples, the following determinations were conducted following the methods described by Bustamante et al. [13]. pH and EC were determined in a sample: water solution (1:10). Total C was determined by dry combustion at 950°C (LECO C Analyzer); NH₄⁺-N, NO₃⁻-N, and total Kjeldahl N (Not) were evaluated by semi micro Kjeldahl method [26]; total P (Pt), K, Ca, Mg, and heavy metals (As, Cd, Cr, Cu, Hg, Mo, Ni, Pb, Se, Zn) were analyzed in the extract obtained by microwave (CEM MARS-5) nitric-perchloric digestion by inductively coupled plasma atomic emission spectroscopy (ICP-AES, Shimadzu 9000) [27]. All the analyses were conducted in triplicate.

2.3. Incubation Experiment

2.3.1. N and P Mineralization

An aerobic incubation was conducted under controlled conditions to evaluate the dynamics of N and P from the different composts after their incorporation into two soils of contrasting texture. A total of one-hundred and sixty-two experimental units were set up in 750 cm³ plastic containers with a perforated lid that allowed gas exchange. This involved the use of triplicate samples of 100 g of dry soil transferred into the containers. The moisture content was adjusted to 50% of the pore space (EP) [28], and the samples were pre-incubated in a dark chamber at constant temperature of 25 °C for one week. Then, the composts were incorporated in three replicates in a completely randomized design, also using a soil without amendment as control treatment (S). Both composts were added in a dose of 6.50 mg N 100 g⁻¹ on S1 and 6.15 mg N 100 g⁻¹ on S2, the mass of the soil being 2.46 Mg ha⁻¹ and 2.60 Mg ha⁻¹, respectively. These doses represent a rate of

160 kg N ha⁻¹, the potential reference demand of a horticultural onion (*Allium cepa* L.) crop. The composts were mixed with the soils at the time of application and there was no airflow over it, thus the losses due to volatilization can be considered negligible [29]. Incubations were developed at a constant temperature of 25 °C in a dark chamber for 17 weeks. The soil moisture was adjusted gravimetrically to 60% during the incubation of the EP by adding distilled water. The initial sampling (0 days) was performed immediately after the application of the treatments. A total of three replicates per treatment were collected destructively at 3, 7, 21, 35, 49, 70, 91, and 119 days. At each sampling date, soil was collected from each repetition for moisture (gravimetric method), N-NH₄⁺, N-NO₃⁻, and extractable Pe determinations.

Compost N inorganic (Ni) values were calculated from NH₄⁺-N and NO₃⁻-N values:

$$\text{Ni} = \text{NH}_4^+ + \text{NO}_3^- \quad (1)$$

Net available N (Nnet) was calculated with the following formula:

$$\text{Nnet} = \text{Ni}_{\text{treatment}} - \text{Ni}_{\text{control}} \quad (2)$$

The net mineralized N (Nmin):

$$\text{Nmin} = (\text{Ni}_{t=119} - \text{Ni}_{t=0})_{\text{treatment}} - \text{reatm}_{t=119} - \text{Ni}_{t=0}_{\text{control}} \quad (3)$$

Lastly, the efficiency of supply available P as percentage of added P source was determined with the following equation:

$$\text{Pef} = (\text{Pe}_{\text{treatment 119d}} - \text{Pe}_{\text{control 119d}}) / \text{P}_{\text{added}} \times 100 \quad (4)$$

2.3.2. C Mineralization

C mineralization was evaluated by the release of CO₂ captured in a solution of NaOH and later titration with HCl [30,31]. This incubation experiment was performed simultaneously with the N mineralization tests, using the same treatments and conditions as in this previous experiment. Briefly, 100 g of soil previously sifted (<2 mm mesh sieve) were placed in hermetically 750 cm³ glass flasks (microcosms) and water was added to adjust soil moisture 60% of the EP. These glass flasks were pre-incubated for a week. Then, the compost was added in 100 g of soil, which was moistened to 60% of the EP and incubated for 17 weeks in a dark chamber at 25 °C. A beaker with 30 mL of NaOH trap solution (0.5 N) was placed in each flask. The containers traps were restored 8 times during the incubation (3, 7, 21, 35, 49, 70, 91, and 119 days). A total of three repetitions per treatment and three controls without soil were added as blanks. At each sampling date, the amount of CO₂ in the flasks was determined by back titration with HCl (0.25 M) in an excess of BaCl₂ saturated solution (1.5 M). Potential microbial respiration was estimated by calculating the daily and cumulative rate of evolution of CO₂. The CO₂-C was calculated by multiplying the CO₂ production by the coefficient 0.273 (C proportion in CO₂ molecule). The apparent mineralization of the organic C (Cam) from the amendments was calculated as the differences between CO₂-C evolved in the amended soil and CO₂-C produced in the unamended soil (control). This was expressed as percentage of the C added with the amendments. This assessment assumes that there is no priming effect.

$$\text{C}_{\text{am}} = ((\text{CO}_2 \text{ C}_{\text{treatment}} - \text{CO}_2 \text{ C}_{\text{control}}) / \text{C}_{\text{added}}) \times 100 \quad (5)$$

2.4. Data Analysis and Statistical Methods

In both assays, completely randomized designs were utilized. A two-way ANOVA was developed with data of N (NH₄⁺-N, NO₃⁻-N, and Ni) and Pe. A split-plot in time analysis of variance (ANOVA), main plot assigned to treatment (T), and subplot to sampling date (D) was deployed with data of rate of CO₂-C evolution, while cumulative CO₂ emission was subjected to a one-way ANOVA. The %Cam curves were adjusted to a single

exponential and nonlinear regressions were adjusted using Curve Expert Professional v.2.4.0 software [32]. When a significant interaction was detected, a one-way ANOVA was conducted within each sampling date. Fisher's least significant difference test (LSD) was used to determine statistical differences wherever statistical significance of ANOVA was observed. Software InfoStat [33] was used for all the analyses.

3. Results and Discussion

3.1. Compost Characteristics

The chemical analyses of the different amendments are summarized in Table 2. Both compost showed suitable concentrations of organic matter (Cot) and macronutrients. The pH and EC values were within the admissible ranges that allow the use of these composts as organic amendments. CSP showed a lower Cot/N ratio (9.4), N was mostly organic (93%), and N/P ratio was low (0.98) due to its composition of poultry manure. The values of heavy metals found were lower than the maximum limits established in the current Argentine regulations ("Resolución Conjunta 1/2019- SENASA, Secretaría de Ambiente" [34], showing the suitability of these composts for their agricultural use.

Table 2. Principal characteristics of the composts used for the mineralization experiment.

		CRUB	CSP
Cot	(g kg ⁻¹)	96.4	136.1
pH		6.59	7.02
EC	(dS m ⁻¹)	0.06	1.17
Not	(mg kg ⁻¹)	6300	13900
NO ₃ ⁻ -N	(mg kg ⁻¹)	28.5	573
NH ₄ ⁺ -N	(mg kg ⁻¹)	75.7	88.5
N	(mg kg ⁻¹)	6328.5	14473
No	(mg kg ⁻¹)	6196	13811.5
Ni	(mg kg ⁻¹)	104	661.5
Pt	(mg kg ⁻¹)	4620	14723
K	(mg kg ⁻¹)	64	293
Ca	(mg kg ⁻¹)	173	255
Mg	(mg kg ⁻¹)	306	1204
Cot/N		15.23	9.40
Cot/No		15.55	9.85
Ni/N		0.01	0.04
N/Pt		1.37	0.98
As	(mg kg ⁻¹)	5.13	1.65
Cd	(mg kg ⁻¹)	<0.1	<0.1
Cr	(mg kg ⁻¹)	0.68	4.60
Cu	(mg kg ⁻¹)	11.5	52.60
Hg	(mg kg ⁻¹)	<0.05	<0.05
Mo	(mg kg ⁻¹)	0.96	2.20
Ni	(mg kg ⁻¹)	1.70	7.20
Pb	(mg kg ⁻¹)	0.27	1.70
Se	(mg kg ⁻¹)	<0.1	< 0.1
Zn	(mg kg ⁻¹)	31	305

CSP: poultry manure and wheat straw; CRUB: biosolids and wood shavings. EC: electrical conductivity; Cot: total organic carbon; Not: total organic nitrogen; Pt: total P; NH₄⁺-N: ammonium; NO₃⁻-N: nitrate. Data values reported as mean values (*n* = 3).

3.2. Nitrogen Mineralization Dynamics

Because the Ni contents showed interactions between sampling date (D) and soils (S) ($p_{\text{interaction}} < 0.0001$), these variables were analyzed separately according to the soil type. Figure 1 shows the dynamics of NH₄⁺, NO₃⁻, and Ni for each of the treatments and for each type of soil. Significant differences were found between NH₄⁺ and NO₃⁻ ($p < 0.0001$). This coincides with other authors [8,35,36], who reported the predominance of the nitrification process after applying compost to the soil. This fact also coincides with

the behavior observed by Griffin and Honeycutt [37], who even recommended studying the accumulation of NO_3^- only instead of total Ni, because NO_3^- constitutes the most abundant fraction of mineral N in the soil and shows a similar release pattern to Ni.

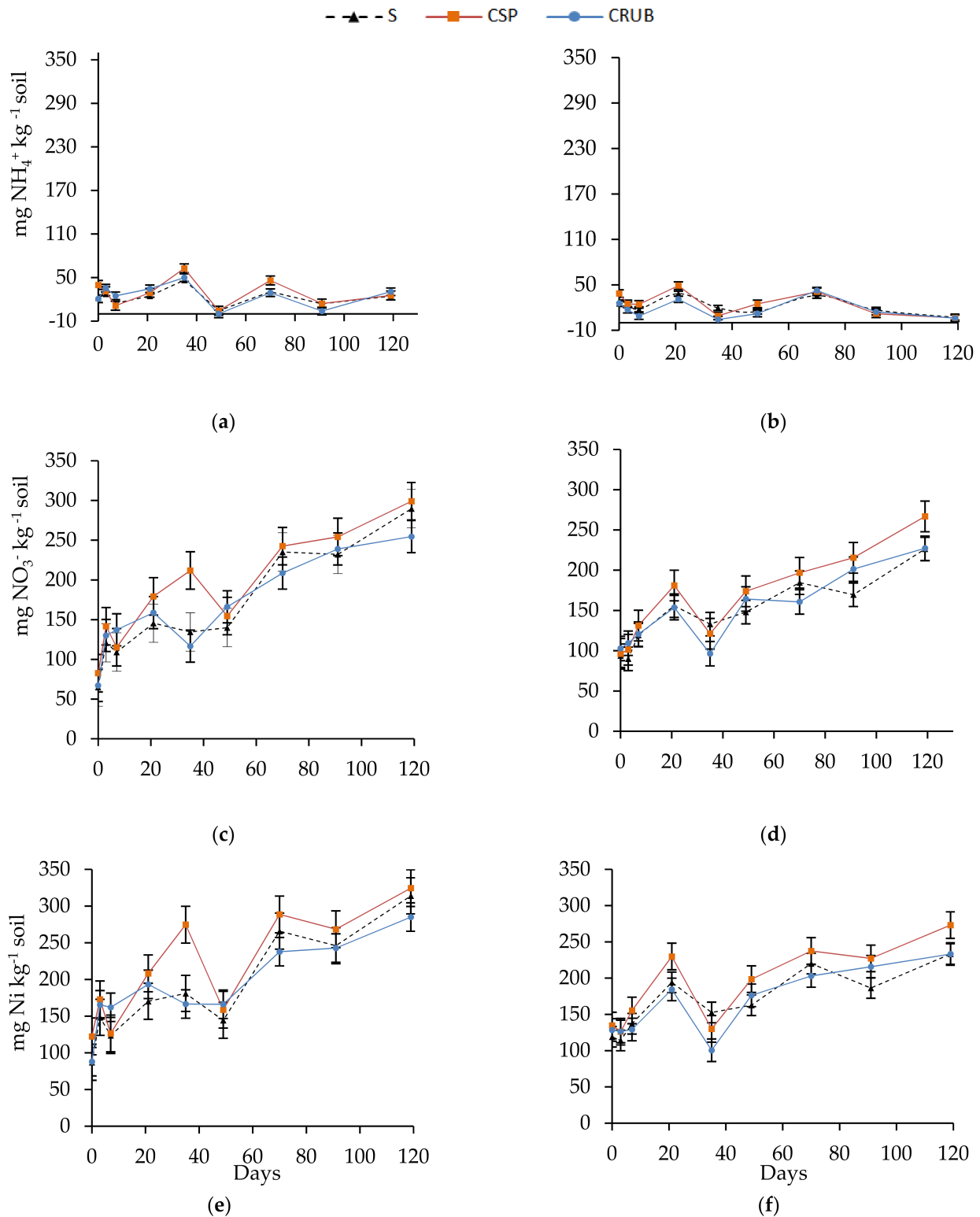


Figure 1. Mineralization of NH_4^+ -N, NO_3^- -N, and Ni for each treatment and date. (a,c,e): S1; (b,d), (f): S2. S: control; CSP: poultry manure and wheat straw; CRUB: biosolids and wood shavings. Bars represent standard error.

In the S1, significant interaction ($p_{\text{interaction}} < 0.001$) was found in the analysis of the data; thus, the dynamics of NO_3^- mineralization were studied, separating days and treatments. In the S2, the treatments also showed significant differences in the interaction ($p_{\text{interaction}} < 0.05$) in the mineralization dynamics of NO_3^- . Figure 1 shows that the treatments followed the trend $S = \text{CRUB} < \text{CSP}$, reaching maximums of 226, 227, and 267 $\text{mg NO}_3^- \text{ soil}^{-1}$, respectively, with the last sampling date showing the maximum distance between the treatments. Tables 3 and 4 show the differences found between the treatments ($p < 0.05$) for each of the sampling dates and between the sampling dates ($p < 0.05$) for each of the treatments.

Table 3. Effect of incubation days on the evolution of NO_3^- -N ($\text{mg NO}_3^- \text{ kg}^{-1}$) in the soil S1 amended with the different composts.

Days	S			CSP			CRUB		
0	87 ± 14	a	A	122 ± 2	a	A	88 ± 0	a	A
3	148 ± 7	a	BC	173 ± 1	b	C	165 ± 7	ab	BC
7	124 ± 10	a	B	126 ± 6	a	B	162 ± 7	b	BC
21	170 ± 9	a	C	208 ± 4	a	D	193 ± 29	a	BC
35	181 ± 29	a	BC	275 ± 17	b	E	167 ± 29	a	AB
49	144 ± 10	a	C	159 ± 6	a	C	166 ± 23	a	CD
70	266 ± 18	a	D	289 ± 2	a	F	238 ± 41	a	DE
91	246 ± 14	a	D	268 ± 5	a	F	243 ± 36	a	E
119	314 ± 14	a	E	324 ± 16	a	G	285 ± 36	a	E

Capital letters indicate significant differences among sampling dates and small letters among treatments ($p < 0.05$). S: soil control, CSP: poultry manure and wheat straw; CRUB: biosolids and wood shavings. Values ± represent standard deviations of the mean values.

Table 4. Effect of incubation days on the evolution of NO_3^- -N ($\text{mg NO}_3^- \text{ kg}^{-1}$) in the soil S2 amended with the different composts.

Days	S			CSP			CRUB		
0	119 ± 5	a	A	135 ± 5	a	A	129 ± 12	a	A
3	114 ± 11	a	A	126 ± 4	a	A	126 ± 19	a	A
7	137 ± 9	a	B	155 ± 2	a	B	129 ± 9	a	A
21	194 ± 4	a	DE	230 ± 6	b	C	184 ± 14	a	B
35	153 ± 13	a	BC	130 ± 19	a	AB	101 ± 22	a	A
49	163 ± 6	a	CD	199 ± 5	a	C	176 ± 25	a	B
70	220 ± 13	a	F	238 ± 32	a	CD	203 ± 33	a	B
91	186 ± 12	a	EF	227 ± 3	b	D	216 ± 8	b	C
119	233 ± 22	a	G	273 ± 34	a	E	233 ± 12	a	C

Capital letters indicate significant differences among sampling dates and small letters among treatments ($p < 0.05$). S: soil control, CSP: poultry manure and wheat straw; CRUB: biosolids and wood shavings. Values ± represent standard deviations of the mean values.

S1 and S2 had similar Ni release dynamics in the first incubation stage, starting with a positive trend followed by a decrease phase until sampling on day 49 for S1 and day 35 for S2 (Figure 1e,f). Concerning NO_3^- dynamics for CSP in both soils, an increase in the NO_3^- content in the soil was observed at the beginning of the experiment, and later a decrease until day 7, coinciding with the trend reported by Amlinger et al. [11] and Mazzarino et al. [38]. Due to the decrease in NH_4^+ in this trial being similar to the increase in NO_3^- , as shown in Figure 1a,b, it can be assumed that immobilization prevailed over gaseous losses [39]. This immobilization may be due to the availability of C after compost application in the first week, stimulating the production of microbial biomass in the soil [12,40,41].

For CSP, between day 7 and 21, a further increase in mineralization occurred, culminating in significant differences between the amended and control soils, but this stage was followed by an immobilization process, where the NO_3^- contents in the amended

soils reached values close to the control soils (Figure 1e,f). These immobilizations are considered as an indicator of stability and maturity of organic amendments [42] and are due to the loss of easily degradable N compounds during the composting process [43]. Therefore, these stable and mature materials do not rapidly mineralize in the initial period after application to the soil, but are gradually stored and released [44]. This coincides with the results observed by other authors [38,45], who explained these periods of negative mineralization as an immobilization of N in the microbial biomass. In these stages, when a decrease in NO_3^- occurred, negative values were observed when performing the N_{net} (Figure 2) and N_{min} (Figure 3) mineralization calculations, coinciding with other works that found the same behavior [14,16].

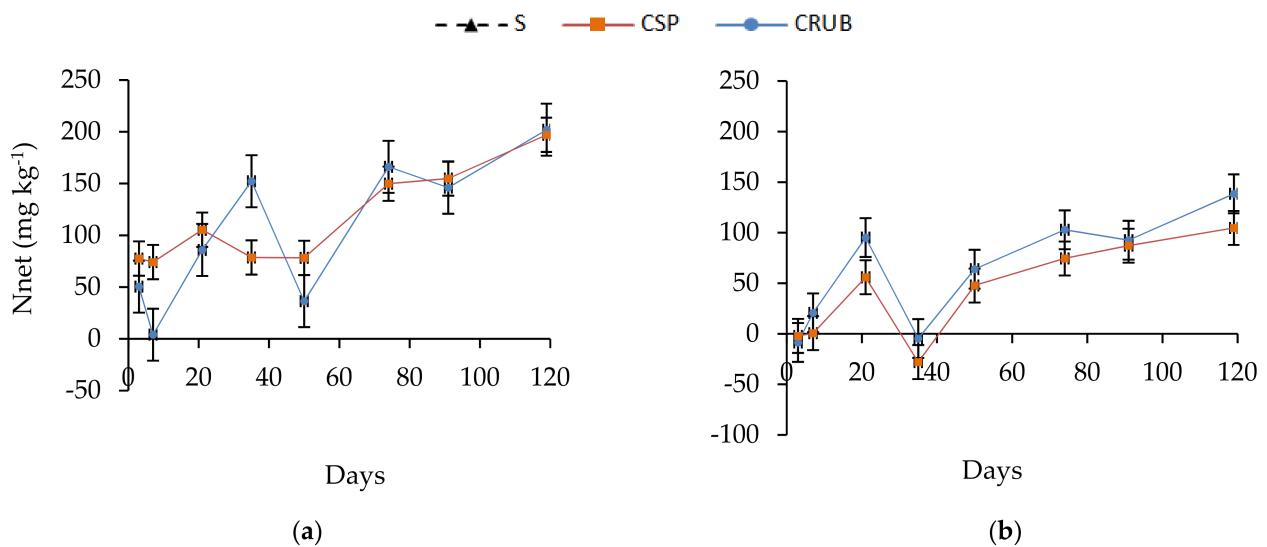


Figure 2. Potential net available N (N_{net}). (a): S1; (b): S2. S: control; CSP: poultry manure and wheat straw; CRUB: biosolids and wood shavings. Bars represent standard error.

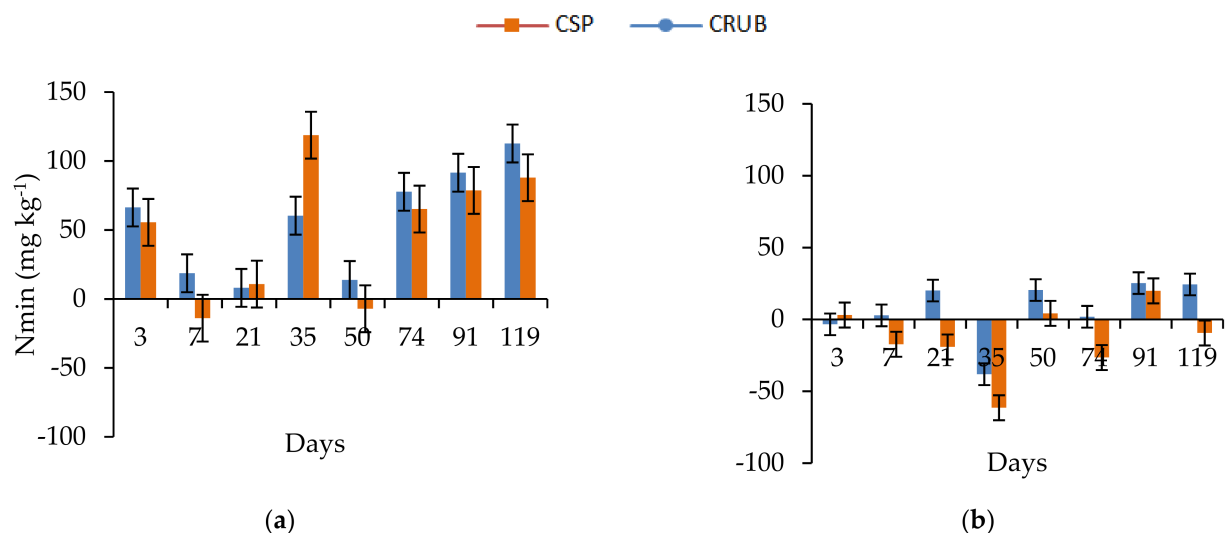


Figure 3. Potential net mineralized N (N_{min}). (a): S1; (b): S2. CSP: poultry manure and wheat straw; CRUB: biosolids and wood shavings. Bars represent standard error.

In the sandy loam soil (S1), CSP mineralization resulted in an increasing proportional progress with time, while the clay loam soil presented a decreasing evolution during most of the incubation experiment (Figure 3b). This coincides with the trends observed by other authors [46,47], who reported immobilization and less mineralization of organic

amendments in soils with fine textures. These differences in mineralization between S1 and S2 were possibly due to the greater protection against microbial attack that clay offers, because it forms complexes with OM [17]. Some authors have also highlighted that the mineralization of raw manures (higher initial Ni content) is not affected by the type of soil, while in stabilized fertilizers (such as compost), mineralization is favored in soils with higher sand content [48]. At the end of the experiment, in the sample corresponding to day 119, significant differences were found in the Ni release ($p > 0.05$) between S1 and S2, the sandy loam soil mineralizing a higher percentage of N during incubation, according to that observed by other authors [14,29,49]. However, Hadas and Portnoy [50] reported that the differences found were of lesser magnitude, and the effects were attributed to the type of amendment used (bovine manure and organic residues of municipal origin).

3.3. P Mineralization Dynamics

Concerning the Pe contents, an interaction between days, compost, and soil was detected ($p_{\text{interaction}} < 0.05$), so the treatments in S1 and S2 soils were compared separately. Figure 4 shows the dynamics of Pe for the different treatments. In S1 soil, the treatments did not show significant interaction ($p_{\text{interaction}} > 0.05$) in the Pe release dynamics, following the trend $S < \text{CRUB} < \text{CSP}$ ($p < 0.0001$) and reaching mean values of 11, 26, and 36 mg kg^{-1} , respectively. In the analysis of the S2 soil data, significant interactions ($p_{\text{interaction}} < 0.001$) were found, attributed to the differences between sampling dates, so the Pe release dynamics were studied separating days and treatments. In Figure 4, it can be observed that the treatments follow the same trend as in the S1 soil ($S < \text{CRUB} < \text{CSP}$).

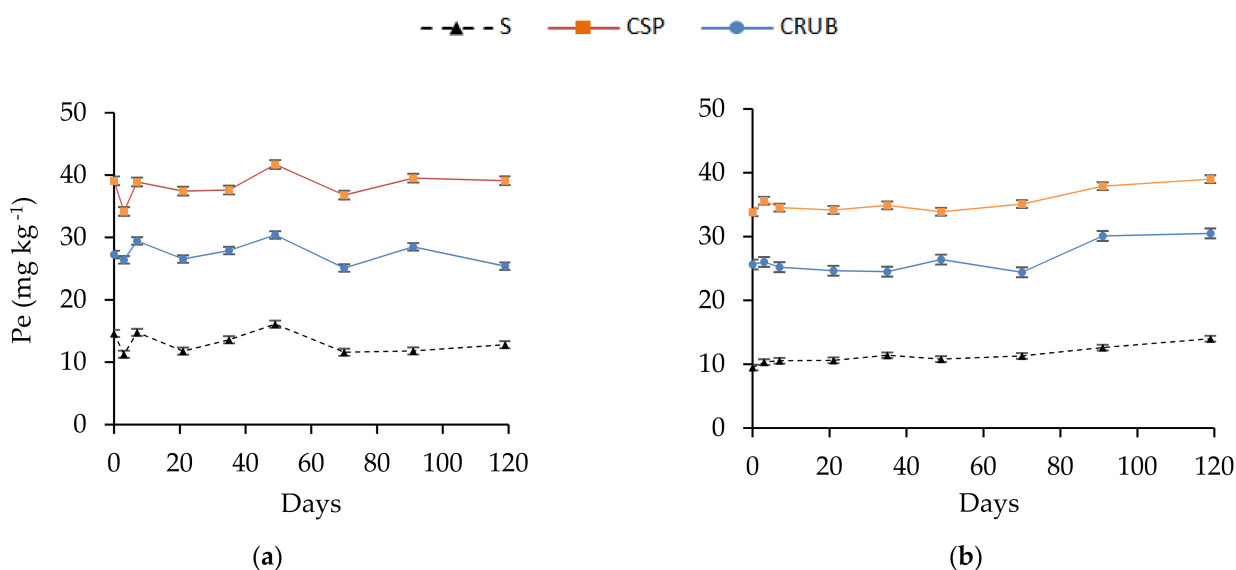


Figure 4. Dynamics of Pe for each treatment and date. (a): S1; (b): S2. S: control; CSP: poultry manure and wheat straw; CRUB: biosolids and wood shavings. Bars represent standard error.

Linear regressions were fitted to evaluate the release of Pe in relation to time for all treatments in each soil type. In the analysis of S1 treatments, significant differences were found between treatments ($p < 0.0001$), with no significant differences ($p > 0.05$) found in the comparison of the slopes of the straight lines. Both composts presented a significant linear adjustment ($p < 0.0001$). On the other hand, in the S2, no significant differences were found between treatments ($p < 0.0001$) and none of the composts were significantly adjusted to the linear regression ($p > 0.05$).

The efficiency of the amendments to increase Pe varied between 27 and 36% in the S1 soil, while in the S2 soil it was higher with values between 34 and 54% (Table 5). Both composts presented high Pe values, but without exceeding 50 mg P kg^{-1} . This is due to the fact that the stable organic P fractions allow for generating a slow release effect that delays

P availability [51]. However, if the objective is to limit P movement in the environment, composted amendments present a higher risk of accumulation by frequent applications due to their high concentrations of inorganic P [44,52]. Due to this, Castán et al. [18] proposed, as a strategy to minimize environmental risks, to mix N- and P-rich composts from animal manures with composts from the organic fraction of municipal wastes that have low N and P contents but are rich in calcium (carbonates), which form complexes with P, which would minimize environmental losses.

Table 5. P availability indicators.

Treatment	Soil	P_{soil} ppm	$P_{applied}$ ppm	P_{medium} ppm	P_{maxim} ppm	P_{eff} %	N/P %
CSP	S1	13.93	69.5	35.4	39.0	36.1	0.9
CRUB			64.8	26.4	30.5	26.6	1.4
CSP	S2	16.07	47.8	38.3	41.7	53.6	0.9
CRUB			42.0	27.5	30.4	34.1	1.4

P_{eff} : efficiency of supply available P. S1: Hilario Ascasubi soil; S2: San Pedro soil; CSP: poultry manure and wheat straw; CRUB: biosolids and wood shavings. S1: Hilario Ascasubi soil; S2: San Pedro soil; CSP: poultry manure and wheat straw; CRUB: biosolids and wood shavings.

3.4. Carbon Mineralization Dynamics

The analysis of the C mineralization data was conducted separating the dynamics of the treatments according to the type of soil dynamics of the potential mineralization of C, because interactions between treatments, soils, and sampling dates were found ($p_{interaction} < 0.0001$). This result coincides with that obtained by Helgason et al. [53] during an incubation test, where a significant interaction in C mineralization between the compost used and the type of soil was found. In the results of this test, it is assumed that the C-CO₂ emission came entirely from the activity of the microorganisms [54], because the remains of plant roots were removed in the preparation of the samples of soil and the formation of CaCO₃ is an edaphic process that requires more time [55]. Moreover, there is no evidence that the dissolution of CaCO₃ contributes significant amounts to the atmosphere [56], and neither do the amendments that contain CaCO₃ [57].

Figure 5 shows the dynamics of cumulative C mineralization at each sampling date. After 17 weeks of incubation, a greater mineralization was observed in the sandy loam soil (SHA) compared to the clay loam soil (SSP). This behavior does not coincide with that reported by Hadas and Portnoy [50], who found less differences between the types of soil. In contrast, Thomsen and Olesen [57] found that C mineralization of compost-amended soils was not affected by texture, but that the initial rate of decomposition is greater in sandy soils and that the protection of organic C from compost by organo-mineral complexes would explain the suppression of mineralization in loamy soils. Possibly, these variations in C mineralization of organic amendments between different soil types may have been minimized by working under controlled trial conditions [53].

In the analysis of the S1 and S2 data, a significant interaction ($p < 0.0001$) was found between the treatments and the sampling date, essentially because in the first two sampling dates no differences were detected between the treatments. For both soils, from day 21, significant differences were found among the sampling dates ($p < 0.0001$) and between the treatments following the trend $S < CSP < CRUB$ ($p < 0.0001$) in S1 and $S < CRUB = CSP$ ($p < 0.0001$) in S2. The cumulative increase in treatment C mineralization (CSP) compared to control (S) indicates the readily available C supplied to the soil by compost [14]. The trend of both treatments showed the highest CO₂ emission and the maximum rate during the first 7 days (Figure 6), gradually decreasing, but maintaining values higher than the control over the course of 119 days.

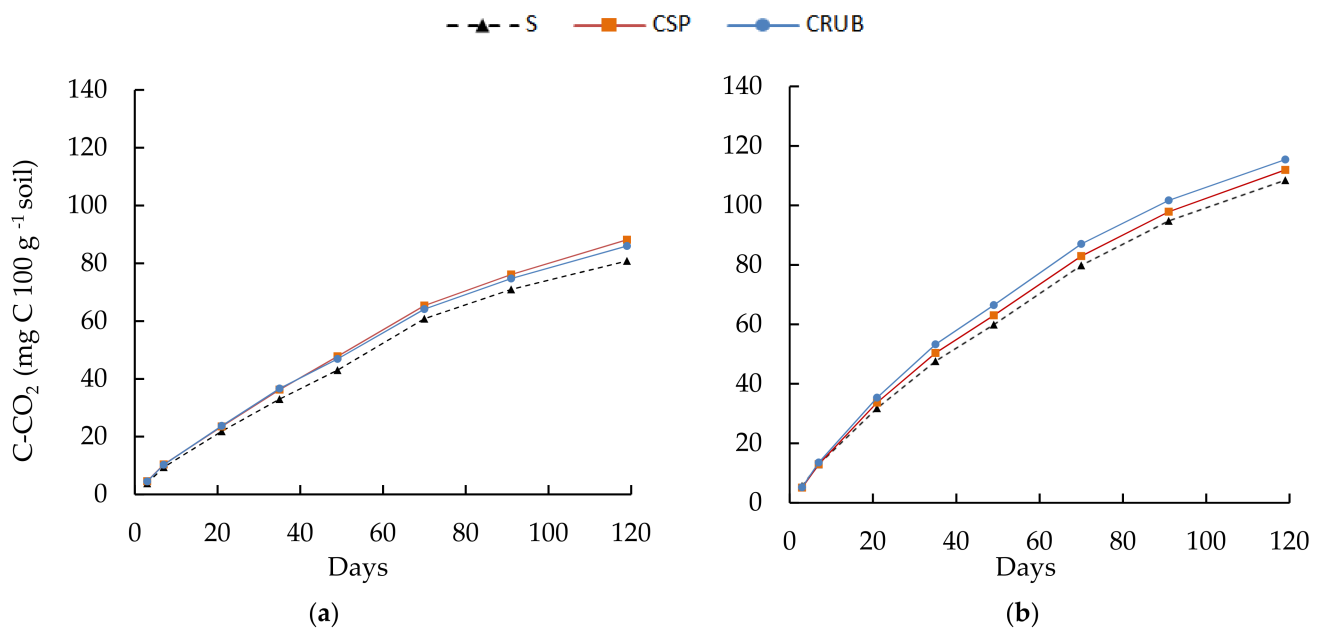


Figure 5. Cumulative mineralization of C-CO₂. (a): S1; (b): S2. S: control. CSP: poultry manure and wheat straw; CRUB: biosolids and wood shavings.

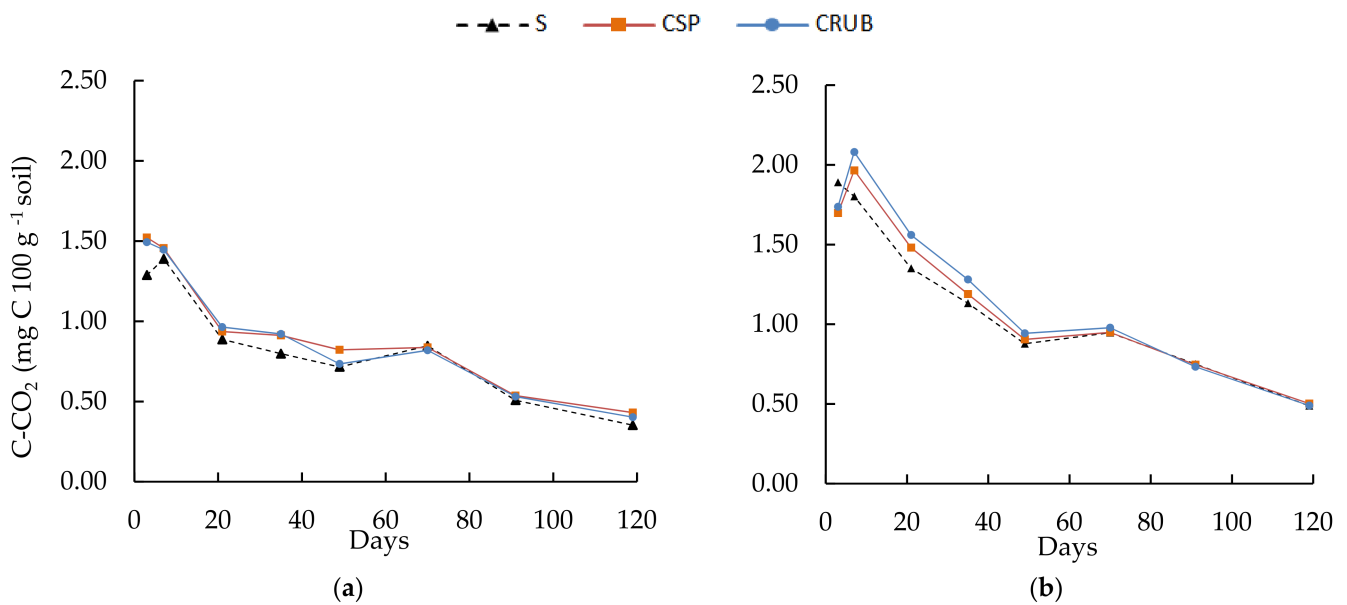


Figure 6. C-CO₂ evolution: (a) S1; (b) S2. S: control. CSP: poultry manure and wheat straw; CRUB: biosolids and wood shavings.

The CSP mineralization rate decreased over time, exhibiting the fastest rate in the first samplings. This coincides with that observed in previous works with amendments of animal origin, where the highest levels of respiration were reached within the interval of 38–42 h, after their application [43]. For each of the amendments applied, a first-order exponential model was adjusted to assess the cumulative evolution of C-CO₂ as proposed by other authors [58]:

$$C_t = C_o (1 - e^{-k_o t}) \tag{6}$$

where:

C_t = cumulative C-CO₂ at time t (mg 100 g⁻¹ of soil)

C_o = potentially mineralizable C stock (mg 100 g⁻¹ of soil)

k_o = first-order constant (day^{-1})

Table 6 shows each of the parameters obtained compared to using *t*-tests. No evidence of differences was found in the C_o ($p > 0.05$), but significant differences were found between the first-order constants ($p < 0.05$) in both S1 and S2.

Table 6. Estimated kinetic model parameters for C-CO₂ release in soil and compost.

Parameter	Soil	CSP	CRUB
C_o	S1	148.92 ± 4.145	149.07 ± 3.262
k_o		0.01167 ± 0.000537	0.01250 ± 0.000467
C_o	S2	129.80 ± 6.665	122.23 ± 5.478
k_o		0.00965 ± 0.000758	0.01031 ± 0.000725

C_o : potentially mineralizable C stock ($\text{mg } 100 \text{ g}^{-1}$ of soil); k_o : first-order constant (day^{-1}); S1: Hilario Ascasubi soil; S2: San Pedro soil; CSP: poultry manure and wheat straw; CRUB: biosolids and wood shavings. Values ± represent standard deviations of the mean values.

An exponential function represents a rapidly mineralizable C reservoir, whose rate depended mainly on the concentration of the substrate, particularly on the soil microbial biomass, known to be in a state of basal metabolism to rapidly respond to labile substrates [59]. In this way, two organic C fractions with different degrees of stability were observed for the evolution of C-CO₂ in the compost used: a first one with a more intense biological transformation of labile organic C, followed by a slower second phase of more organic C resistance [60].

Due to this, it can be inferred that the content of potentially mineralizable C of the treatments was the same, but that the rate of its degradation was different, and varied according to the type of soil considered.

4. Conclusions

The results obtained confirmed that both composts showed a period of N immobilization during the first 30–45 days after their application into the pampean soils, so it would be recommendable to anticipate their incorporation to avoid this lack period for crops. No significant differences on the mineralization were found in the compost comparison (despite the different raw materials), but a higher mineralization was found in the sandy soil. The knowledge of the dynamics of this N_i release has been useful not only for estimating N availability from amendments during the season, but also to improve the synchrony between N supply and crop N demand. The principal contribution of compost as fertilizer was P supply, reducing N:P ratio, and producing a relative deficit of N. In order to obtain an optimal management, minimize the risks of losses associated with contamination processes, and cover the requirements of organic farming systems, it would be advisable to use compost as a base fertilization. Future studies should be conducted to evaluate fertilization strategies that combine different types of amendments on field conditions, in order to exploit their complementary agronomic characteristics and to estimate potential environmental risks derived from a possible overfertilization.

Author Contributions: Conceptualization, R.A.R. and R.M.; methodology, L.O.; software, L.O.; validation, M.Á.B., G.A.I. and L.O.; formal analysis, G.A.I. and L.O.; investigation, L.O.; resources, L.O.; data curation, R.A.R.; writing—original draft preparation, L.O.; writing—review and editing, M.Á.B. and G.A.I.; visualization, G.A.I.; supervision, M.Á.B. and R.M.; project administration, R.A.R.; funding acquisition, R.A.R. and L.O. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by Ministerio de Agricultura, Ganadería y Pesca (Argentina) under INTA national research projects.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors want to thank to Jorge Ullé (EEA INTA San Pedro) for giving us the soil S2, to Grupo de Suelos CRUB (INIBIOMA, UNCOMA) for providing us the compost CRUB, to Luciana G. Dunel Guerra and Romina Storniolo (EEA INTA Ascasubi) for their collaboration in laboratory determinations.

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

References

1. Sayara, T.; Basheer-Salimia, R.; Hawamde, F.; Sánchez, A. Recycling of Organic Wastes through Composting: Process Performance and Compost Application in Agriculture. *Agronomy* **2020**, *10*, 1838. [\[CrossRef\]](#)
2. Muhammad, J.; Khan, S.; Su, J.Q.; Hesham, A.E.; Ditta, A.; Nawab, J.; Ali, A. Antibiotics in poultry manure and their associated health issues: A systematic review. *J. Soils Sediments* **2020**, *20*, 486–497. [\[CrossRef\]](#)
3. Goss, M.J.; Tubeileh, A.M.; Goorahoo, D. A Review of the Use of Organic Amendments and the Risk to Human Health. *Adv. Agron.* **2013**, *130*, 275–379.
4. Lazicki, P.; Geisseler, D.; Lloyd, M. Nitrogen mineralization from organic amendments is variable but predictable. *J. Environ. Qual.* **2019**, *49*, 483–495. [\[CrossRef\]](#) [\[PubMed\]](#)
5. Melo Araújo, M.D.; Monteiro Feitosa, M.; Alves Primo, A.; Kenji Taniguchi, C.A.; Antunes De Souza, H. Mineralization of nitrogen and carbon from organic compost from animal production waste. *Rev. Caatinga* **2020**, *33*, 310–320. [\[CrossRef\]](#)
6. Pinto, R.; Brito, L.M.; Coutinho, J. Nitrogen Mineralization from Organic Amendments Predicted by Laboratory and Field Incubations. *Commun. Soil Sci. Plant Anal.* **2020**, *51*, 515–526. [\[CrossRef\]](#)
7. Bastida, F.; Kandeler, E.; Moreno, J.L.; Ros, M.; Garcia, C.; Hernandez, T. Application of fresh and composted organic wastes modifies structure, size and activity of soil microbial community under semiarid climate. *Appl. Soil Ecol.* **2008**, *40*, 318–329. [\[CrossRef\]](#)
8. Laos, F.; Satti, P.; Walter, I.; Mazzarino, M.J.; Moyano, S. Nutrient availability of composted and non-composted residues in a Patagonian Xeric Mollisol. *Biol. Fertil. Soils* **2000**, *31*, 462–469. [\[CrossRef\]](#)
9. Campitelli, P.; Ceppi, S. Chemical, physical and biological compost and vermicompost characterization: A chemometric study. *Chemometr. Intell. Lab.* **2008**, *90*, 64–71. [\[CrossRef\]](#)
10. Benítez, C.; Tejada, M.; González, J.L. Kinetics of the Mineralization of Nitrogen in a Pig Slurry Compost Applied to Soils. *Compost. Sci. Util.* **2003**, *11*, 72–80. [\[CrossRef\]](#)
11. De Neve, S.; Sleutel, S.; Hofman, G. Carbon mineralization from composts and food industry wastes added to soil. *Nutr. Cycl. Agroecosystems* **2003**, *67*, 13–20. [\[CrossRef\]](#)
12. Hernandez, T.; Moral, R.; Perez-Espinosa, A.; Moreno-Caselles, J.; Perez-Murcia, M.D.; Garcia, C. Nitrogen mineralisation potential in calcareous soils amended with sewage sludge. *Bioresour. Technol.* **2002**, *83*, 213–219. [\[CrossRef\]](#)
13. Bustamante, M.A.; Said-Pullicino, D.; Paredes, C.; Cecilia, J.A.; Moral, R. Influences of winery–distillery waste compost stability and soil type on soil carbon dynamics in amended soils. *Waste Manag.* **2010**, *30*, 1966–1975. [\[CrossRef\]](#) [\[PubMed\]](#)
14. Griffin, T.S.; He, Z.; Honeycutt, C.W. Manure composition affects net transformation of nitrogen from dairy manures. *Plant Soil* **2005**, *273*, 29–38. [\[CrossRef\]](#)
15. Bowden, C.; Spargo, J.; Evanylo, G. Mineralization and N Fertilizer Equivalent Value of Composts as Assessed by Tall Fescue (*Festuca arundinacea*). *Compost Sci. Util.* **2007**, *15*, 111–118. [\[CrossRef\]](#)
16. Chadwick, D.R.; John, F.; Pain, B.F.; Chambers, B.J.; Williams, J. Plant uptake of nitrogen from the organic nitrogen fraction of animal manures: A laboratory experiment. *J. Agric. Sci.* **2000**, *134*, 159–168. [\[CrossRef\]](#)
17. Amlinger, F.; Götz, B.; Dreher, P.; Geszti, J.; Weissteiner, C. Nitrogen in biowaste and yard waste compost: Dynamics of mobilisation and availability—A review. *Eur. J. Soil Biol.* **2003**, *39*, 107–116. [\[CrossRef\]](#)
18. Castán, E.; Satti, P.; González-Polo, M.; Iglesias, M.; Mazzarino, M.J. Managing the value of composts as organic amendments and fertilizers in sandy soils. *Agric. Ecosyst. Environ.* **2016**, *224*, 29–38. [\[CrossRef\]](#)
19. Kaur, G.; Reddy, M.S. Role of phosphate-solubilizing bacteria in improving the soil fertility and crop productivity in organic farming. *Arch. Agron. Soil Sci.* **2014**, *60*, 549–564. [\[CrossRef\]](#)
20. Bustamante, M.A.; Ceglie, F.G.; Aly, A.; Mihreteab, H.T.; Ciaccia, C.; Tittarelli, F. Phosphorus availability from rock phosphate: Combined effect of green waste composting and sulfur addition. *J. Environ. Manag.* **2016**, *182*, 557–563. [\[CrossRef\]](#)
21. Chi, R.; Xiao, C.; Huang, X.; Wang, C.; Wu, Y. Bio-decomposition of rock phosphate containing pyrites by *Acidithiobacillus ferrooxidans*. *J. Cent. South Univ. Technol.* **2007**, *14*, 170–175. [\[CrossRef\]](#)
22. Rick, T.L.; Jones, C.A.; Engel, R.E.; Miller, P.R. Green manure and phosphate rock effects on phosphorus availability in a northern Great Plains dryland organic cropping system. *Org. Agric.* **2011**, *1*, 81–90. [\[CrossRef\]](#)
23. Stanisławska-Głubiak, E.; Korzeniowska, J.; Hoffmann, J.; Górecka, H.; Józwiak, W.; Wisniewska, G. Effect of sulphur added to phosphate rock on solubility and phytoavailability of phosphorus. *Pol. J. Chem. Technol.* **2014**, *16*, 81–85. [\[CrossRef\]](#)
24. Lerch, R.N.; Barbarick, K.A.; Sommers, L.E.; Westfall, D.G. Sewage sludge proteins as labile C and N sources. *Soil Sci. Soc. Am. J.* **1992**, *56*, 1470–1476. [\[CrossRef\]](#)

25. Sparks, D.L.; Page, A.L.; Helmke, P.A.; Loeppert, R.H.; Soltanpour, P.N.; Tabatabai, M.A.; Johnston, C.T.; Sumner, M.E. *Methods of Soil Analysis, Part 3. Chemical Methods*; Soil Science Society of America: Madison, WI, USA, 1996; Volume 5, p. 1390.
26. Bremner, J.M.; Keeney, D.R. Steam distillation methods for determination of ammonium, nitrate and nitrite. *Anal. Chim. Acta* **1965**, *32*, 485–495. [[CrossRef](#)]
27. Martin, T.D.; Brockhoff, C.A.; Creed, J.T. EMMC Methods Work Group. Method 200.7; Revision 4.4; In *Determination of Metals and Trace Elements in Water and Wastes by Inductively Coupled Plasma-Atomic Emission Spectrometry*; USEPA: Cincinnati, OH, USA, 1994; p. 58.
28. Honeycutt, C.W.; Griffin, T.S.; He, Z. Manure nitrogen availability: Dairy manure in northeast and central US soils. *Biol. Agric. Hortic.* **2005**, *23*, 199–214. [[CrossRef](#)]
29. de la Fuente, C.; Clemente, R.; Martínez, J.; Bernal, M.P. Optimization of pig slurry application to heavy metal polluted soils monitoring nitrification processes. *Chemosphere* **2010**, *81*, 603–610. [[CrossRef](#)]
30. Pell, M.; Stenström, J.; Granhall, U. Soil Respiration. In *Microbiological Methods for Assessing Soil Quality*; Bloem, J., Hopkin, D.W., Benedetti, A., Eds.; CABI International: Wallingford, CT, USA, 2005; pp. 117–126.
31. Zibilske, L.M. Carbon Mineralization. In *Methods of soil analysis. Part 2. Microbiological and Biochemical Properties*; Weaver, R.W., Angle, J.S., Bottomley, P.S., Eds.; Soil Science Society of America: Madison, WI, USA, 1994; pp. 835–863.
32. Hyams, D.G. Curve Expert Software v.2.4.0. 2016. Available online: <http://www.curveexpert.net> (accessed on 28 February 2022).
33. Di Rienzo, J.A.; Casanoves, F.; Balzarini, M.G.; González, L.; Tablada, M.; Robledo, C.W. *InfoStat Software 2020*; Universidad Nacional de Córdoba: Córdoba, Argentina; Available online: <https://www.infostat.com.ar/> (accessed on 28 February 2022).
34. Compost: Marco normativo para la producción, Registro y aplicación de compost. In *Resolución Conjunta 1/2019*; Servicio Nacional de Sanidad y Calidad Agroalimentaria-Secretaría de Control y Monitoreo Ambiental: Buenos Aires, Argentina, 2019; Available online: <https://www.argentina.gob.ar/normativa/nacional/resoluci%C3%B3n-1-2019-318692> (accessed on 28 February 2022). (In Spanish)
35. Satti, P.S. Biodisponibilidad de Nitrógeno y Fósforo en Suelos Volcánicos Bajo Bosque Nativo. Disturbados y Enmendados. Ph.D. Thesis, Universidad Nacional del Comahue, San Carlos de Bariloche, Argentina, 2007. (In Spanish).
36. Tognetti, C. Compostaje de Residuos Orgánicos Urbanos: Optimización Del Proceso Para Una Mayor Calidad Del Producto Final. Ph.D. Thesis, Universidad Nacional del Comahue, San Carlos de Bariloche, Argentina, 2007. (In Spanish).
37. Griffin, T.S.; Honeycutt, C.W. Using growing degree days to predict nitrogen availability from livestock manures. *Soil Sci. Soc. Am. J.* **2000**, *64*, 1876–1882. [[CrossRef](#)]
38. Mazzarino, M.J.; Satti, P.; Moyano, S.; Laos, F. Compost de Biosólidos: Efecto del tamizado sobre la inmovilización de nitrógeno del suelo. *Cienc. Del Suelo* **2004**, *22*, 19–26. (In Spanish)
39. Cardoso, C.; López, F.M.; Orden, L.; Rodríguez, R.A.; Díaz, J. Phosphorous availability of seven organic manures in a sandy soil. *Acta Hortic.* **2016**, *1146*, 149–155. [[CrossRef](#)]
40. Bernal, M.; Roig, A. Nitrogen transformations in calcareous soils amended with pig slurry under aerobic incubation. *J. Agric. Sci.* **1993**, *120*, 89–97. [[CrossRef](#)]
41. Cayuela, M.L.; Sinicco, T.; Mondini, C. Mineralization dynamics and biochemical properties during initial decomposition of plant and animal residues in soil. *Appl. Soil Ecol.* **2009**, *41*, 118–127. [[CrossRef](#)]
42. Hadas, A.; Portnoy, R. Rates of decomposition in soil and release of available nitrogen from cattle manure and municipal waste composts. *Compost. Sci. Util.* **1997**, *5*, 48–54. [[CrossRef](#)]
43. Eghball, B.; Wienhold, B.J.; Gilley, J.E.; Eigenberg, R.A. Mineralization of manure nutrients. *J. Soil Water Conserv.* **2002**, *57*, 470–473.
44. Sánchez, F.I.; Delgado, J.L.R. Efecto de la aplicación del compost sobre las propiedades físicas y químicas del suelo. In *Compostaje*; Moreno Casco, J., Moral Herrero, R., Eds.; Mundi Prensa: Madrid, Spain, 2008; pp. 307–327. (In Spanish)
45. Cardoso, C.; Laurent, G.; Rodríguez, R.A.; Miglierina, A.M.; Minoldo, G.; Dagna, N.; Orden, L. Potentially crop-N supply from different organic amendments to a soil from the low valley of the Río Negro province. Argentine. *Acta Hortic.* **2013**, *1076*, 193–198. [[CrossRef](#)]
46. Griffin, T.; Honeycutt, C.W.; He, Z. Effects of temperature, soil water status, and soil type on swine slurry nitrogen transformations. *Biol. Fertil. Soils* **2002**, *36*, 442–446.
47. Shah, G.M.; Rashid, M.I.; Shah, G.A.; Groot, J.C.J.; Lantinga, E.A. Mineralization and herbage recovery of animal manure nitrogen after application to various soil types. *Plant Soil* **2013**, *365*, 69–79. [[CrossRef](#)]
48. Mubarak, A.R.; Gali, E.A.; Mohamed, A.G.; Steffens, D.; Awadelkarim, A.H. Nitrogen mineralization from five manures as influenced by chemical composition and soil type. *Soil Sci. Plant Anal.* **2010**, *41*, 1903–1920. [[CrossRef](#)]
49. Thomsen, I.K.; Schjøning, P.; Christensen, B.T. Mineralisation of ¹⁵N-labelled sheep manure in soils of different texture and water contents. *Biol. Fert. Soils* **2003**, *37*, 295–301. [[CrossRef](#)]
50. Hadas, A.; Portnoy, R. Nitrogen and carbon mineralization rates of composted manures incubated in soil. *J. Environ. Qual.* **1994**, *23*, 1184–1189. [[CrossRef](#)]
51. Dao, T.H.; Schwartz, R.C. Effects of manure management on phosphorus biotransformations and losses during animal production. In *Phosphorus in Action*; Bünemann, E.K., Oberson, A., Frossard, E., Eds.; Springer: Berlin/Heidelberg, Germany, 2011; pp. 407–429.
52. Zvomuya, F.; Helgason, B.L.; Larney, F.J.; Janzen, H.H.; Akinremi, O.O.; Olson, B.M. Predicting phosphorus availability from soil-applied composted and non-composted cattle feedlot manure. *J. Environ. Qual.* **2006**, *35*, 928–937. [[CrossRef](#)] [[PubMed](#)]

53. Helgason, B.L.; Larney, F.J.; Janzen, H.H. Estimating carbon retention in soils amended with composted beef cattle manure. *Can. J. Soil Sci.* **2005**, *85*, 39–43. [[CrossRef](#)]
54. Aber, J.D.; Melillo, J.M. *Terrestrial Ecosystems*; Saunders College Pub.: Philadelphia, PA, USA, 1999; p. 430.
55. Landi, A.; Mermut, A.R.; Anderson, D.W. Origin and rate of pedogenic carbonate accumulation in Saskatchewan soils, Canada. *Geoderma* **2003**, *117*, 143–156. [[CrossRef](#)]
56. Serna-Pérez, A.; Monger, H.C.; Herrick, J.E.; Murray, L. Carbon dioxide emissions from exhumed petrocalcic horizons. *Soil Sci. Soc. Am. J.* **2006**, *70*, 795–805. [[CrossRef](#)]
57. Thomsen, I.; Olesen, J.C. N mineralization of composted and anaerobically stored ruminant manure in differently textured soils. *J. Agric. Sci.* **2000**, *135*, 151–159. [[CrossRef](#)]
58. Murwira, H.K.; Kirchmann, H.; Swift, M.J. The effect of moisture on the decomposition rate of cattle manure. *Plant Soil* **1990**, *122*, 197–199. [[CrossRef](#)]
59. De Nobili, M.; Contin, M.; Mondini, C.; Brookes, P.C. Soil microbial biomass is triggered into activity by trace amounts of substrate. *Soil Biol. Biochem.* **2001**, *33*, 1163–1170. [[CrossRef](#)]
60. Antil, R.S.; Bar-Tal, A.; Fine, P.; Hadas, A. Predicting nitrogen and carbon mineralization of composted manure and sewage sludge in soil. *Compost. Sci. Util.* **2011**, *19*, 33–43. [[CrossRef](#)]